

Experimental investigation of the beam dynamics of the MESA photoinjector

Dissertation

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Abstract

The Institute of Nuclear Physics at Johannes Gutenberg University Mainz is building a new accelerator called Mainz Energy-recovering Superconducting Accelerator (MESA). MESA will be a recirculating machine like the existing Mainz Microtron (MAMI) delivering a c.w. electron beam with a repetition rate of 1.3 GHz. In the ERL operating mode the average beam current should be 1 mA, and in a second stage increased up to 10 mA. The beam quality, which is described by the emittance, is very important for a reliable accelerator operation.

The normalized emittance of the electron beam should be $\epsilon_n < 1 \text{ mm mrad} = 1 \text{ }\mu\text{m}$. The desired beam currents of up to 10 mA in combination with an emittance of $\epsilon_{n,\text{max}} = 1 \text{ }\mu\text{m}$ create high electron densities. The latter will act as a detrimental effect on the beam quality due to nonlinear space charge forces. Therefore, diagnostic elements are very important, in particular to characterize the properties of the electron source, since they are difficult to simulate because of the complexity of photoemission.

The thesis describes emittance measuring methods for low-energy electron beams (100 keV) and investigations of their temporal distribution in the picosecond regime. A diagnostic test beam line has been built, and the diagnostic elements have been designed and put into action. The diagnostic elements consist of screens and wires to perform quadrupole scans for the emittance determination. In addition, slit masks are installed, which allow to reduce space charge effects during the emittance determination.

Furthermore, a reliable laser system which allows to simulate the operating parameters of MESA has been constructed and commissioned. The laser system contains two different laser diodes with different wavelengths and enables to investigate the effect of the temporal bunch structure and the emitter area on the evolution of the emittance within the low-energy beam transport system. The electron beam parameters could be determined up to a current of about 2.4 mA, which corresponds to a bunch charge of approximately 2 pC. A circular deflecting cavity was employed to characterize the bunch length of the electron pulses. With the existing electron source satisfying bunchlengths and emittances have been observed at $I_{\text{beam}} \leq 1 \text{ mA}$, which is sufficient to start MESA operations. The experiments performed cover the requirements for MESA stage-1.

Zusammenfassung

Das Institut für Kernphysik der Johannes Gutenberg-Universität Mainz baut einen neuen Beschleuniger mit der Bezeichnung “Mainz Energy-recovering Superconducting Accelerator” (MESA). MESA wird, ähnlich wie das bereits existierende Mainz Mikrotron (MAMI), ein rezirkulierender Beschleuniger sein, der einen c.w. Strahl mit einer Frequenz von 1,3 GHz liefern wird. Im sogenannten ERL Betrieb soll der mittlere Strahlstrom zunächst 1 mA betragen, was in einer weiteren Ausbaustufe auf 10 mA erhöht werden wird. Für einen zuverlässigen Betrieb des Beschleunigers ist die Strahlqualität entscheidend, die durch die Emittanz beschrieben wird.

Die normierte Emittanz des Elektronenstrahls sollte $\epsilon_n < 1 \text{ mm mrad} = 1 \mu\text{m}$ betragen und wird maßgeblich durch die Eigenschaften der Elektronenquelle definiert. Durch die angestrebten Strahlströme von bis zu 10 mA in Verbindung mit einer Emittanz von $\epsilon_{n,\text{max}} = 1 \mu\text{m}$ können hohe Elektronendichten auftreten, welche durch die nichtlinearen Raumladungskräfte die Strahlqualität nachteilig beeinflussen. Deswegen ist eine geeignete Strahldiagnose unerlässlich, nicht zuletzt um die Eigenschaften der Elektronenquelle zu bestimmen, die sich aufgrund der Komplexität des Photoemissionsprozesses nur schwer modellieren lassen.

Die vorliegende Arbeit beschäftigt sich mit Emittanzmessungen an niederenergetischen Elektronenstrahlen (100 keV) sowie der Messung der Elektronenpulslänge im Pikosekundenbereich. Für diesen Zweck wurde eine Teststrahlführung aufgebaut und die nötigen Diagnoseelemente wurden entwickelt und in Betrieb genommen. Die Strahldiagnoseeinheiten bestehen aus Leuchtschirmen und Drähten, mit denen Quadrupolscans ausgewertet werden können um eine Emittanzbestimmung durchzuführen. Zusätzlich sind auch noch Schlitzmasken verbaut, die eine Reduzierung der Raumladungskräfte während der Emittanzvermessung ermöglichen.

Da die Strahldiagnoseelemente für den Betrieb an MESA konzipiert sind, werden diese unter realitätsnahen Bedingungen—wie sie auch später an MESA vorliegen—getestet. Anhand dieser Anforderungen wurde ein zuverlässiges Lasersystem aufgebaut und in Betrieb genommen. Das Lasersystem besteht aus zwei Laserdioden mit unterschiedlichen Wellenlängen und Pulseigenschaften. Dies ermöglicht es die Auswirkungen der zeitlichen Struktur der Bunche sowie der emittierenden Fläche auf die Entwicklung der Emittanz zu untersuchen. Im Rahmen dieser Arbeit konnten die Strahlparameter bis zu einem Strahlstrom von 2,4 mA bestimmt werden, was einer Bunchladung von 2 pC entspricht. Ein Deflektorresonator wurde verwendet, um die auftretenden Pulslängen zu charakterisieren. Die beobachteten Bunchlängen und Emittanzen für $I_{\text{beam}} \leq 1 \text{ mA}$ sind ausreichend, um mit dem Betrieb von MESA zu beginnen. Die durchgeführten Messungen decken die Anforderungen für die erste Ausbaustufe von MESA ab.

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1. Introduction and motivation

Nowadays and in the past, producing a low-emittance, high-brilliance beam has been desirable for accelerator facilities. To achieve this aim, different methods to create and accelerate electron beams^a exist, e.g. laser-driven RF (ELBE^b at the Helmholtz Center Dresden Rossendorf or bERLinPro^c at the Helmholtz Center Berlin) or dc photoelectron guns (CEBAF^d at Jefferson Lab). At the Institute of Nuclear Physics (KPH) of Johannes Gutenberg University, there exist several dc photoelectron guns with an electric potential of 100 kV to accelerate the electrons. These electrons are produced using the photoeffect. A laser spot is focused onto a semiconductor cathode, in which electrons excited by the photons can reach the surface after a few collisions depending on the depth where they were created. Then they can be accelerated by the electric field afterwards (more details are presented in Sec. 3.2). The photocathodes are made of gallium arsenide (GaAs), and there are two different types of cathodes in use at KPH. One is a bulk cathode^e, and the other one is a strained layer super lattice (SLSL) with which it is possible to reach an electron polarization of 80% [AuAT12]. Unfortunately, the cathodes have a finite lifetime and have to be replaced after a specific time, depending on the extracted charge. Due to this effect, every electron is valuable and should be used for the experiment. To ensure that not too many electrons are wasted, the drive laser operates in a pulse mode so that the electrons are produced in phase with the accelerator radio frequency.

The MESA^f facility will be a recirculating accelerator with a laser-driven dc photoelectron gun operating at 100 kV. The floor plan is shown in Fig. 1.1, and the area occupied by MESA will be approximately $(10 \times 26) \text{ m}^2$. As photocathode material, SLSL GaAs and KCsSb (PCA)^g will be used for spin-polarized and high-current operation, respectively. The drive laser is RF-synchronized to the accelerator radio frequency of $\nu_{\text{MESA}} = 1.3 \text{ GHz}$, and the produced electron bunches undergo a spin manipulation section comprising two Wien filters and a solenoid before they pass the chopper/buncher section for a longitudinal emittance adjustment. A magnified overview of the MELBA^h system is visualized in Fig. 1.2. To achieve the required

^aThis thesis focuses on electrons because MAMI and MESA are electron accelerators.

^bELBE: Electron Linear accelerator for beams with high Brilliance and low Emittance

^cbERLinPro: Berlin Energy Recovery Linear accelerator Project - under construction

^dCEBAF: Continuous Electron Beam Accelerator Facility

^eWafer Technology Inc. - 2", p-type, doped with Zinc, 500 μm thickness

^fMESA - Mainz Energy-recovering Superconducting Accelerator

^gPCA - Potassium Cesium Antimonite. This photocathodes will be manufactured in-house with a dedicated cathode production vacuum chamber.

^hMELBA - MEsa Low-energy Beam Apparatus

1. Introduction and motivation

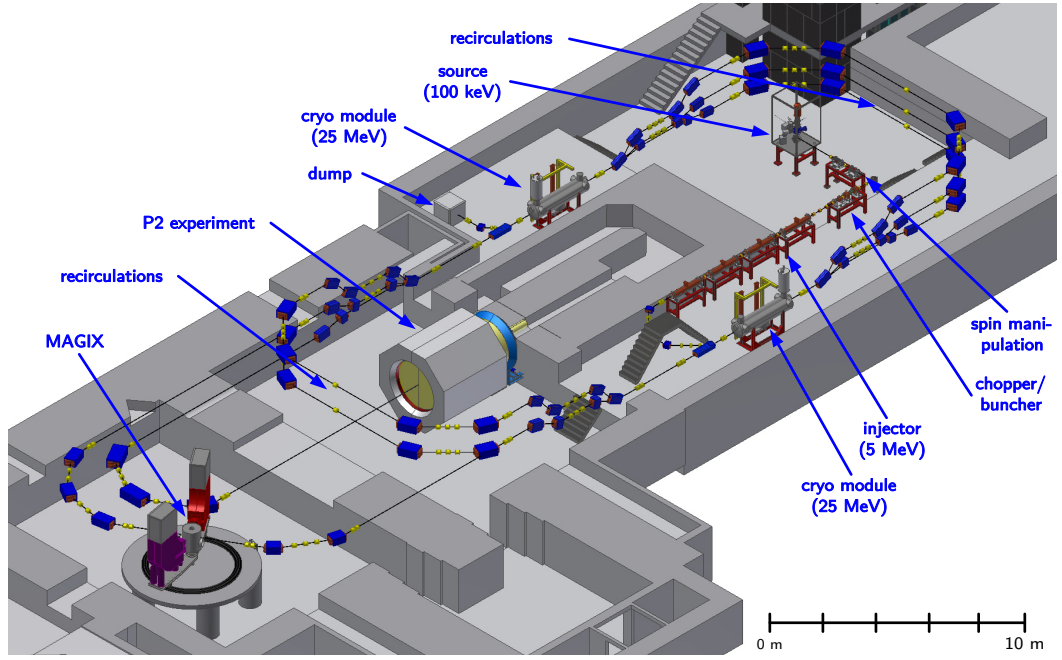


Figure 1.1.: Floor plan of the planned MESA facility. The accelerator will occupy an area of approximately $(10 \times 26) \text{ m}^2$. The electron source is located in the upper right corner, followed by the spin manipulation and chopper/buncher sections to get a longitudinal emittance adjustment. The next element is the injector with a final energy of 5 MeV. Each cryo module of the main accelerator has an energy gain of 25 MeV, and with three recirculations MESA will achieve an energy of 155 MeV. The MAGIX experiment will do research on the dark photon, and the goal of the P2 experiment is a precision measurement of the weak mixing angle $\sin^2(\theta_W)$.

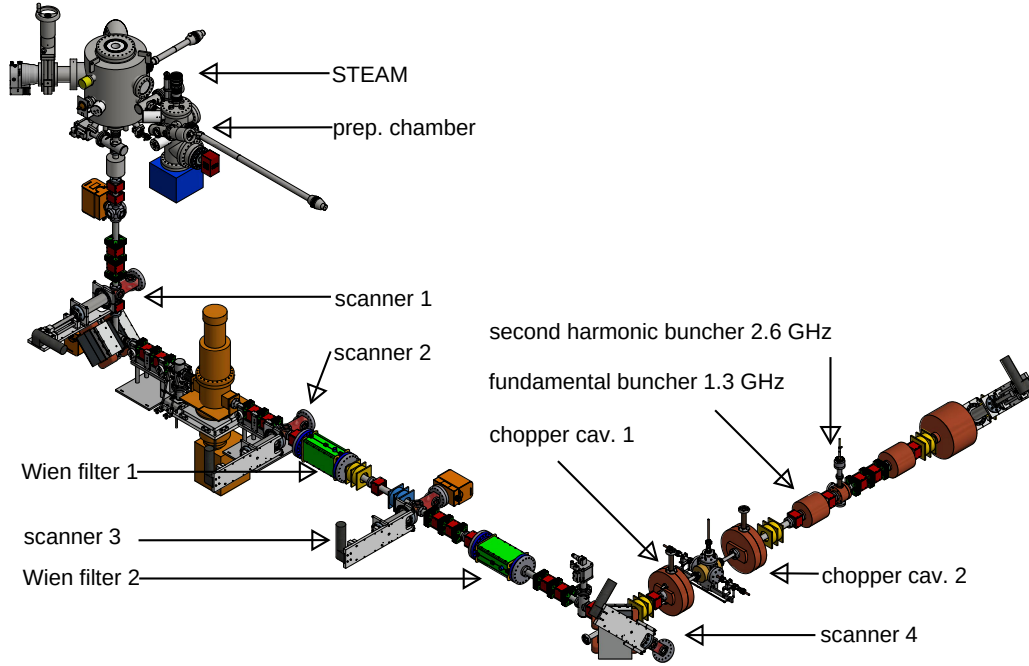


Figure 1.2.: Magnified overview of the MELBA system and its components. The electrons are produced in the upper left corner and accelerated in the vertical direction. At the first α -magnet, they are bent by 270° into the horizontal direction, where they undergo the spin manipulation section comprising two Wien filters and a solenoid. After the second α -magnet comes the chopper/buncher section for a longitudinal emittance adjustment. Furthermore, in MELBA five scanner systems will be mounted for the beam diagnostics. (courtesy of C. Matejcek; modified)

1. Introduction and motivation

RF-synchronized electron bunches, a laser system with different laser diodes (LD) has been built. The setup is described in Sec. 5.2. This laser system provides an effective means to create conditions similar to the MESA operation and to investigate the beam dynamics. Later it will be replaced by a dedicated laser system similar to [OBD+07].

The MAMBOⁱ section is built using normal conducting technology and has a final energy of 5 MeV. The injection into the main accelerator is done with a 180° arc. Each of the two cryo modules of the main accelerator has an energy gain of 25 MeV, and with three recirculations MESA will reach an energy of 155 MeV.

MESA will be able to run in two different operating modes. One is the energy recovery mode (ERL), which will handle the high current needed for the MAGIX^j experiment [Deni15]. In this mode, MESA will reach an energy of 105 MeV with an electron current of 1 mA in stage-1 and 10 mA in stage-2. Here, the length of the last arc—where the target is located (see left side of Fig. 1.1)—will be a half integer multiple of the RF wave length, and so it is possible to decelerate the electron bunches, restoring their energy in the RF field of the cavities. If the ERL mode runs efficiently, the dumped electrons have an energy of only 5 MeV.

The MAGIX experiment will include a variety of physics topics, one of which is the search for the dark photon. In the past, the A1 collaboration at MAMI has engaged in the dark photon search [Merk14]. The physics model investigated contains an interaction of the dark photon with particles of the standard model (SM). This approach was used to try to explain the observed deviation of the anomalous magnetic moment of the muon $((g - 2)_\mu)$ from the SM-value. Since 2016, new data analyses have covered the complete parameter space of interest. But there are other physical models to be investigated which include a coupling of the dark photon with dark matter. The model used for the new investigations is still able to explain the discrepancy in the magnetic moment of the muon. These measurements can be performed via a missing mass method to take invisible decays into account. In Fig. 1.3, the Feynman diagrams of the investigated model and the new approach are shown on the left and right side, respectively.

The other operating mode is the external beam mode (EB) with an external target and spin-polarized electrons. This mode is called external beam because there will be no recuperation of the electron beam like in the case of the ERL mode. Here MESA will reach an energy of 155 MeV. The experiment which is carried out in this mode is called P2, and its location is shown in the middle of Fig. 1.1. The main purpose of the P2 experiment is to determine the weak mixing angle θ_W of the proton and electron [BA+15]. This experiment is a parity-violation experiment where the spin-polarized electrons hit a liquid hydrogen target and will be scattered elastically. By flipping the spin orientation of the electrons,

ⁱMAMBO - Milliampere Booster (final energy $E_{\text{MAMBO}} = 5 \text{ MeV}$)

^jMAGIX - MAInz Gas Internal eXperiment

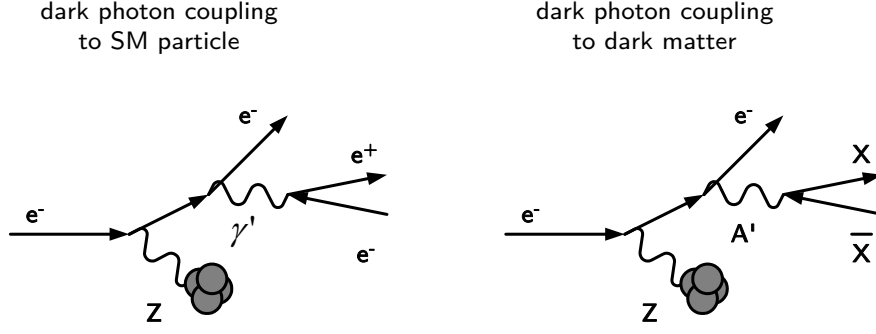


Figure 1.3.: The diagram on the left side shows the interaction of a dark photon with particles of the standard model (SM). The parameter space investigated to explain the discrepancy of $(g - 2)_\mu$ using the model on the left side has been covered by various experiments without sufficient hints at the dark photon. The interaction depicted on the right side proposes a coupling between a dark photon and the dark matter. This model is still able to explain the discrepancy in the magnetic moment of the muon. Measurements can be performed via a missing mass method to take the invisible decays into account.

an asymmetry A_{pv} in the count rates of the detectors will be measured. This asymmetry A_{pv} is proportional to

$$A_{pv} \propto P_e Q^2 (1 - 4 \sin^2(\theta_W))$$

where P_e is the electron polarization and Q is the momentum transfer. Within the P2 project, it will be tried to measure $\sin^2(\theta_W)$ with a relative uncertainty of 0.15%. This means that very high statistics are needed, which require 10^4 h of data taking [BBM+18]. This amount of data taking will be hard to achieve in a shared facility like MAMI but feasible at MESA. An additional point is the lower operating costs caused by the smaller dimensions compared to MAMI. Moreover, MESA will be an excellent choice for this experiment since the error prediction shows a minimum at an energy of 200 MeV. In Fig. 1.4, $\sin^2(\theta_W)$ is plotted over the momentum transfer Q , and the blue line is the prediction of the standard model. The values for existing (black), as well as the predictions for ongoing (blue) and planned (green) experiments are also included.

Concerning the planned MESA facility, there are some questions to be answered. One of the main important questions is if it is possible to achieve the promised electron current of 1 mA (10 mA in stage-2) for an unpolarized and also 1 mA for a polarized electron beam with the existing 100 kV electron gun (PKA2) or if a new 200 kV gun (STEAM^k) should be used, which has already been constructed and will be commissioned by the end of the year 2018. The PKA2 is a reliable and proven electron gun, and STEAM, on the other hand, may involve some technical risks. In

^kSTEAM - Small Thermalized Electron source At Mainz

1. Introduction and motivation

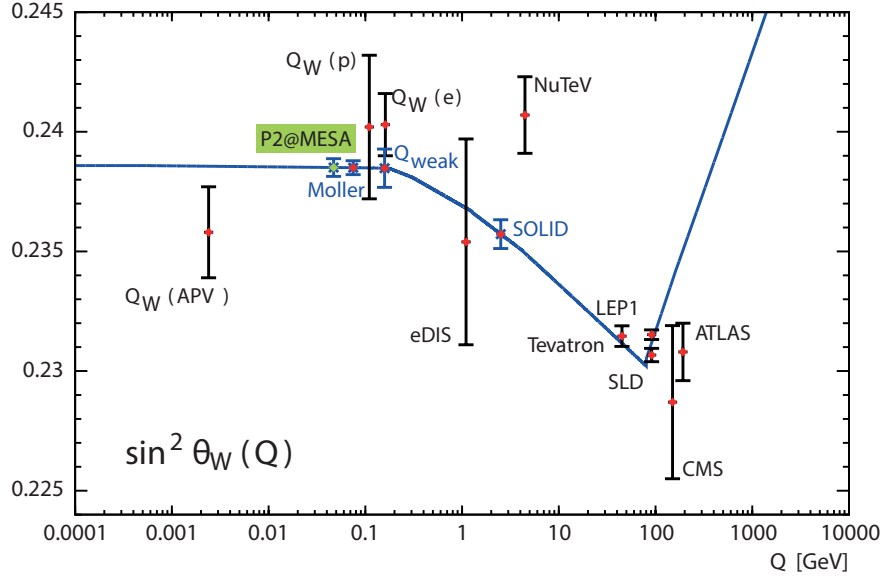


Figure 1.4.: The value of $\sin^2(\theta_W)$ is plotted over the momentum transfer Q for existing (black), ongoing (blue) and planned (green) experiments along with the prediction of the standard model (blue line). [BA+15]

the planned regime of electron current, the charge within one bunch reaches 8 pC, and we are stepping over the border from the emittance-dominated to the space charge-dominated beams, i.e. trajectories are largely determined by the repulsive forces between the electrons inside the bunch.

It is necessary to know where the space charge-dominated regime begins and how big the influence in a 100 keV beam line of several meters would be. To find an answer to these questions, some experiments and investigations were carried out during this work, which are explained and discussed in Sec. 6. To generate similar operating parameters compared to MESA, a laser system was built which enables to produce RF-synchronized electron bunches. The laser system contains two different laser diodes to investigate the influence of the temporal distribution on the emittance growth. Moreover, the diagnostic elements have been designed and implemented into the beam line. The developed diagnostic elements are not only needed for beam diagnostics but furthermore for the characterization of the electron gun. These elements have to fulfill some requirements with respect to the vacuum conditions and the available space. This thesis introduces two different methods—the quadrupole scan and the slit mask method—to determine the transverse emittance. In addition, the evolution of the longitudinal electron distribution will be investigated with a deflecting cavity.

2. Beam dynamics and space charge

In this chapter, an introduction to some physical basics used in this thesis will be given. It begins with some general remarks on emittance and the emittance measuring methods followed by a mathematical description of the emittance determination via a quadrupole scan. This is followed by an explanation of some space charge effects and it ends with a description of the working principle of the slit mask method.

2.1. General remarks on emittance

At the beginning, it is necessary to define a coordinate system for the particles. It is common to declare a co-moving coordinate system (depicted in Fig. 2.1) to reduce the mathematical effort because the beam dimensions are very small compared with the size of the accelerator. The coordinate system moves along the orbit set by the magnetic structure of the accelerator. Thus, the orbit describes the ideal particle trajectory. The coordinate system is spanned by the axes x , y and s , and so it is possible to describe all particle coordinates with respect to the orbit [Will05].

The emittance is a measure of the six-dimensional phase space volume of the emitted particles. At the Institute of Nuclear Physics at the University of Mainz, there are only electron sources, and thus, the particles will be called electrons in the further chapters. The six-dimensional phase space can be divided into three two-dimensional phase spaces independent of each other, because it is assumed that there is no coupling between the transverse directions and the longitudinal one. Thus, there are two transverse phase spaces: (x, x') , (y, y') , and one longitudinal phase space, (s, dE) or $(d\phi_{\text{RF}}, dE)$ with the accelerator phase ϕ_{RF} . In the case of the longitudinal phase space (s, dE) , the parameter dE indicates the energy spread. The three parameters x , y , s span a three-dimensional coordinate system (see Fig. 2.1), and the parameters $x' = dx/ds$ and $y' = dy/ds$ are the associated angles. In Fig. 2.2, an example of one of the three phase spaces with the relations of the Twiss parameters and the acceptance ellipse of a fixed position (e.g. the entrance of the MAMBO) in the accelerator (green) is shown. The distribution shown in blue illustrates the density distribution of the electron occupancy in phase space, and the blue dashed line marks a certain amount of particles (1σ , 2σ , etc.) that are taken into account.

In general, any distribution of the electrons in phase space can be captured by an ellipse. For complex geometries—e.g. spiral-shaped or “s”-shaped geometries—the ellipse area will be larger than the true occupied area in phase space. The description of the electron distribution via an ellipse is convenient because if linear forces

2. Beam dynamics and space charge

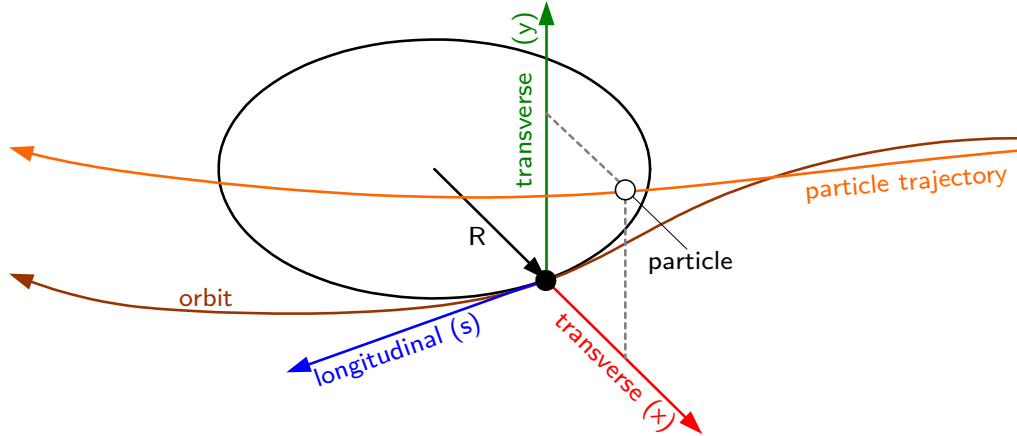


Figure 2.1.: Illustration of a co-moving coordinate system. The origin of the coordinate system moves along the orbit defined by the magnetic structure of the accelerator. The axes are x , y and s . The black circle illustrates the possibility of a piecewise mathematical description of the orbit.

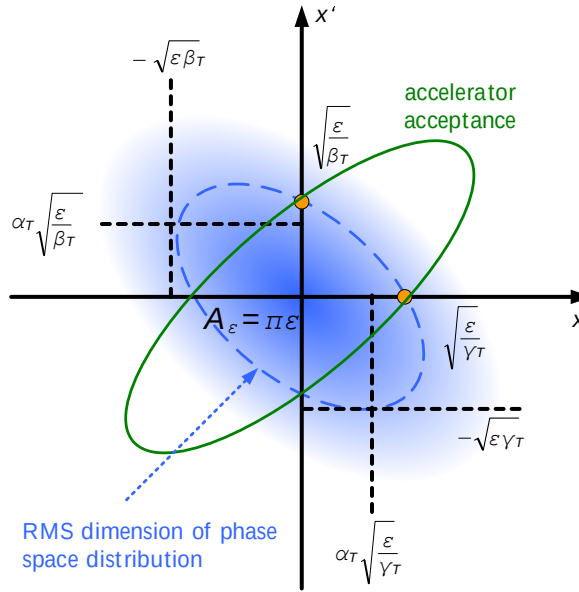


Figure 2.2.: Example of a two-dimensional phase space with the relations of the Twiss parameters and the acceptance ellipse of the accelerator (green). The density distribution of the particle occupancy in phase space is illustrated in blue, and the blue dashed line marks a certain amount of particles (1σ , 2σ , etc.) that are taken into account.

act on an ellipse, it will be transformed into an ellipse. This formalism reduces the mathematical complexity and provides a conservative estimate for the emittance. The general expression for an ellipse can be written as

$$\gamma_T x^2 + 2\alpha_T x x' + \beta_T x'^2 = \epsilon_x \quad (2.1)$$

with

$$\gamma_T \beta_T - \alpha_T^2 = 1.$$

These parameters are called Twiss or Courant-Snyder parameters [Wied93, MiZi03].

The emittance ϵ and the area A_ϵ of the ellipse have the relation $\epsilon = A_\epsilon/\pi$ (see also Fig. 2.2). Since the beam has no sharp edges, it is necessary to define the amount of the electron distribution that should be considered, i.e. FWHM^a or 4σ , corresponding to 76% or 95%, respectively, in the case of a one-dimensional Gaussian distribution. It has become common to calculate the RMS emittance based on the second momenta of the distribution. The RMS values can be calculated for any kind of distribution which is constrained by a physical boundary (e.g. the beam pipe).

As shown in Fig. 2.2, the RMS values of the beam size x and the beam divergence x' are related to the ellipse parameters via

$$\langle x^2 \rangle = \beta_T \epsilon_x = m_{11}$$

and

$$\langle x'^2 \rangle = \gamma_T \epsilon_x = m_{22},$$

respectively. The parameter α_T is calculated with $\alpha_T^2 = -\langle x x' \rangle / \epsilon_x$. The relations for α_T , β_T and γ_T are also valid for the y axis. These parameters can be merged in a beta matrix M_{beta} with the following relations [Hint08, MiZi03, Will05]:

$$M_{\text{beta}} = \begin{pmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{pmatrix} = \epsilon \begin{pmatrix} \beta_T & -\alpha_T \\ -\alpha_T & \gamma_T \end{pmatrix} \quad (2.2)$$

With these definitions, the RMS emittance can be expressed as

$$\epsilon_x = \sqrt{\det(M_{\text{beta}})} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2} \quad (2.3)$$

The $\langle \dots^2 \rangle$ indicates that the second momenta of the variable are calculated. At this point, Liouville's theorem should be mentioned. This theorem is fundamental and generally valid in accelerators if radiative effects or collisions can be neglected [Will05, Hint08]. Liouville's theorem states that a phase space volume occupied by particles that obey the Hamiltonian equation of motion and are affected only by conservative forces does not change in time. Thus, the six-dimensional phase space volume remains constant; however, the shape can change [Nolt04, Rebh06, Reis08, Will05]. Furthermore, it is possible to derive from this fact that the phase

^aFWHM: full width at half maximum

2. Beam dynamics and space charge

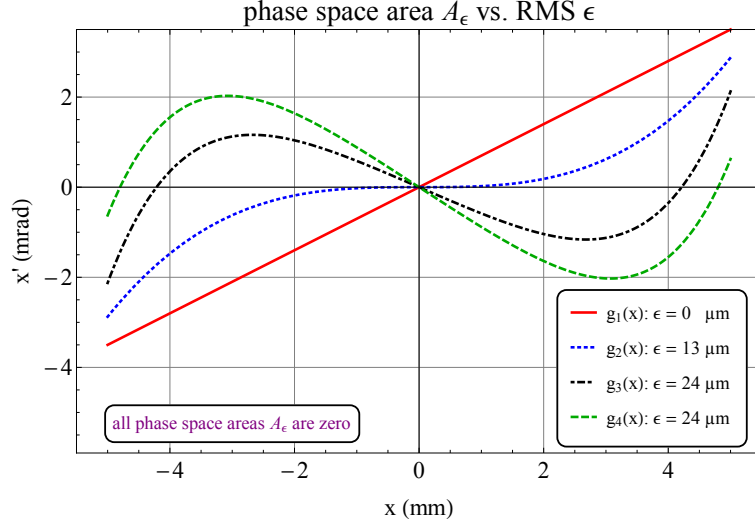


Figure 2.3.: Phase space example for linear and nonlinear conservative forces. All phase spaces have no area but the curved ones have an RMS emittance which is calculated with Eq. 2.3 and indicated in the legend.

space volume and the emittance cannot be reduced because the particles in phase space behave like an incompressible liquid [Nolt04]. Space charge is a result of the electric potential inside the electron bunch, i.e. space charge is a conservative force, and therefore, Liouville's theorem can be applied.

Fig. 2.3 illustrates an example of four different emittance shapes—all with the area $A_\epsilon = \pi\epsilon = 0$ —in the (x, x') phase space. The shapes are calculated with

$$\begin{aligned} g_1(x) &= A_1 x \\ g_2(x) &= B_2 x^3 \\ g_3(x) &= A_3 x + B_3 x^3 + C_3 x^5 \\ g_4(x) &= 1.5 A_3 x + B_3 x^3 + C_3 x^5 \end{aligned} \quad (2.4)$$

and if Eq. 2.3 is applied to them defining the integration limits as ± 5 mm, it follows that the condition

$$A_\epsilon = \pi \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2} = 0$$

is only valid for linear forces ($g_1(x)$). The other equations $g_{i \geq 2}(x)$ cause a non-zero emittance indicated in the legend of Fig. 2.3, even though they have no area. This leads to the conclusion that if nonlinear forces are acting on the beam, this can increase the RMS emittance without increasing the occupied area. For bunched beams with non-rectangular shapes in all three dimensions, space charge results in a nonlinear force [Chau14]. This aspect implies that the RMS emittance should be used with care since the electron distribution in phase space is usually curved.

Fig. 2.2 shows a phase space ellipse for a converging beam in blue and the orientation of the acceptance ellipse, e.g. at the entrance of the accelerator, in green.

2.2. Basic discussion of emittance measurements at the MESA source

All particles which are not inside the acceptance of the accelerator cannot be transported through it and will be lost. Therefore, it is necessary to match the phase space ellipse to the acceptance by manipulating its orientation using beam optical elements such as quadrupoles or solenoids.

Within the matrix formalism, the orientation of the emittance ellipse can be evolved for each position s in the beam line. This can be done with a 2×2 transport matrix R , the transposed transport matrix R^T and the beta matrix M_{beta} in the following way [MiZi03, Hint08, Wied93, Will05]

$$M_{\text{beta},1} = R M_{\text{beta},0} R^T. \quad (2.5)$$

The indices 0 and 1 indicate the position s_0 and s_1 in the beam line at which the beta matrix is determined. The transport matrix R can contain n elements in the accelerator and is built with

$$R = R_n R_{n-1} \dots R_1 R_0. \quad (2.6)$$

The elements R_i describe the linear transfer of particle coordinates in arbitrary blocks.

It is necessary to normalize the emittance with $\beta_L \gamma_L^b$ because of the acceleration process, during which the longitudinal momenta increase and the transverse momenta stay the same. This phenomenon distorts a comparison of the emittances for different energies in the same accelerator.

Thus, in the further text, the indicated emittances always refer to the normalized RMS emittance

$$\epsilon_{n,x} = \beta_L \gamma_L \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}. \quad (2.7)$$

2.2. Basic discussion of emittance measurements at the MESA source

The beam line used to test the developed emittance measurement system should be as simple as possible. This requirement is not absolutely necessary but helpful to avoid additional systematic errors. All elements mentioned in the further text will be explained in more detail in their own sections. The minimum number of elements needed contains an electron source (see Sec. 3.1), at least two electron-optical elements like quadrupoles (introduced in the following section) or solenoids and some correction magnets to ensure a centered electron beam within the beam line. Fig. 2.4 illustrates a sketch of the composition of the beam line elements. A more detailed introduction of the complete beam line is given in Sec. 5.1. The following components are included in the emittance measurement system:

^bThe relativistic velocity $\beta_L = \frac{v}{c_{\text{vac}}}$ and the Lorentz factor $\gamma_L = 1 + \frac{E_{\text{kin}}}{E_0} = \left(\sqrt{1 - \left(\frac{v}{c_{\text{vac}}} \right)^2} \right)^{-1}$

2. Beam dynamics and space charge

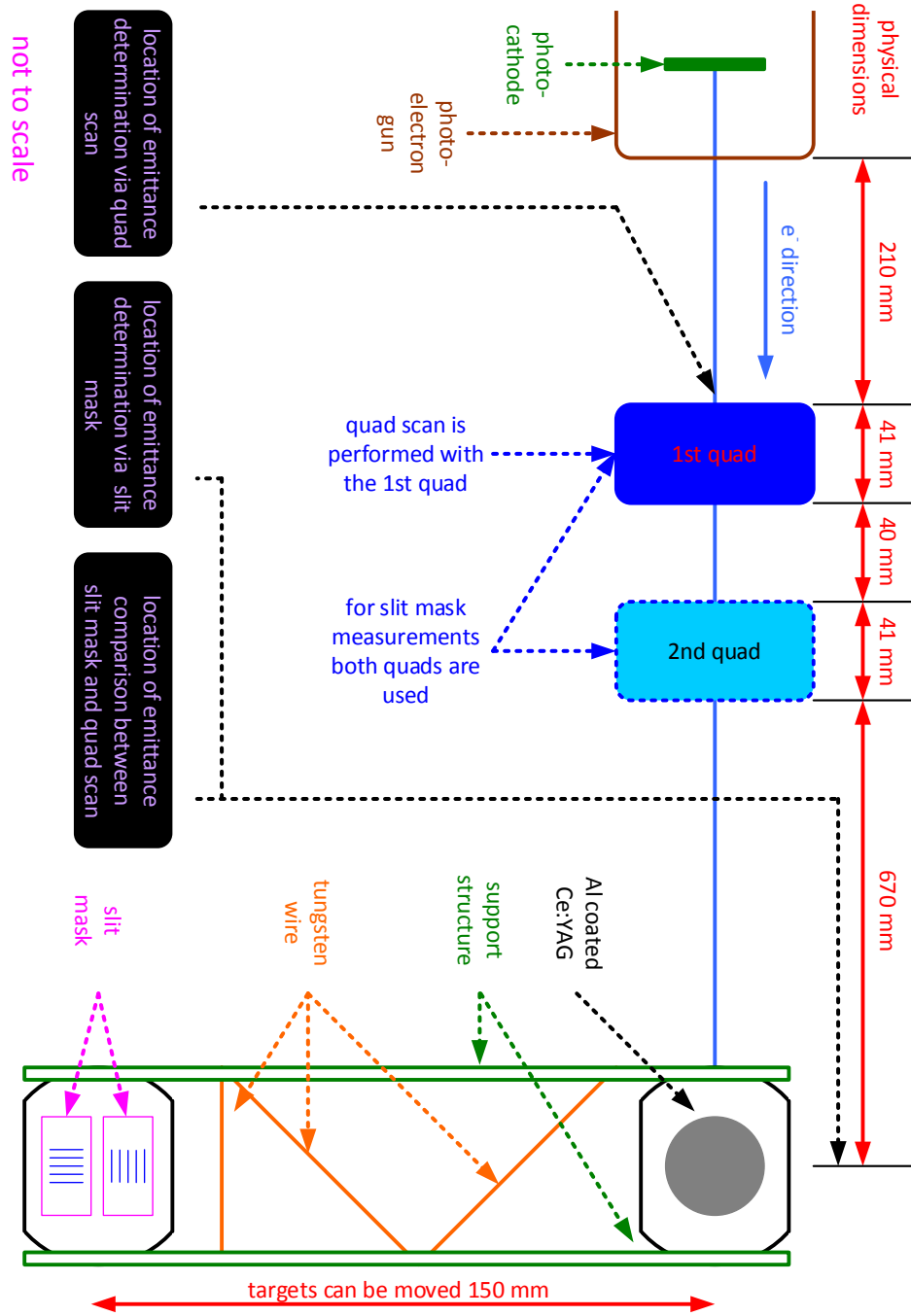


Figure 2.4.: Overview of the emittance measuring methods and the locations of the determined emittances along the beam line. A movable sled (shown here rotated by 90°) carries several devices for emittance measurements.

2.3. Emittance determination with a quadrupole scan

- a screen
- three wires, two of which are oriented perpendicularly to each other, and the third one is mounted at 45° with respect to the previous one
- two masks with slits aligned perpendicularly to each other

An overview about the emittance measurement system and the occupancy of the target frame—which will be called “sled”—follows in Sec. 4.1. The screen and the wires are used to characterize the electron beam via a quadrupole scan. A description of the procedure follows in the next section. For the slit masks, another method is used for the beam characterization. This method is explained in Sec. 2.5. Results are presented in Sec. 6.2.1.1, Sec. 6.2.1.2 and Sec. 6.2.2 for the screen measurements, the wire measurements, and the slit masks, respectively. Since two different techniques are applied to determine the emittance, also the location of the determination differs. Thus, the results of one of the two methods need to be transformed forward or backward along the beam line via Eq. 2.5.

2.3. Emittance determination with a quadrupole scan

For a quadrupole-based emittance measurement, it is necessary to determine the beam profile at more than three positions in the beam line or for different focusing strengths of a quadrupole or a solenoid at the same position [Hint08, Wied93, Will05]. At the PKA2, the focusing strength of a quadrupole is changed, which is schematically shown in the upper part of Fig. 2.5. The lower part of this figure illustrates an example of three different beam shapes during a quad scan for -2.75 diopters, 0 diopters and 2.75 diopters (from left to right). The different beam dimensions can be observed with a screen and a CMOS camera (results will be presented in Sec. 6.2.1.1) or with a movable wire and a scintillator PMT configuration (results will be presented in Sec. 6.2.1.2).

Through the relation

$$\langle x^2 \rangle = \beta_T \epsilon_x = m_{11},$$

the beam size is linked to the beta matrix presented in Eq. 2.2. The beta matrix can be transformed along the beam line with Eq. 2.5. In Eq. 2.5, $M_{\text{beta},1}$ is the beta matrix at the position of the screen/wire, and R is the transfer matrix which contains all electron optical elements and drift spaces between the varied quadrupole and the screen. $M_{\text{beta},0}$ describes the Twiss parameters at the entrance of the quadrupole. At the PKA2, there is only a drift space between the quadrupole and the screen/wire, and thus, the transfer matrix is $R = R_{\text{drift}} R_{\text{quad}}$.

Each quadrupole has a focusing (CQF) and a defocusing (CQD) plane, and therefore, it is necessary to have two different matrices

$$R_{\text{CQF}} = \begin{pmatrix} \cos(\Theta) & \frac{\sin(\Theta)}{\sqrt{k}} \\ -\sqrt{k} \sin(\Theta) & \cos(\Theta) \end{pmatrix} \quad (2.8)$$

2. Beam dynamics and space charge

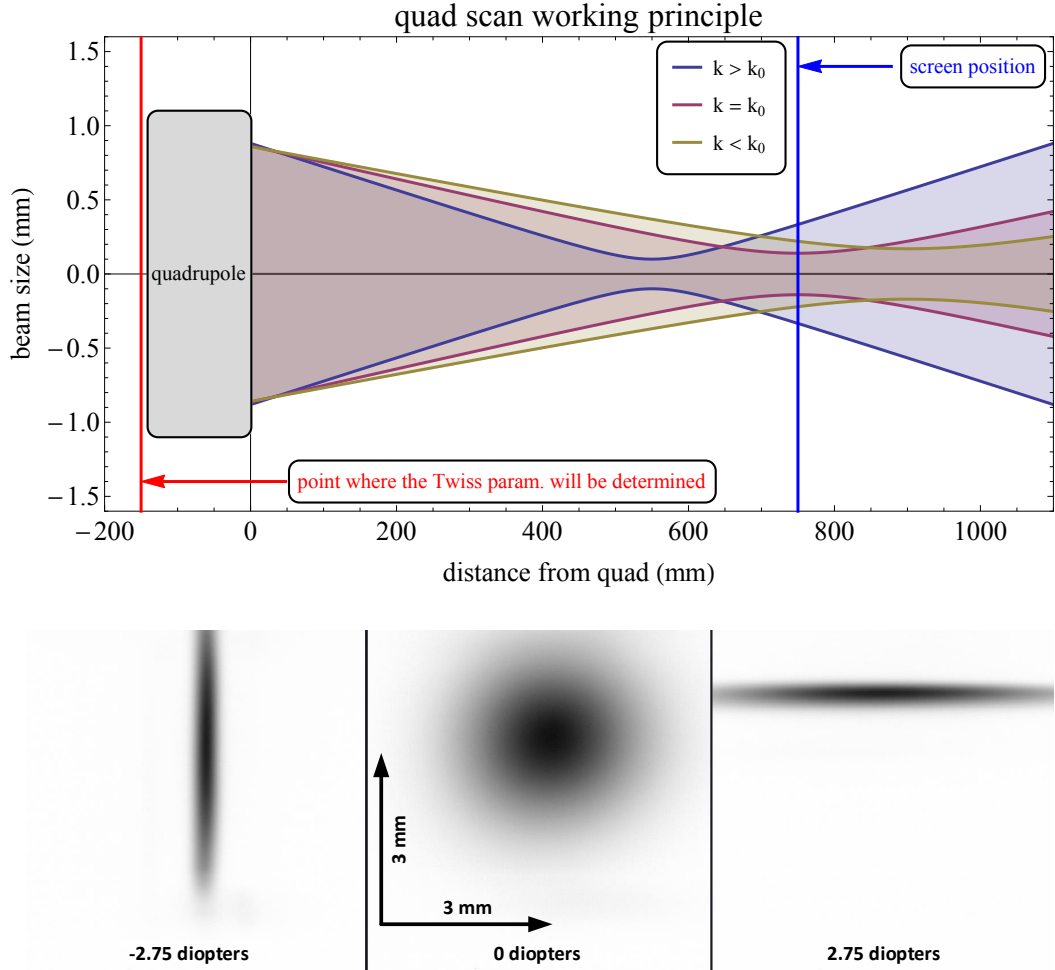


Figure 2.5.: The upper part of the figure illustrates a schematic sketch of the applied quad scan technique. Here, the variation of the focusing strength of a quadrupole changes the beam dimensions on a screen. The size of the visualized quadrupole is not to scale. Using a 45° mirror, the screen can be observed with a CMOS camera located outside the vacuum chamber. The lower part shows three examples of the beam shape during a quad scan for -2.75 diopters, 0 diopters and 2.75 diopters (from left to right) which are obtained by a CMOS camera (inverted color).

2.3. Emittance determination with a quadrupole scan

and

$$R_{\text{CQD}} = \begin{pmatrix} \cosh(\Theta) & \frac{\sinh(\Theta)}{\sqrt{k}} \\ \sqrt{k} \sinh(\Theta) & \cosh(\Theta) \end{pmatrix}. \quad (2.9)$$

The additional “C” in front of QF and QD refers to the quadrupole model used, which in turn stands for “conventional”. The parameter $\Theta = \sqrt{k}l_{\text{eff}}$ contains the quadrupole strength k , which can be calculated with

$$k = \frac{|B_0|}{\sigma_{\text{quad}}(B\rho)_0},$$

$l_{\text{eff}} = 48 \text{ mm}$ is the effective length of the quadrupole [Heid12]. The value B_0 describes the field strength at the pole tip of the quadrupole, and $\sigma_{\text{quad}} = 40 \text{ mm}$ is its aperture. The parameter

$$B\rho = \frac{p_e}{q_e}$$

is called the magnetic rigidity, which is equal to the ratio between the electron momentum p_e and the elementary charge q_e and is usually expressed in the unit Tesla meter. The last matrix needed is the one for a drift space with

$$R_{\text{drift}} = \begin{pmatrix} 1 & l_{\text{drift}} \\ 0 & 1 \end{pmatrix}. \quad (2.10)$$

To determine the Twiss parameters for the emittance calculation with Eq. 2.7, the following Eq. 2.11 and Eq. 2.12 are fitted to a dataset of squared beam diameters for different k values. If the transfer matrix R is determined, it is possible to derive the fit equations $m_{11}(k)|_1$ for the focusing and defocusing case.

$$m_{11, \text{foc}}(k)|_1 = \left. \begin{aligned} & m_{11} \left(\cos(\Theta) - l_{\text{drift}} \sqrt{k} \sin(\Theta) \right)^2 \\ & + m_{22} \left(l_{\text{drift}} \cos(\Theta) + \frac{\sin(\Theta)}{\sqrt{k}} \right)^2 \\ & + 2m_{12} \left(\cos(\Theta) - l_{\text{drift}} \sqrt{k} \sin(\Theta) \right) \\ & \times \left(l_{\text{drift}} \cos(\Theta) + \frac{\sin(\Theta)}{\sqrt{k}} \right) \end{aligned} \right|_0 \quad (2.11)$$

$$m_{11, \text{def}}(k)|_1 = \left. \begin{aligned} & m_{11} \left(\cosh(\Theta) - l_{\text{drift}} \sqrt{k} \sinh(\Theta) \right)^2 \\ & + m_{22} \left(l_{\text{drift}} \cosh(\Theta) + \frac{\sinh(\Theta)}{\sqrt{k}} \right)^2 \\ & + 2m_{12} \left(\cosh(\Theta) - l_{\text{drift}} \sqrt{k} \sinh(\Theta) \right) \\ & \times \left(l_{\text{drift}} \cosh(\Theta) + \frac{\sinh(\Theta)}{\sqrt{k}} \right) \end{aligned} \right|_0 \quad (2.12)$$

The values l_{eff} and l_{drift} are known since they are given by the experimental setup. Thus, only three parameters in Eq. 2.11 and Eq. 2.12 are left, namely m_{11} , m_{12} and m_{22} , which have to be determined by the fit.

Before Eq. 2.11 and Eq. 2.12 can be applied, it is necessary to check whether the introduced model (CHE^c) is able to describe the beam line. In addition, this model

^cCHE - conventional hard edge

2. Beam dynamics and space charge

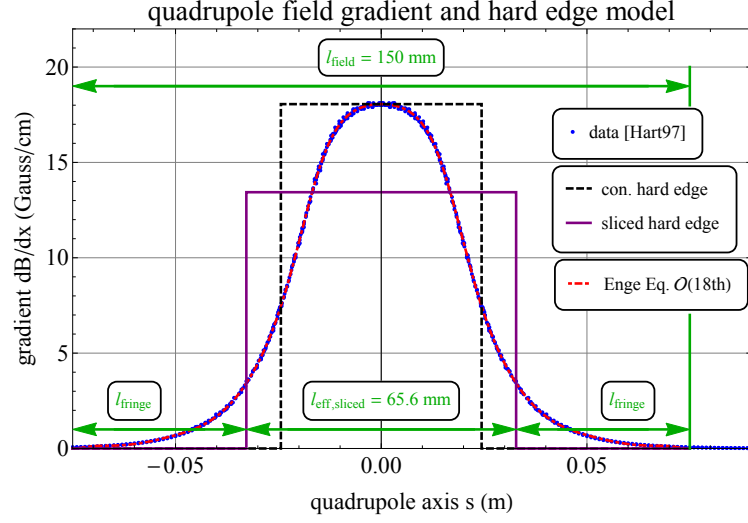


Figure 2.6.: Visualization of the quadrupole field gradient and a comparison between two different hard edge models. The data are represented by the solid dots and fitted with an 18th order Enge function (Eq. 2.13). The conventional hard edge model (dashed black line) determines the effective length via an integration over the field profile, and the sliced hard edge model (solid purple line) via a matrix multiplication over a finite number N of small quadrupole matrices.

does not consider space charge. The defocusing forces of space charge can be taken into account—in a first approximation—as defocusing lenses.

Experimental results presented in [Aule07, BLK+06] have figured out that the well-established approach to determine the effective length and strength of a quadrupole can lead to false reconstructed phase spaces if it is applied to a short quadrupole. Short quadrupoles are those whose length is approximately equal to their aperture. The assumption of a short quadrupole is valid for the quadrupoles used in the beam line since the ratio $l_{\text{quad}}/\sigma_{\text{quad}}$ is approximately equal to one. $l_{\text{quad}} = 41$ mm denotes the physical length of the quadrupole. A consequence of this ratio is that there is almost no region with a constant field gradient dB/dx .

Table 2.1.: Coefficients for the Enge function (Eq. 2.13) used to describe the field gradient of the quadrupole.

m	a_m	m	a_m	m	a_m
0	-3.48	6	67.64	12	-8.99
1	-1.22×10^{-7}	7	2.05×10^{-5}	13	-5.98×10^{-6}
2	21.29	8	-58.79	14	1.39
3	1.78×10^{-6}	9	-2.49×10^{-5}	15	1.07×10^{-6}
4	-46.94	10	30.38	16	-0.08
5	-8.78×10^{-6}	11	1.66×10^{-5}	17	-7.29×10^{-8}

2.3. Emittance determination with a quadrupole scan

In Fig. 2.6, the field gradient is plotted over the longitudinal axis s of the quadrupole. The data are taken from [Hart97]. The shape of the field gradient can be described by an Enge function [Enge64]. These functions have the form

$$g_{\text{Enge}}(s) = \frac{k_0}{1 + \exp\left(\sum_{m=0}^{N-1} \left(a_m \left(-\frac{s}{l_{\text{quad}}}\right)^m\right)\right)}. \quad (2.13)$$

The parameter k_0 indicates the maximum quadrupole strength, and the a_m are the coefficients of the Enge function. The relation between the field gradient dB/dx and the quadrupole strength k is given by [Wied93, Will05]

$$k = 0.2998 \frac{\frac{dB}{dx} \left(\frac{T}{m}\right)}{p_e (\text{GeV})}.$$

In the case visualized in Fig. 2.6, the function fitted has 18 coefficients that are presented in Tab. 2.1. A view on the odd coefficients indicates a symmetric shape of the field gradient around the central plane. Generally, the fringe field is taken into account by applying a hard edge model to the field profile. The hard edge model needs two parameters [Wied93, Will05]. These parameters are the effective length

$$l_{\text{eff}} = k_0^{-1} \int_{-\infty}^{+\infty} \frac{dB}{dx} ds = k_0^{-1} \int_{-\infty}^{+\infty} g_{\text{Enge}}(s) ds$$

and the maximum quadrupole strength k_0 . An integration over $g_{\text{Enge}}(s)$ leads to an effective length of $l_{\text{eff}} = 48.8$ mm, which confirms the calculations presented in [Hart97, Heid12]. Due to the short physical length of the quadrupole compared to its aperture, the shape of the field gradient causes a focusing of the beam already before reaching the physical dimensions of the quadrupole. This should not be neglected. An additional approach to determine the parameters for the hard edge model is to divide the field profile with $l_{\text{field}} = 150$ mm into a finite number N of slices of equal length l_i [Wied93, Will05]. Each slice is represented by a matrix and with a matrix multiplication of the form

$$R_{\text{quad}} = \begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix} = \prod_{n=1}^N R_{\text{quad},n} = R_{\text{quad},N} R_{\text{quad},N-1} \dots R_{\text{quad},2} R_{\text{quad},1}$$

it is possible to derive a matrix for the quadrupole that includes the fringe field. The length l_i and strength k_i for each slice i are determined via

$$l_i = \frac{l_{\text{field}}}{N} \text{ and } k_i \left(\frac{dB}{dx}\right) = k_i \left(g_{\text{Enge}}\left(0.5 \left(l_i (2i - 1) - l_{\text{field}}\right)\right)\right).$$

The content of R_{quad} has to be equal to

$$R_{\text{SQF}} = \begin{pmatrix} 1 & l_{\text{fringe}} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(\Theta) & \frac{\sin(\Theta)}{\sqrt{k}} \\ -\sqrt{k} \sin(\Theta) & \cos(\Theta) \end{pmatrix} \begin{pmatrix} 1 & l_{\text{fringe}} \\ 0 & 1 \end{pmatrix} \quad (2.14)$$

2. Beam dynamics and space charge

in the case of the focusing plane of the quadrupole. The additional “S” marks the “sliced” quadrupole model. The same matrix can be evolved for the defocusing plane of the quadrupole by replacing the center matrix by Eq. 2.9. The fringe field length is defined by $l_{\text{fringe}} = 0.5(l_{\text{field}} - l_{\text{eff,sliced}})$. From the matrix R_{SQF} , two equations can be obtained to determine the effective length $l_{\text{eff,sliced}}$ and strength k_{sliced} for the sliced quadrupole following [BLK+06] with

$$\begin{aligned} \cos(\Theta) + 0.5\Theta \sin(\Theta) &= r_{11} - 0.5l_{\text{field}}r_{21} \\ l_{\text{eff,sliced}} &= \frac{-\Theta \sin(\Theta)}{r_{21}^2} \\ k_{\text{sliced}} &= \frac{\Theta^2}{l_{\text{eff,sliced}}^2} \end{aligned} \quad (2.15)$$

for the focusing case, and for the defocusing case it follows that

$$\begin{aligned} \cosh(\Theta) - 0.5\Theta \sinh(\Theta) &= r_{11} - 0.5l_{\text{field}}r_{21} \\ l_{\text{eff,sliced}} &= \frac{\Theta \sinh(\Theta)}{r_{21}^2} \\ k_{\text{sliced}} &= \frac{\Theta^2}{l_{\text{eff,sliced}}^2} \end{aligned} \quad (2.16)$$

If these steps are applied to the field profile depicted in Fig. 2.6 with $N = 10^4$, the quadrupole used has an effective length of $l_{\text{eff,sliced}} = 65.3\text{mm}$ and an effective strength of $k_{\text{sliced}} = 0.74k_0$. Both approaches for the hard edge model (CHE and SHE^d) are compared in Fig. 2.6.

By changing the maximum field gradient of the quadrupole, also the effective length and the ratio k_{sliced}/k_0 changes. How strongly $l_{\text{eff,sliced}}$ and k_{sliced} are influenced by the maximum field gradient is shown in Fig. 2.7 and Fig. 2.8. For the k values used during a quadrupole scan, the effective length varies by about $\pm 0.46\%$ (see Fig. 2.7). This effect is neglected in the evaluation of the data. A comparison between k_{sliced} and k_0 with respect to the dependence on the maximum field gradient is visualized in Fig. 2.8 on the left side. Due to the fact that the k values for the focusing and defocusing plane of the sliced hard edge model are not well distinguishable in this plot, their deviation with respect to the mean k value is presented on the right side of Fig. 2.8. The normalized deviation of k stays below $\pm 0.65\%$ for both quadrupole planes. Due to this small variation, this effect is neglected in the evaluation of the data.

Investigations performed with the majority of the datasets have shown that the difference between both models is not as grave as expected. Fig. 2.9 depicts an example of the residuals between some measured data and the fit functions derived here. The comparison is performed for screen and wire measurements, respectively. All residuals stay below $\pm 5\%$ for both models and both methods. The results for the conventional hard edge model are calculated using Eq. 2.8 and Eq. 2.9. But in the case of the sliced hard edge model, the matrix-based definition of the quadrupole has changed, and thus, the fitted model has to be derived from the new transfer matrix $R_{\text{sliced}} = R_{\text{drift}}R_{\text{SQF}}$. The following two equations represent the fit functions for the sliced hard edge model of the quadrupole.

^dSHE - sliced hard edge

2.3. Emittance determination with a quadrupole scan

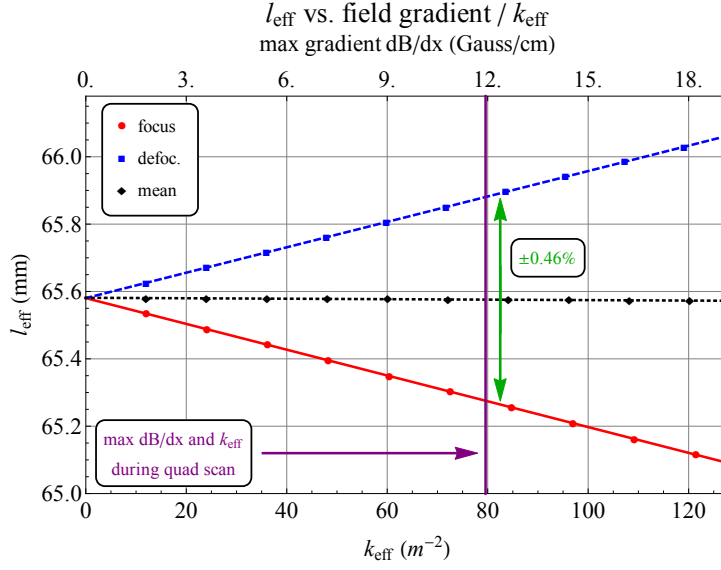


Figure 2.7.: Visualization of the effective length $l_{\text{eff,sliced}}$ dependency on both the maximum field gradient and the effective quadrupole strength k_{sliced} . Within the parameter space used for the quad scans, the effective length changes by about $\pm 0.46\%$ of its initial value. This effect is neglected in the evaluation of the data.

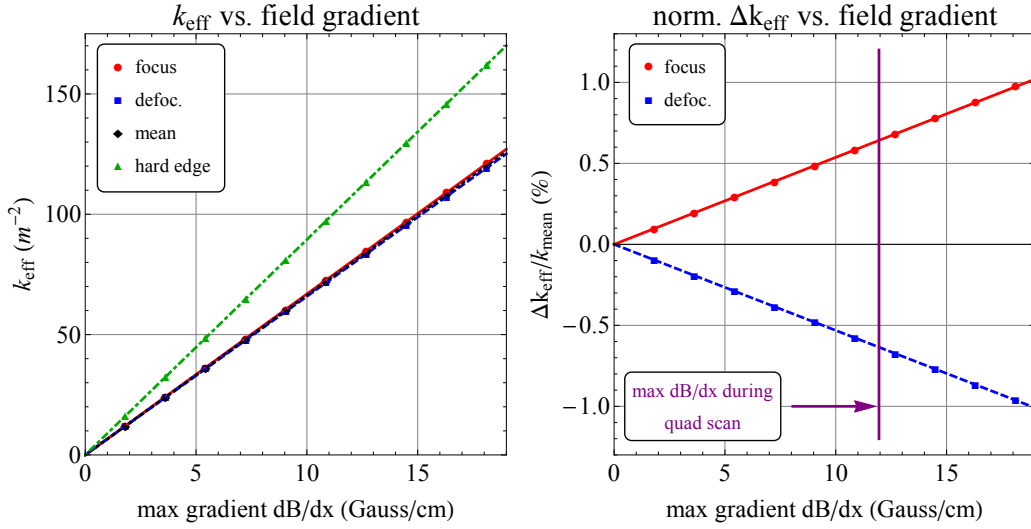


Figure 2.8.: The plot on the left shows the resultant strength k_{eff} as a function of the field gradient and compares the strength of the conventional hard edge model with the strength of the sliced hard edge model (focusing and defocusing case). On the right, the normalized deviation between the mean k value and the k values for both quadrupole planes is visualized as a function of the field gradient. Due to the small variation of around $\pm 0.65\%$, this effect is neglected in the evaluation of the data.

2. Beam dynamics and space charge

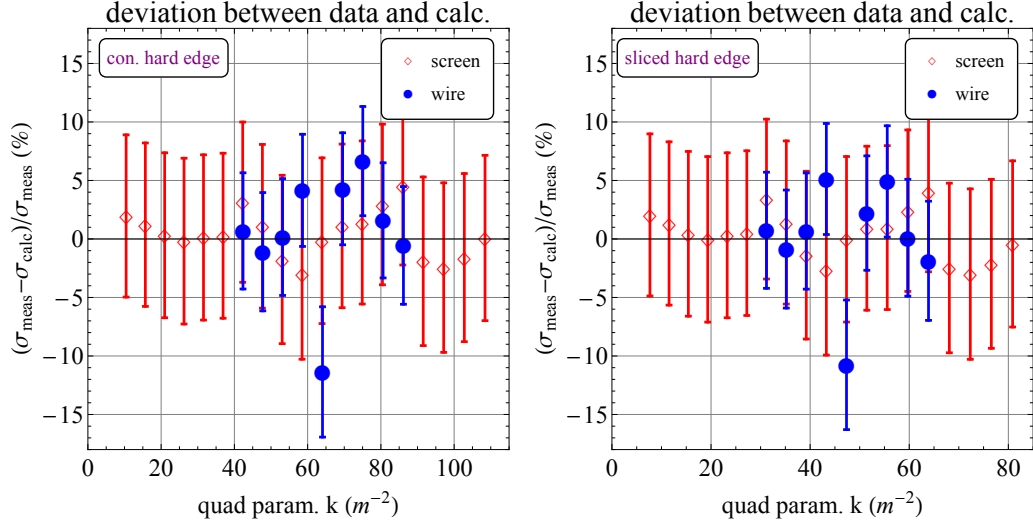


Figure 2.9.: Comparison between both quadrupole models. The left side shows the conventional hard edge model and the right side the sliced one. Both plots contain screen and wire measurements. For details see Sec. 6.2.1.1 and Sec. 6.2.1.2 for the screen and wire measurements, respectively.

$$\begin{aligned}
 m_{11, \text{foc, sliced}}(k)|_1 = & \left. \begin{aligned} & m_{11} \left(\cos(\Theta) - l_{\text{drift}} \sqrt{k} \sin(\Theta) \right)^2 \\ & + \frac{m_{22}}{k} \left(\begin{aligned} & (l_{\text{fringe}} + l_{\text{drift}}) \sqrt{k} \cos(\Theta) \\ & + (1 - l_{\text{fringe}} l_{\text{drift}} k) \sin(\Theta) \end{aligned} \right)^2 \\ & + \frac{2m_{12}}{\sqrt{k}} \left(\cos(\Theta) - l_{\text{drift}} \sqrt{k} \sin(\Theta) \right) \\ & \times \left(\begin{aligned} & (l_{\text{fringe}} + l_{\text{drift}}) \sqrt{k} \cos(\Theta) \\ & + (1 - l_{\text{fringe}} l_{\text{drift}} k) \sin(\Theta) \end{aligned} \right) \end{aligned} \right|_0
 \end{aligned} \quad (2.17)$$

$$\begin{aligned}
 m_{11, \text{def, sliced}}(k)|_1 = & \left. \begin{aligned} & m_{11} \left(\cosh(\Theta) - l_{\text{drift}} \sqrt{k} \sinh(\Theta) \right)^2 \\ & + \frac{m_{22}}{k} \left(\begin{aligned} & (l_{\text{fringe}} + l_{\text{drift}}) \sqrt{k} \cosh(\Theta) \\ & + (1 - l_{\text{fringe}} l_{\text{drift}} k) \sinh(\Theta) \end{aligned} \right)^2 \\ & + \frac{2m_{12}}{\sqrt{k}} \left(\cosh(\Theta) - l_{\text{drift}} \sqrt{k} \sinh(\Theta) \right) \\ & \times \left(\begin{aligned} & (l_{\text{fringe}} + l_{\text{drift}}) \sqrt{k} \cosh(\Theta) \\ & + (1 - l_{\text{fringe}} l_{\text{drift}} k) \sinh(\Theta) \end{aligned} \right) \end{aligned} \right|_0
 \end{aligned} \quad (2.18)$$

Both quadrupole models introduced—the conventional hard edge and the sliced hard edge one—have neglected space charge effects up to now. The presence of space charge forces and their strength are considered and discussed in the following section. Furthermore, a comparison between the matrix-based approach and the fully evolved equation of motion enables to estimate if the matrix-based one is sufficient to describe the beam line.

2.4. Space charge-dominated emittance

2.4.1. Calculation of space charge by means of parameters of plasma physics

An electron beam can be seen as a non-neutral plasma. In plasma physics, the Debye length λ_D is an important parameter, and it can be used also in accelerator physics. The electric potential of a single electron reaches to infinity, but an electron bunch with a charge of 0.8 pC contains around 5×10^6 electrons. Thus, the electrons will influence the range of the electric potential of their neighbors depending on the electron density inside the bunch. The Debye length describes the distance at which the electric potentials are screened and is defined as [Wang08, Reis08]

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{q_e^2 n}}. \quad (2.19)$$

The symbol k_B is the Boltzmann constant, the charge density

$$n = \frac{q_{\text{bunch}}}{q_e \beta_L c_{\text{vac}} \tau_{\text{bunch}} \sigma_{\text{beam}}^2}$$

which contains the bunch charge q_{bunch} , the temporal bunch length τ_{bunch} , the RMS dimension of the transverse projection of the beam σ_{beam} and the electron charge q_e . The temperature T of the electron beam is related to the emittance ϵ via

$$k_B T = \frac{E_0 \epsilon^2}{\sigma_L^2},$$

which was introduced by K. Floettmann [Flo97]. Here, E_0 is the rest mass energy of an electron and σ_L is the RMS dimension of the laser spot. If λ_D is taken as the radius of a sphere, this allows to calculate the number of electrons N_D which occupy the sphere volume—which is also known as the Debye sphere—with

$$N_D = n \frac{4\pi \lambda_D^3}{3}. \quad (2.20)$$

If $\lambda_D \gg \sigma_{\text{beam}}$, the Debye shielding is very weak, which indicates the emittance-dominated regime where the electrons inside the bunch can be affected by external forces. In this case, the number of electrons inside a Debye sphere becomes $N_D \gg 1$. But if $\lambda_D \ll \sigma_{\text{beam}}$, the amount of electrons inside a Debye sphere can shrink to $N_D = 1$, and this leads to the space charge-dominated regime, where the electrons inside the bunch are affected more by their neighbors than by external forces. This is because the electric fields of the electrons shield them from the external fields. Fig. 2.10 gives an example for λ_D and N_D inside a Debye sphere. For this calculation, the charge density is a uniform distribution. Both parameters λ_D and N_D are plotted over a bunch length of $50 \text{ ps} < \tau_{\text{bunch}} < 500 \text{ ps}$, which corresponds to an RF phase range of $23^\circ < \phi_{\text{RF}} < 235^\circ$, and for different RMS beam dimensions as

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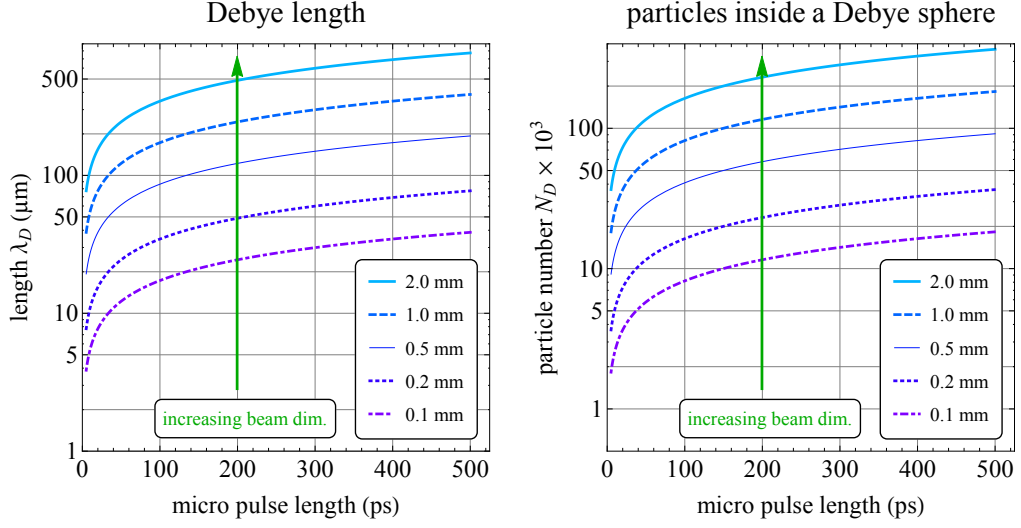


Figure 2.10.: Debye length λ_D (left) and number of electrons N_D inside a Debye sphere (right) plotted over the bunch length and for different RMS beam sizes indicated in the legend. λ_D is always smaller than the beam dimensions, but for each case, there are enough electrons inside a Debye sphere to avoid a complete shielding. The studied beam parameters are: $\beta_L = 0.55$ and $q_{\text{bunch}} = 10 \text{ pC}$.

indicated in the legend. The bunch charge q_{bunch} to calculate the charge density n is $q_{\text{bunch}} = 10 \text{ pC}$, which is 30% above the upper design value for the bunch charge to be achieved at MESA in stage-2. In the case of a quadrupole scan, the beam is focused to measure ϵ_n , and during this procedure, the RMS dimensions of the beam can decrease down to several $100 \mu\text{m}$. As illustrated in Fig. 2.10, a complete Debye shielding will never occur in the whole plotted parameter space. Even though the Debye length is smaller than the bunch dimensions for each case, the Debye sphere always contains more than 2000 electrons, which is enough to avoid a complete shielding. But this does not mean that space charge effects will not be present.

The internal magnetic field caused by the radial Lorentz force increases with the velocity (scales with γ_L^{-2}) and compensates for the defocusing caused by space charge. Thus, space charge is a non-relativistic effect that has to be taken into account primarily between the source and the MAMBO. There are many ways to calculate the presence of space charge or its dominance. In general, a space charge-dominated beam can be treated as a cold plasma and is dominated by collective effects, whereas an emittance-dominated one is dominated by random and thermal effects.

2.4.2. Adding space charge forces into the equations of motion

The single particle motion in an accelerator can be described via a set of differential equations each for one axis. The equation used is known as Hill's equation [Wied93,

2.4. Space charge-dominated emittance

Will05]. By adding an emittance term into the equation of motion, the formalism can be extended to describe a particle ensemble. One way to take the space charge forces into account is to include an additional term in Hill's equation to describe the envelope of the beam along the propagation direction. Based on the theory presented in [Wang08, Reis08], it is possible to derive these equations for the x and y axes:

$$\frac{\sigma_{\text{beam},x}}{d^2s} + \kappa_x(s) \sigma_{\text{beam},x} - \frac{\epsilon_x^2}{\sigma_{\text{beam},x}^3} - \frac{K_{\text{sc}}}{2(\sigma_{\text{beam},x} + \sigma_{\text{beam},y})} = 0 \quad (2.21)$$

$$\frac{\sigma_{\text{beam},y}}{d^2s} + \kappa_y(s) \sigma_{\text{beam},y} - \frac{\epsilon_y^2}{\sigma_{\text{beam},y}^3} - \frac{K_{\text{sc}}}{2(\sigma_{\text{beam},x} + \sigma_{\text{beam},y})} = 0 \quad (2.22)$$

These equations were derived for a dc beam ($\sigma_{\text{beam},s} = \infty$), but they are also valid for a bunched beam in the low-energy beam transport section if the bunch length is in the same order of magnitude as the accelerating structure of the electron gun. This condition is fulfilled in the case discussed here. Since the beam energy is low, the bunches will occupy about 100° of the RF phase until they reach the harmonic buncher system close to the injector, which is where they are compressed to a few degrees of the RF phase. Here $\sigma_{\text{beam},i}$ are the RMS dimensions of the beam for the axes $i = x, y$, respectively, κ_i is a measure of the external forces, s is the propagation direction of the beam, and the third terms in the equations are the emittance terms. Furthermore, the last missing constant is the space charge parameter

$$K_{\text{sc}} = \frac{q_e I_{\text{beam}}}{2\pi\epsilon_0 E_0 c_{\text{vac}} \gamma_L^3 \beta_L^3} = \frac{2I_{\text{beam}}}{I_{\text{Alfven}} \gamma_L^3 \beta_L^3},$$

which is also known as a generalized perveance with the permittivity ϵ_0 , the Lorentz factor γ_L and the relativistic velocity β_L . I_{beam} denotes the average beam current, E_0 corresponds to the electron rest mass, and q_e is the charge of an electron. The average beam current is multiplied by a factor 4–6 to get the peak beam current, which is used in the following presentations. When the Alfven current I_{Alfven} is used, the expression for K_{sc} becomes even simpler.

Space charge effects can be divided into two parts, which are hard to separate. One of which takes place in the electron gun and is particularly difficult to model on the surface of the photocathode. The experiments carried out in this thesis reach the space charge limit of the electron gun (Eq. 3.2) and it can be assumed that by increasing the beam current also the emittance of the electron gun increases. The second part of space charge effects occurs in the beam line and can be covered by Eq. 2.21 and Eq. 2.22.

The validity of the envelope equations in the present beam line (see Fig. 5.1) can be checked by extracting the RMS dimensions of the beam in a quadrupole scan procedure and comparing them with the results of the envelope equations. All beam sizes used for the following discussion are obtained using the screen method (see Sec. 6.2.1.1). The beam line for this comparison contains one quadrupole followed

2. Beam dynamics and space charge

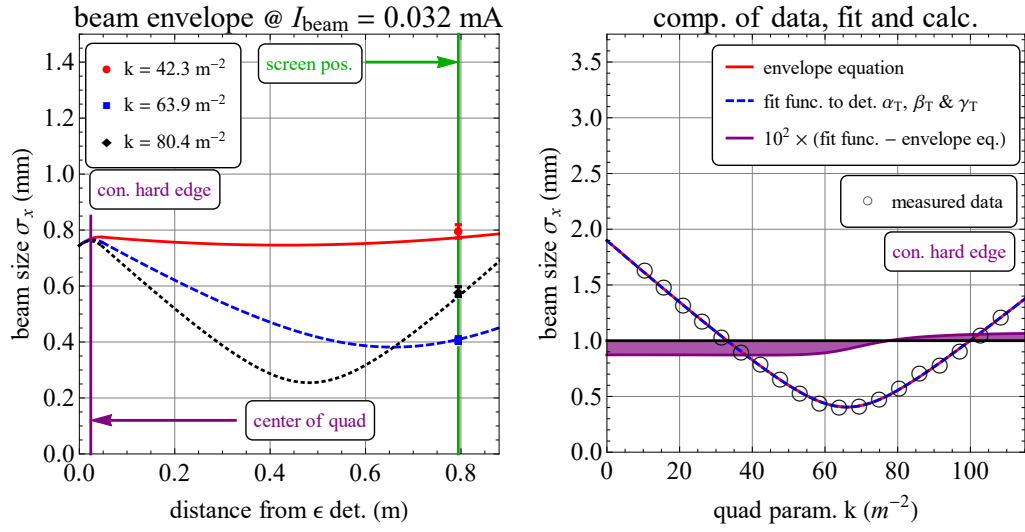


Figure 2.11.: Visualization of the way taken to check the validity of the envelope equation in the beam line given. On the left, the calculated beam size along the beam line is shown together with the measured data for three different k values. The plot depicted on the right side contains the measured beam sizes and compares these values with the results of the envelope equation and the fit function taken to determine the Twiss parameters. Both equations overlap each other. The $100\times$ magnified deviation between both equations is shown with the purple line whose zero is marked by the thick black horizontal line.

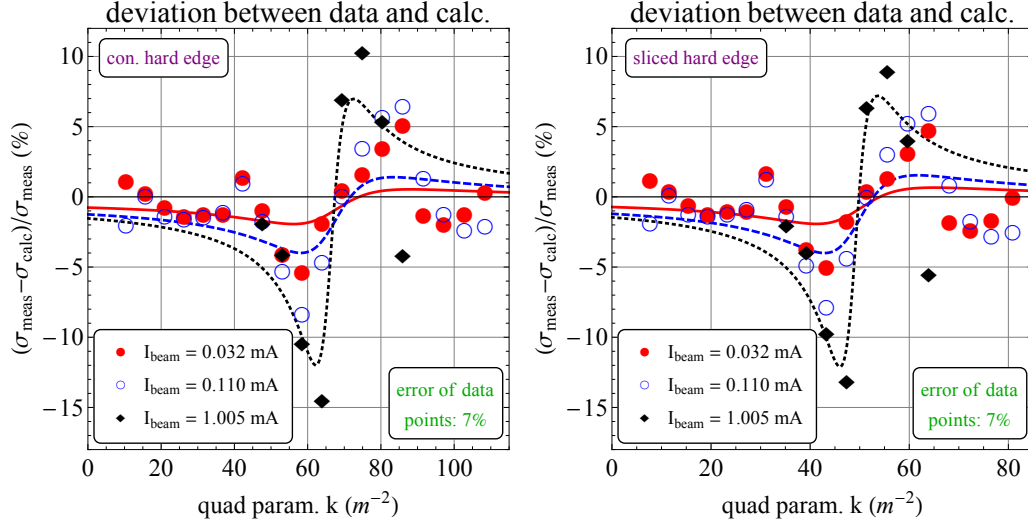


Figure 2.12.: In the left plot, the parameters of the conventional hard edge model are used. The deviations between the calculation and the data are in general smaller than $\pm 7\%$ but can reach up to $\pm 15\%$ in the case of the highest electron current. In the right plot, the parameters of the sliced hard edge model are used, which leads to a slightly different deviation between the calculations and the data. Furthermore, both plots contain the deviation between the fit function used to determine the Twiss parameters and the calculations of the envelope equation. These deviations are shown as lines. The calculations are performed using the peak beam current, which is 4 – 6 times I_{beam} .

by a drift space of $l_{\text{drift}} = 0.75$ m. After performing a quad scan, the different beam sizes of the quadrupole strengths used are taken and Eq. 2.11, Eq. 2.12 and Eq. 2.17, Eq. 2.18 are applied to them. The datasets discussed here are depicted in Fig. 6.4. Based on the emittance and the set of Twiss parameters—as a result of the measurement—the dimension and divergence of the beam at the entrance of the quadrupole can be determined. Subsequently, these values (x , x' and ϵ_x) are taken as starting parameters of the equations of motion (Eq. 2.21 and Eq. 2.22). Solving these equations results in a beam envelope similar to those shown in the left plot of Fig. 2.11. By setting s equal to the screen position, the k dependent evolution of the beam size can be directly compared with the measured ones. In addition, the fit function used to determine the starting parameters of Eq. 2.21 and Eq. 2.22 may also be included in the comparison to illustrate the influence of space charge forces. This is visualized on the right of Fig. 2.11. In the case shown, both functions differ only very slightly. As a reminder, Eq. 2.11, Eq. 2.12 and Eq. 2.17, Eq. 2.18 do not consider any possible influences of space charge forces.

In Fig. 2.12, the deviation

$$\Delta\sigma_{\text{beam}} = \frac{\sigma_{\text{meas}} - \sigma_{\text{calc}}}{\sigma_{\text{meas}}}$$

2. Beam dynamics and space charge

between a selection of measured data and the solutions of the envelope equations is visualized for three different currents: $I_{\text{beam}} = 0.032 \text{ mA}$, $I_{\text{beam}} = 0.110 \text{ mA}$ and $I_{\text{beam}} = 1.005 \text{ mA}$. Due to the different effective lengths for both hard edge models, the quadrupole strength yields different values. In contrast to Fig. 2.11, the beam line used within the calculations presented in Fig. 2.12 is extended by an additional drift space in front of the quadrupole. With this extension, the calculation now takes into account the complete beam line after leaving the electron gun. Using the parameters of the conventional hard edge model (left plot) generally leads to deviations smaller than $\pm 7\%$ but can reach up to $\pm 15\%$ in the case of the highest electron current. The sliced hard edge model (right plot) leads to a slightly different deviation between the calculations and the data. In addition, both plots in Fig. 2.12 contain the deviation between the fit function used to determine the Twiss parameters and the results of the envelope equation. Within this comparison, the deviations stay below $\pm 4\%$ —except for the highest beam current ($\pm 12\%$)—for both quadrupole models used. The change in sign close to the focus is caused by the defocusing effect of the space charge forces that shifts the focus to higher k values. If small beam currents ($I_{\text{beam}} \leq 0.1 \text{ mA}$) are used, the measured beam sizes can be reproduced by solving the equations of motion, independent of the quadrupole model used. With increasing I_{beam} the influence of space charge forces becomes stronger, resulting in an increase of the deviations. Since the discrepancies are within the error bars, which are mainly caused by the beam size determination, both quadrupole models (Eq. 2.11, Eq. 2.12 and Eq. 2.17, Eq. 2.18) can be used to determine the emittances.

From the comparison presented in Fig. 2.12, it seems that both quadrupole models do not differ much. Nonetheless, this difference is perceptible. Inspired by the results shown last, a closer look at the phase spaces at the physical entrance of the quadrupole and the exit of the PKA2 is given in Fig. 2.13. The divergences of both models at the respective positions are about the same, whereas the SHE model has larger beam diameters. Since the peak beam current is four to six times higher compared to its average current, the space charge limit of the electron gun—calculated via Eq. 3.2—is exceeded. This results in a strong increase of the emittance. The conclusion of the phase spaces visualized in Fig. 2.13 is that the increase in emittance is most likely caused by the electron gun.

In order to illustrate the extent to which the properties of the electron beam are dominated by space charge forces, a ratio between the space charge term and the emittance term of Eq. 2.21 and Eq. 2.22 can be formed. This is done via the following expression:

$$\frac{2(\sigma_{\text{beam},x} + \sigma_{\text{beam},y}) \epsilon^2}{K_{\text{sc}} \sigma_{\text{beam}}^3}$$

In Fig. 2.14, the space charge over emittance ratio is shown taking the complete beam line into consideration. On the left side this is performed using a low beam current, and on the right side with a high beam current. In the comparison are included three different k values. One value lies in front of the focal plane, one lies

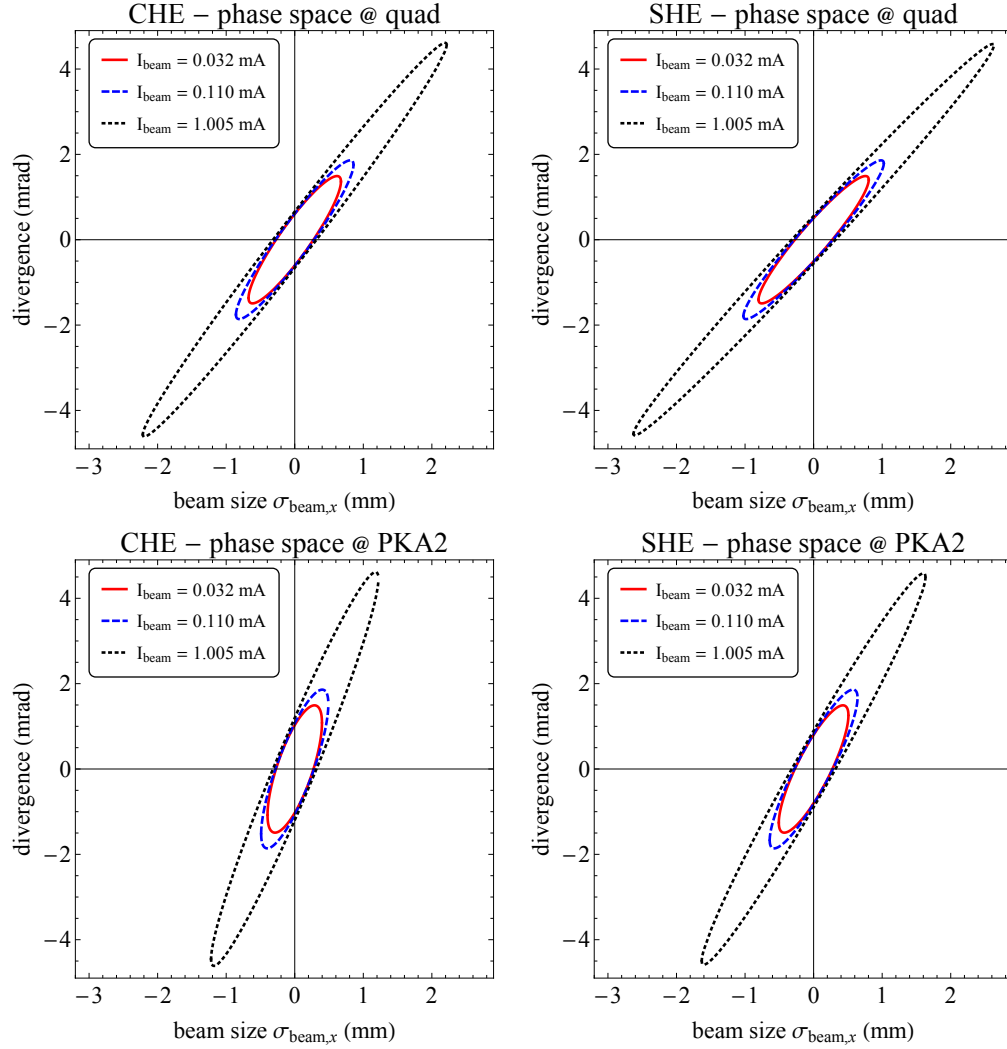


Figure 2.13.: The plots visualize the phase spaces for both models each at the physical entrance of the quadrupole (top row) and the exit of the electron source (bottom row). Although the emittances for the CHE and SHE model are about the same, there is a bigger difference in phase space. The major statement of the plots is that the increase in emittance is most likely caused by the electron gun.

2. Beam dynamics and space charge

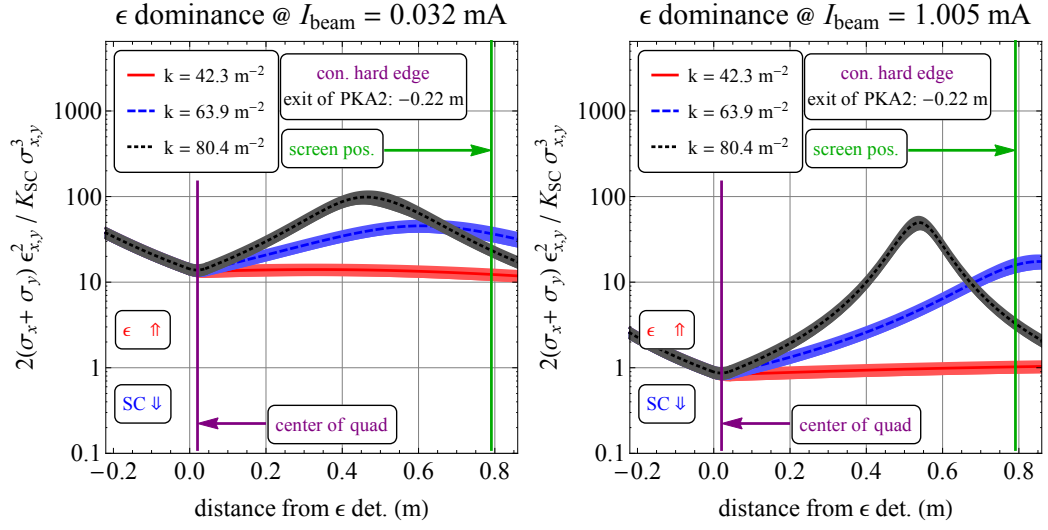


Figure 2.14.: In both plots, the emittance over space charge ratio is visualized considering the entire beam line. The left plot represents the situation in the case of a low beam current and the right one in the case of a high beam current. In both cases, the beam properties are mainly dominated by emittance. Values below one denote space charge dominance. Errors are indicated by the bands. The calculations are performed using the peak beam current, which is 4 – 6 times I_{beam} .

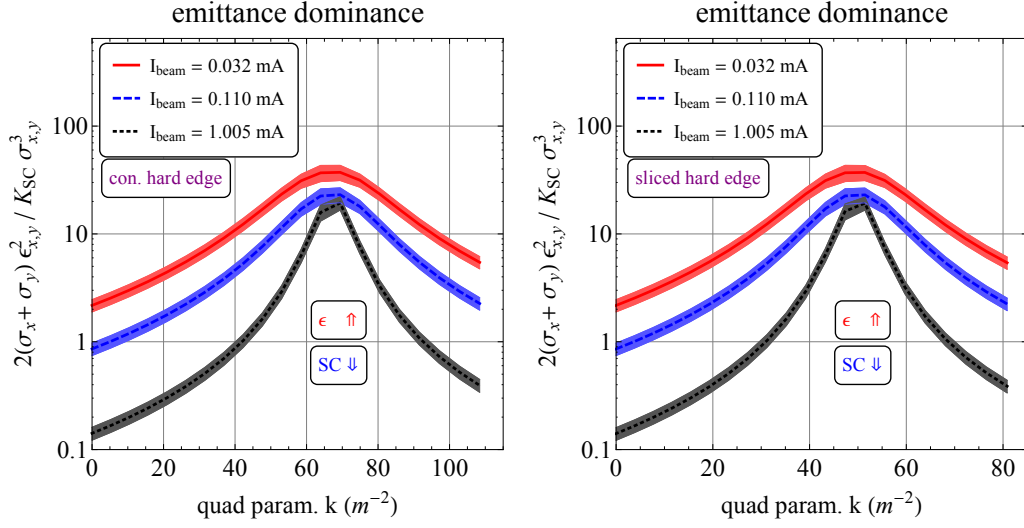


Figure 2.15.: The ratio of the third and fourth term in the equations of motion is taken and calculated for each k value used. In this presentation of the results, values below one denote space charge dominance. The emittance over space charge ratio indicates that emittance dominates during a quad scan procedure for k values close to the focus, which are the most important data point. This statement is regardless of the hard edge model used. Errors are indicated by the bands and the calculations are performed using the peak beam current, which is 4 – 6 times I_{beam} .

behind it and one represents the focus. Both plots in Fig. 2.14 indicate that the beam properties are dominated by emittance along the entire beam line. Referring to Fig. 2.12, in Fig. 2.15, the emittance over space charge ratio for all k values of a quadrupole scan at the position of the screen is depicted. Comparing both plots visualized in Fig. 2.15 yields that an increasing influence of space charge forces will occur with increasing I_{beam} . Regardless of the hard edge model used in the envelope equations, the emittance is the dominant term during the quad scan procedure for k values close to the focus, which are the most important data point. With increasing electron current, the emittance over space charge ratio decreases. This confirms the statement from the Debye length calculations made above and depicted in Fig. 2.10, namely that space charge effects will not be dominant but can be present. As a quadrupole has a focusing and a defocusing plane, both axes are represented in the space charge term. This fact compensates for an increase in the electron density during the focusing procedure. Space charge will result in an increase of the divergence angle. But if the electron beam is strongly focused, the electrons within the beam already have high divergence angles and the additional contribution due to space charge can be neglected. Thus, space charge effects can slightly influence the results of a quad scan, but they will not distort the measurement results completely.

2. Beam dynamics and space charge

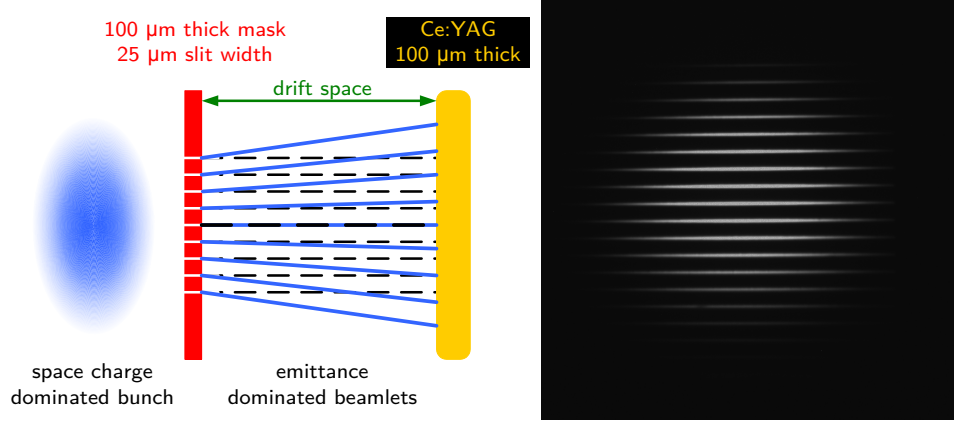


Figure 2.16.: Sketch of the working principle of a slit mask emittance measurement. From the left side, an electron bunch (can be space charge-dominated) hits a mask, and after this, the beamlets can spread out through a drift space until they are stopped by a screen. By determining their width and displacement, the phase space can be reconstructed. The picture to the right illustrates an example of what the intensity pattern on the screen behind the slit mask can look like and is obtained by a CMOS camera.

The conclusion of this comparison is that it can be assumed that space charge effects affect the beam size for low k values during a quadrupole scan procedure with average beam currents above 0.1 mA. To reduce the influence of space charge effects during an emittance measurement, the emittance can be determined by means of a slit mask. This technique will be discussed in the next section.

2.5. Emittance determination with a slit mask

In Fig. 2.16, a sketch of the working principle for a slit mask emittance measurement is shown. An electron bunch passes through a mask with one or more slits or holes in it. After a drift space d_{drift} behind the mask, a screen is mounted to observe the resulting intensity profile. Depending on the position of the transmitted electrons in the phase space, the beamlet^e position on the screen after a distance d_{drift} becomes a displacement in relation to the slit/hole position on the mask. The displacement is a measure of the mean value of the divergence x' , y' . To get information about the width of the divergence, it is necessary to measure the width of the beamlets σ_i of the intensity pattern on the screen. The last important parameter is the maximum intensity $\text{Int}_{\text{slit},i}$ of each slit. The intensity is a measure of the amount of electrons within a beamlet, and knowledge about this is necessary to weight the beamlet for the emittance calculation. With these three values (beamlet intensity,

^eBeamlet will describe the final fraction of the initial beam behind the slit mask.

2.5. Emittance determination with a slit mask

displacement and width), the phase space can be reconstructed in the following way. The emittance is defined as

$$\epsilon_{n,x} = \beta_L \gamma_L \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

(Eq. 2.7), and the individual parts $\langle x^2 \rangle$, $\langle x'^2 \rangle$ and $\langle xx' \rangle^2$ carry information about the beam size, the correlated and uncorrelated beam divergence, and the correlation between beam size and divergence, respectively [Evtu09]. $\langle x^2 \rangle$ can be calculated with

$$\langle x^2 \rangle = \sum_i w_{\text{Int},i} (x_i)^2 \quad (2.23)$$

where

$$w_{\text{Int},i} = \frac{\text{Int}_{\text{slit},i}}{\sum_i \text{Int}_{\text{slit},i}}$$

is a weighting factor with the maximum intensity $\text{Int}_{\text{slit},i}$ of the i -th beamlet and

$$x_i = d_{\text{slit}} i - \sum_i w_{\text{Int},i} d_{\text{slit}} i.$$

The parameter d_{slit} indicates the distance of the slits on the slit mask. The sum in the equation of x_i results in a constant value, which represents the center of all slits on the mask. This constant is subtracted to obtain a symmetrical representation in phase space. A similar expression $\langle x_0 \rangle$ to center the positions $x_{0,i}$ on the screen is included in the equation of $\langle x'^2 \rangle$. $\langle x'^2 \rangle$ can be estimated as

$$\langle x'^2 \rangle = \sum_i w_{\text{Int},i} \frac{\sigma_i^2 + (x_{0,i} - \langle x_0 \rangle - x_i)^2}{d_{\text{drift}}^2}. \quad (2.24)$$

The last part $\langle xx' \rangle$, which contains the correlation between the beam size and the divergence, can be determined with

$$\langle xx' \rangle = \sum_i x_i w_{\text{Int},i} \frac{x_{0,i} - \langle x_0 \rangle - x_i}{d_{\text{drift}}}. \quad (2.25)$$

Combining these terms results in:

$$\epsilon_{x,n} = \frac{\beta_L \gamma_L}{d_{\text{drift}}} \sqrt{\left(\sum_i w_{\text{Int},i} (x_i)^2 \right) \left(\sum_i w_{\text{Int},i} \left(\sigma_i^2 + (x_{0,i} - \langle x_0 \rangle - x_i)^2 \right) \right) - \left(\sum_i x_i w_{\text{Int},i} (x_{0,i} - \langle x_0 \rangle - x_i) \right)^2} \quad (2.26)$$

A different way to calculate the emittance with a slit or pepper pot mask is presented in [Zhan96] and is comparable with the formulas introduced in [AnRo02].

$$\epsilon_{x,n} = \frac{\beta_L \gamma_L}{N} \sqrt{\left(\sum_i n_i (x_i - \bar{x}_0)^2 \right) \left(\sum_i n_i \left(\sigma_i^2 + (\bar{x}'_i - \bar{x}')^2 \right) \right) - \left(\sum_i n_i x_i \bar{x}'_i - N \bar{x}_0 \bar{x}' \right)^2} \quad (2.27)$$

2. Beam dynamics and space charge

- n_i - number of particles passing through the i -th slit and hitting the screen. Practically, it is a weighting of spot intensity.
- N - number of all particles
- x_i - position of the i -th slit on the mask
- $\overline{x_0}$ - mean position of all beamlets
- $\overline{x'_i}$ - mean divergence of i -th beamlets
- $\overline{x'}$ - mean divergence of all beamlets
- σ_i - RMS width of the i -th beamlet representing the width of the divergence

Eq. 2.26 and Eq. 2.27 do not differ much, but the calculations can lead to slightly different outcomes as presented in Fig. 6.19. Space charge issues are discussed in Sec. 6.2.2.

3. Building blocks of the experiments and their physics background

At the beginning of this chapter, the photoelectron source is introduced followed by a description of the photoeffect, which is used to produce the electrons, and some photocathode properties. Next, the physics basis of gain-switched laser diodes is discussed, which are used to produce RF-synchronized electron pulses. Furthermore, the penultimate section includes a description of the RF system used to provide the necessary RF power for the laser system and the deflection cavity. Their working principles are explained in the last section of this chapter.

3.1. Photoelectron source (PKA2)

The electron source PKA2 is a dc photoelectron source with a static electric potential of 100 kV. Photoelectron source means that the electrons are produced by illuminating a semiconductor photocathode with laser light. As photocathode material, GaAs is used because it delivers a high quantum efficiency (see Fig. 3.6) and a short response time. An additional reason why a photoelectron source is used is that the electron beam can be modulated by the laser light, which enables a much faster modulation ($\mathcal{O}(\text{ps})$) than in the case of a thermionic gun ($\mathcal{O}(\text{ns})$). The Landau symbol $\mathcal{O}$ is used in this work to represent orders of magnitude.

In the PKA2 the photocathode is located at an electric potential of 100 kV, and the main electrode is surrounded by an intermediate electrode with an electric potential of 50 kV. A CAD drawing of the electrode configuration and their potentials is depicted in the upper row of Fig. 3.1. In the lower row, a closer view of the inner structure and a more detailed presentation of the electrode shape is given. The distance between the main electrode and the intermediate electrode is 50 mm, and the distance from the intermediate electrode to ground potential (bottom of the source chamber) is 100 mm. This electrode configuration divides the accelerating field into two sections. The first section close to the photocathode has a field of 1 MV/m, and the second one has a field of 0.5 MV/m.

The kinetic energy of the electrons depends on their position within the electron gun. Under the assumption of an approximately constant electric field, this can be expressed as

$$E_{\text{kin}}(s) = \begin{cases} s \frac{\text{keV}}{\text{mm}} & (0 < s \leq 50) \text{ mm} \\ (50 \text{ mm} + 0.5 (s - 50 \text{ mm})) \frac{\text{keV}}{\text{mm}} & (50 < s \leq 150) \text{ mm} \\ 100 \text{ keV} & s > 150 \text{ mm} \end{cases}$$

3. Building blocks of the experiments and their physics background

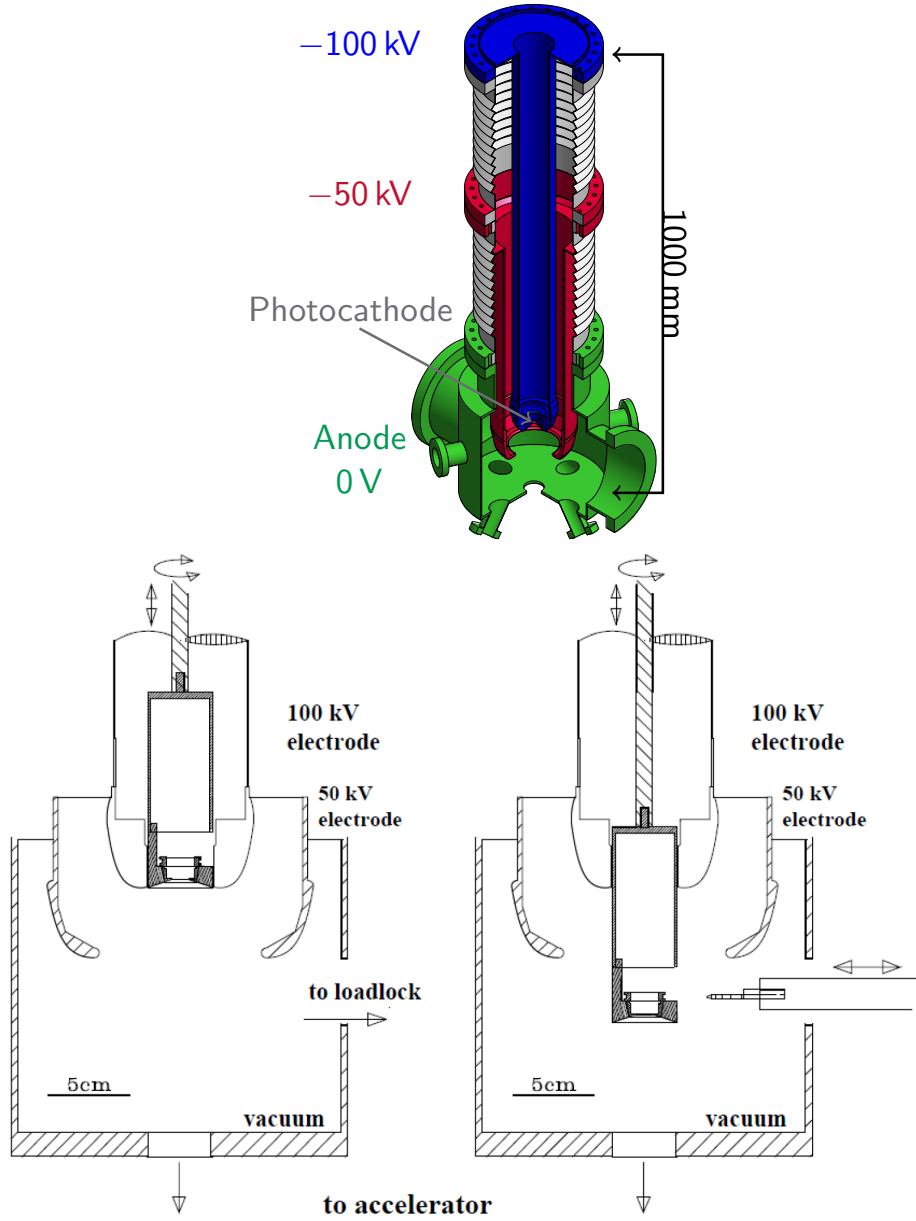


Figure 3.1.: CAD model of the inner electrode configuration of the PKA2 (top of figure). The photocathode is located at the bottom of the main electrode (blue), which has an electric potential of 100 kV. An additional intermediate electrode (red) surrounds the main electrode and has an electric potential of 50 kV. The distance between the main electrode (blue) and the intermediate electrode (red) is 50 mm, and the distance from the intermediate electrode to ground potential (bottom of the source chamber (green)) is 100 mm. In the bottom row, a closer view of the inner structure of the gun is illustrated including the photocathode exchange mechanism (taken from [Hart97]).

3.1. Photoelectron source (PKA2)

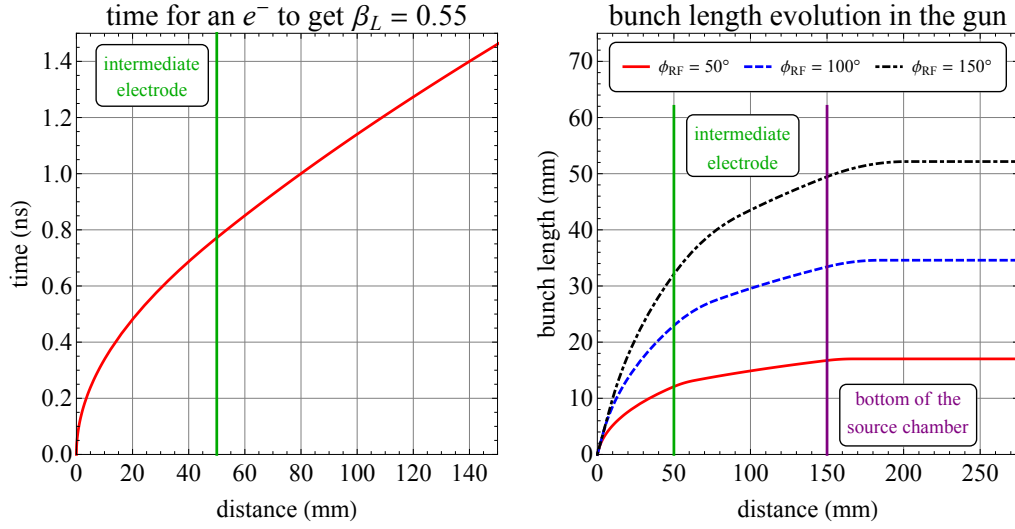


Figure 3.2.: The left side visualizes the time an electron needs for a specific distance within the PKA2. The photocathode is located at 0 mm, and the bottom of the source chamber is at the position 150 mm. Due to the acceleration process, the curve becomes flatter with increasing distance. An electron needs 1.46 ns to pass through the PKA2. The graph on the right shows the bunch length evolution within the electron gun for three different initial laser pulse durations ϕ_{RF} . Due to the different velocities of the first and last electron, the bunch still grows after the first electron has left the gun until all electrons are accelerated to $\beta_L \simeq 0.55$.

3. Building blocks of the experiments and their physics background

As the electrons are initially non-relativistic, the electron velocity

$$v_e(s) = \beta_L(s) c_{\text{vac}}$$

is strongly dependent on their kinetic energy E_{kin} , which is linked to the position s within the electron gun. The relative amount $\beta_L(s)$ of the velocity with respect to the speed of light c_{vac} can be calculated via

$$\beta_L(s) = \sqrt{1 - \gamma_L(s)^{-2}}$$

with the Lorentz factor

$$\gamma_L(s) = 1 + \frac{E_{\text{kin}}(s)}{E_0}.$$

The spatial evolution of the electron velocity $v_e(s)$ can now be taken to calculate the time $\tau_{\text{PKA2}}(d)$ an electron needs to pass through the gun. This time is calculated via

$$\tau_{\text{PKA2}}(d) = \int_0^d (v_e(s))^{-1} ds. \quad (3.1)$$

The resulting time for the first electron of an electron bunch is illustrated on the left in Fig. 3.2. Thus, each electron with an initial energy of 0 eV will spend $\tau_{\text{PKA2}}(150 \text{ mm}) = 1.46 \text{ ns}$ within the electron gun. With the knowledge about the time an electron needs to pass through the electron gun, the longitudinal spatial bunch length evolution within the gun can be calculated. The result is visualized on the right in Fig. 3.2 for three different temporal bunch lengths. If an energy spread is included in the calculation, the spatial and temporal distribution of the electron bunch will increase further after leaving the gun and also in the gun, but only $\mathcal{O}(1 \text{ ps})$.

The energy distribution of the PKA2 was simulated with a “particle in cell” program^a and compared to the new 200 kV source (STEAM) [Frie16]. The results for bunch charges of 1 pC and 10 pC are shown in Fig. 3.3. Although computer simulations are very useful, the results should usually be taken with caution. Simulation programs are sensitive to e.g. the mesh size, the used model or the input parameters. In this respect, simulation results should be verified with measurements.

With the results of the energy distribution shown in Fig. 3.3, the extension of these electron bunches within a drift space of several meters can be calculated. The results for both bunch charges are visualized in Fig. 3.4. The influence of the energy width on the temporal evolution can be interesting for higher bunch charges like those desired in MESA stage-2. One of the main statements of Fig. 3.4 is that the smaller energy distribution of STEAM will suppress a rapid increase of the bunch length. The drift space mentioned here represents the MELBA system of MESA. With the energy distribution delivered by STEAM, it will be possible to transport the electron bunches up to 1.5 m along the beam line compared to a quarter of a meter using the PKA2. At these distances the electron bunch becomes longer

^aComputer Simulation Technology - CST PARTICLE STUDIO

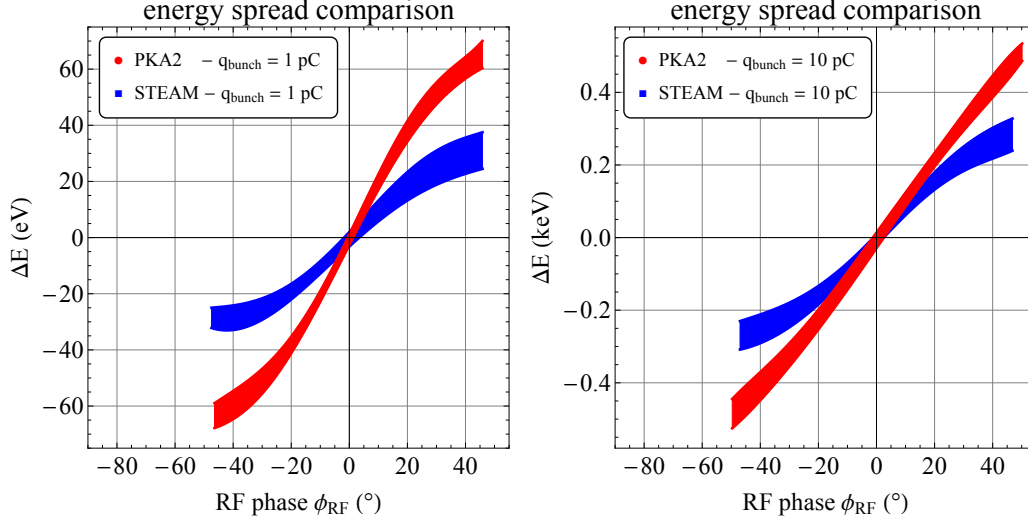


Figure 3.3.: The plots show a comparison of the energy distribution between PKA2 and STEAM for a bunch charge of 1 pC (left) and 10 pC (right). The initial laser pulse length is 200 ps with a laser spot size of $\sigma_L = 0.5$ mm. (data taken from [Frie16])

than $\phi_{RF} = 100^\circ$. The RF phase value is based on experience gained during the operation of MAMI and contains a safety margin to guarantee c.w. operation. This RF phase value is referred to as “suitable” in the following text.

Another important property of an electron source is the current limit. The current limit $I_{sc,lim}$ of the source due to space charge can be estimated by the Child-Langmuir law

$$I_{sc,lim} = p_0 \frac{A_{emit}}{d^2} U_{acc}^{3/2}. \quad (3.2)$$

Here, $p_0 = 2.33 \times 10^{-6} \text{A}/\text{V}^{3/2}$ is the so-called perveance [SLee07] and $\frac{A_{emit}}{d_{PKA2}^2} = 44.4 \times 10^{-6}$ is a geometric factor that includes the emitting area, e.g. $A_{emit} = 1 \text{ mm}^2 \triangleq \sigma_L \simeq 0.56 \text{ mm}$ and the cathode-anode distance of the source $d_{PKA2} = 150 \text{ mm}$. The last parameter U_{acc} is the applied accelerating voltage $U_{acc} = -100 \text{ kV}$. With all these parameters, the emittance is still $< 1 \mu\text{m}$ [AlAu15] (see also Fig. 6.13), and the current limit is $I_{sc,lim} \simeq 3 \text{ mA}$. Thus, with a dc beam, the PKA2 can deliver an electron current of $\simeq 3 \text{ mA}$, but in c.w. operation^b, the peak electron current would also be limited to $\simeq 3 \text{ mA}$. This limitation would result in a lower average electron current. If the current limit is exceeded, this leads to an increase in the emittance. Anyhow, the result of $I_{sc,lim} \simeq 3 \text{ mA}$ leads to the expectation that the PKA2 can fulfill the requirements of MESA stage-1. This is also supported by CST computer simulations [FrAu15], and the achieved average electron currents in this thesis have also proven this. Nevertheless, a new 200 kV source (STEAM)

^bC.w. operation describes the generation of RF-synchronous electron bunches.

3. Building blocks of the experiments and their physics background

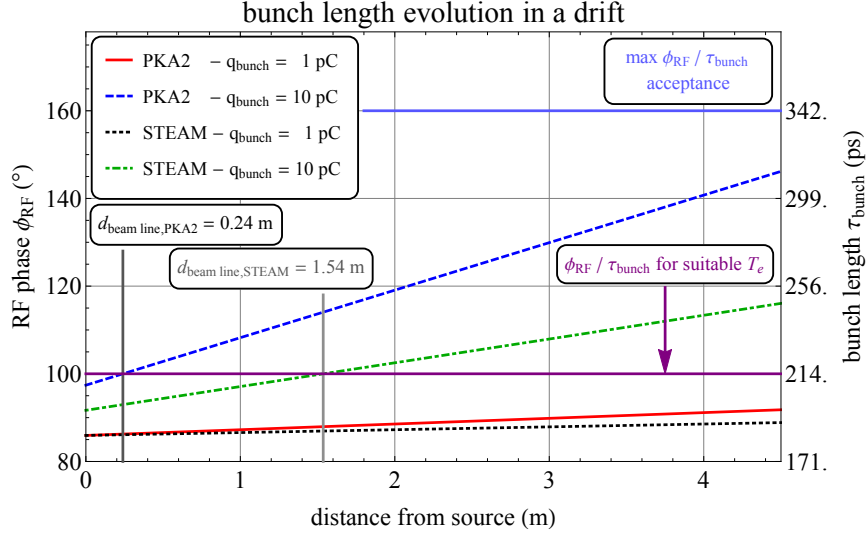


Figure 3.4.: Visualization of the bunch length evolution within a drift space of several meters for both electron sources and for two different bunch charges. The graph contains the bunch length in both RF phase and time domain units. One of the main statements of the plot is that the smaller energy distribution of STEAM will suppress a rapid increase of the bunch length. The drift space mentioned here represents the MELBA system of MESA. Setting the RF phase to 100° for a suitable electron transmission T_e it follows that this value is reached after a quarter of a meter using the PKA2. When STEAM will be used, transport of the electron bunches up to 1.5 m along the beam line will be possible.

3.2. Photoeffect and photocathode properties

to increase the current limit $I_{\text{sc,lim}}$ to the requirements of MESA stage-2 is in commissioning [FrAu15]. The inverted gun from CEBAF served as a model for the design of STEAM [ACG+11]. If the current limit is exceeded, a real enlargement of the phase space occurs and the emittance increases. This enlargement takes place because the electrons close to the photocathode have a very low velocity and are influenced by space charge very easily.

STEAM will have some improvements compared to the PKA2. First of all, STEAM will be a 200 kV source, and the higher energy will suppress the influence of space charge forces on the beam dimensions. Moreover, the cathode-anode distance is reduced to $d_{\text{STEAM}} = 37 \text{ mm}$, and with the higher accelerating voltage, this would make it possible to achieve a field strength of up to 5 MeV/m at the position of the photocathode. The PKA2 instead has a field strength of 1 MeV/m at the photocathode position. The higher field strength influences the energy distribution in a positive way (see Fig. 3.3). Inserting the decreased cathode-anode distance d_{STEAM} in Eq. 3.2 increases the current limit $I_{\text{sc,lim}}$ of the source by a factor of ~ 16 , and with the higher acceleration voltage, the current limit can be increased by a factor ~ 46 .

Nevertheless, employing STEAM in MESA would also be a technical risk because the photocathode lifetime cannot be estimated and has to be proven. In addition, it is not clear if the electrode design in combination with the source chamber design will sustain the desired voltage with a sufficiently low dark current I_{dark} . As an upper limit for the dark current, $I_{\text{dark}} \simeq 1 \text{ nA}$ can be taken [ACG+11]. If any difficulties that may arise should prevent or strongly delay the commissioning process, the PKA2 can be used as well.

The PKA2 in the diagnostic test beam line has delivered 700 C [AuAl11] within one charge lifetime at average currents exceeding 1 mA (MESA stage-1) (more details can be found in Sec. 6.1). One experiment planned at MESA will need an average current of 1(10) mA corresponding to an extracted charge of 3.6(36) C/h, assuming a transmission of 100% through the accelerator. To achieve the highest possible transmission, an RF-synchronized laser must excite the photoemission. Close to the injector, the so-produced bunches will be captured by a harmonic buncher system which can accept bunches with a length of about 160° with respect to the RF phase [Heil15]. This leads to the requirement that the emitted intensity—which is the convolution of the temporal laser intensity profile and the response of the photocathode—must fit into this interval. Fractions outside the interval may be suppressed by a chopper system to provide very clean operating conditions for MESA [Ledr16]. In the setup described here (see Sec. 5.1), one of the circularly deflecting cavities which were developed for the chopper system of MESA [Bech13] is used as a temporal diagnostic instrument. Some results will be presented in Sec. 6.3.

3. Building blocks of the experiments and their physics background

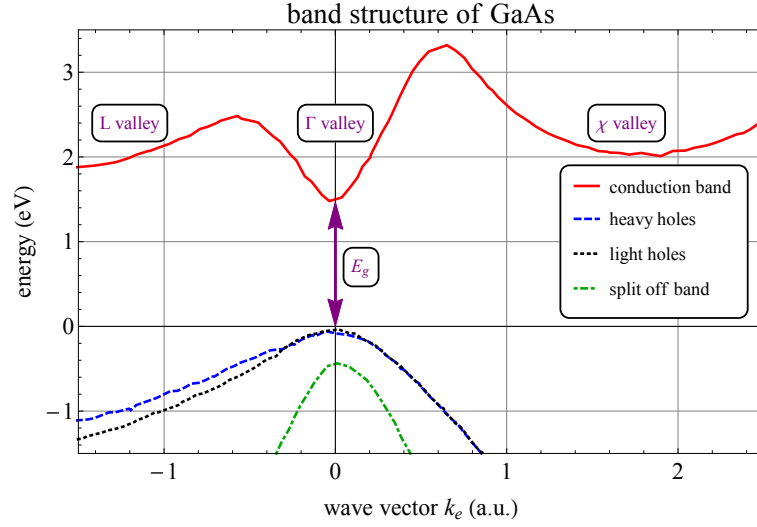


Figure 3.5.: Band structure of the direct semiconductor GaAs plotted over the wave vector $\vec{k}_e$. The upper line represents the conduction band, and the lines with an energy below 0 eV indicate the valence band. The valence band can be divided into three different bands, which represent the heavy holes, light holes and the split off band, respectively.

3.2. Photoeffect and photocathode properties

The electron source for MESA is a dc photoelectron gun with mono-crystalline (GaAs) or poly-crystalline (multi alkali - KCsSb) semiconductor cathodes that emit electrons when illuminated with laser light because of the photoelectric effect. The semiconductor cathodes used are made of GaAs, which is a direct semiconductor, and for these the $\vec{k}_e$ -preserving transitions^c are the ones with the highest absorption probability. If the energy of the valence band E_V and conduction band E_C are plotted over $\vec{k}_e$, the minimum of E_C and the maximum of E_V are located at the same value of $\vec{k}_e$ [Kitt04]. The wave vector dependent evolution of the band structure for GaAs is shown in Fig. 3.5. The distance between the minimum and the maximum is called band gap energy E_g . Within this energy region, no occupied states exist. If the photons have the energy $\hbar\omega_{\text{ph}} = E_g \simeq 1.4 \text{ eV}$, the absorption coefficient $\alpha_{0,\text{GaAs}}$ is very small and amounts to $\sim 500 \text{ cm}^{-1}$, but with an energy increase of 0.1 eV, it can increase to $\sim 10^4 \text{ cm}^{-1}$ [KuSe62]. The increasing $\alpha_{0,\text{GaAs}}$ affects the quantum efficiency (QE) in a positive way and also the lifetime of the photocathode. The quantum efficiency is a measure of the amount of electrons produced per incident photon and can be calculated via:

$$QE (\%) = \frac{I_{\text{beam}}}{P_L} (\text{A/W}) \frac{100 \hbar c_{\text{vac}}}{q_e \lambda_{\text{ph}}} = \frac{I_{\text{beam}}}{P_L} (\text{A/W}) \frac{100 \times 1.24}{\lambda_{\text{ph}} (\mu\text{m})}. \quad (3.3)$$

^c $\vec{k}_e$: wave-vector of an electron

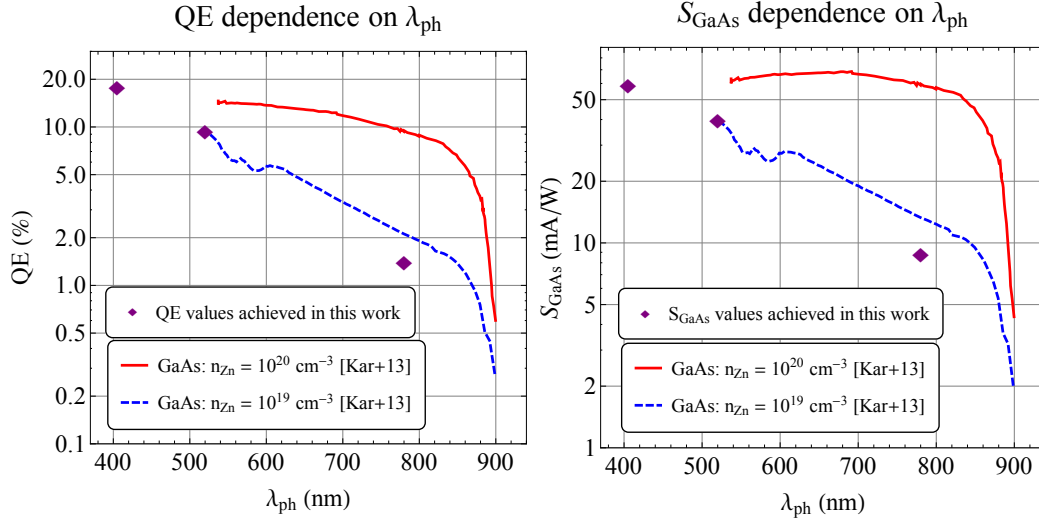


Figure 3.6.: Measured wavelength dependence of the quantum efficiency for GaAs photocathodes. Both plots visualize the influence of the doping concentration n_{Zn} on the QE in (%) and on the responsivity in (mA/w) on the left and right side, respectively. Both plots also include experimental values of the photocathodes used in this thesis. The sharp drop of the quantum efficiency at high wavelengths ($\lambda_{\text{ph}} > 850 \text{ nm}$) is caused by $E_{\text{ph}} < E_g$. Data points mark the QE values obtained in this work. (data taken from [Kar+13])

Here, h is the Planck constant, c_{vac} is the speed of light, q_e is the elementary charge of an electron, and λ_{ph} is the wavelength of the incident photons. I_{beam} and P_L will be measured and denote the produced electron current and the incident laser power, respectively. The typical wavelength-dependent evolution of the quantum efficiency for GaAs photocathodes is depicted in Fig. 3.6 for two different doping concentrations n_{Zn} . Furthermore, Fig. 3.6 illustrates one example of the QE in % and in the unit mA/w on the left and right side, respectively, for each of the two doping concentrations. If the semiconductor is neither p- nor n-doped, the Fermi level $E_{\text{Fermi}}^{\text{d}}$ is located in the middle of E_g .

The outer photoeffect can be divided into three steps [Spic93]:

- The first step is the absorption of a photon by an electron with a probability $\alpha_{0,\text{GaAs}}(E_{\text{ph}})$ dependent on the energy of the incident photon.
- In the second step, the electrons in the conduction band have to travel to the surface of the semiconductor. In this step, the escape depth d_{esc} is important, and with d_{esc} the transport probability can be calculated with an exponential relation. During the transport through the semiconductor, the electrons lose energy.

^d At the Fermi energy, the occupancy probability is 50% for both bands.

3. Building blocks of the experiments and their physics background

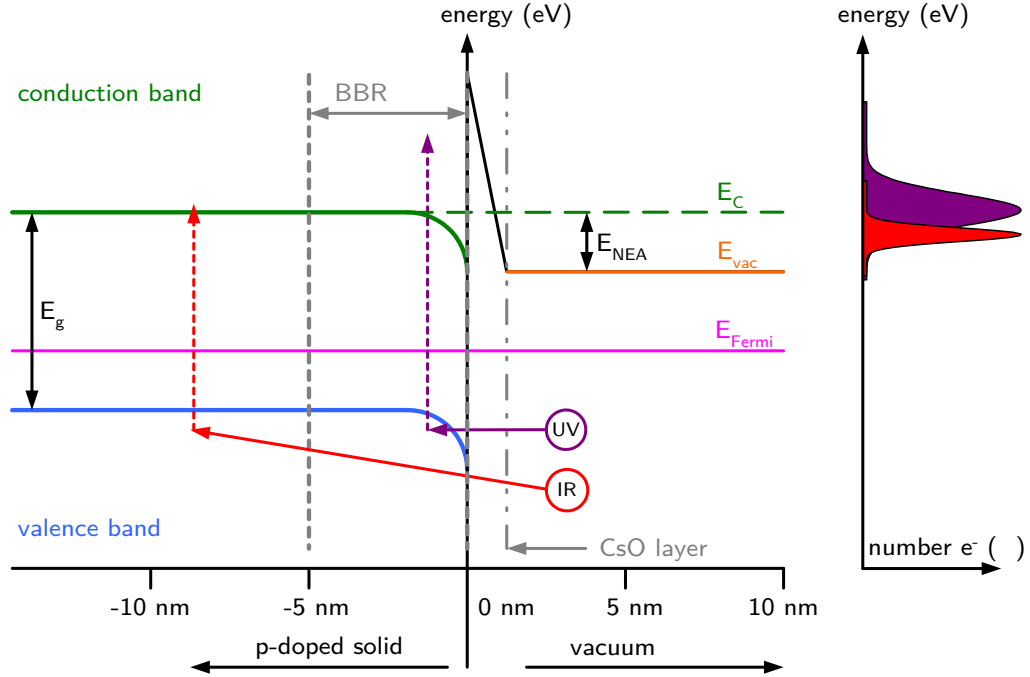


Figure 3.7.: Sketch of a simplified band structure of a semiconductor. The energy of an IR photon excites electrons from the valence band to the lower states in the conduction band. Electrons reaching the surface have a very sharp energy distribution (red). In the case of a UV photon, the excited electrons can occupy higher states in the conduction band, and depending on the depth where they have been created, they do not have enough time to thermalize, thereby ending up with a broader energy distribution (purple). The width of the energy distribution has an influence on the thermal emittance.

- The third and last step is the escape of the electrons from the surface. In order for them to be able to overcome the surface potential barrier, they have to reach the surface with an energy higher than the vacuum energy E_{vac} . Once beyond the barrier, they are accelerated by the electric field created by the gun electrodes.

To increase the escape probability of the electrons from the surface of the GaAs cathodes, it is necessary to create a negative electron affinity (NEA). The electron affinity χ_{EA} is defined as

$$\chi_{EA} = E_{vac} - E_C$$

where E_C indicates the energy of the conduction band minimum. A negative value of χ_{EA} corresponds to a vacuum energy lower than the conduction band minimum. Fig. 3.7 illustrates the spatial distribution of the band structure for GaAs with a realized negative electron affinity. To reach this, the GaAs is p-doped with a Zn atom concentration of around $n_{Zn} \approx 1 \times 10^{19} \text{ cm}^{-3}$. Due to the high doping

3.2. Photoeffect and photocathode properties

concentration, the Fermi level is shifted closer to the valence band maximum inside the semiconductor, which can be described via the Joyce-Dixon approximation [JoDi77]. Near the surface, E_{Fermi} is still located in the middle of the band gap. This phenomenon is known as Fermi level pinning. The different locations of E_{Fermi} with respect to the valence band maximum and conduction band minimum form a band bending region (BBR) behind the surface inside the semiconductor. Within the BBR E_C and E_V are bent to lower energies. The BBR can be calculated via

$$d_{\text{BBR}} = \sqrt{\frac{2\varepsilon_0\varepsilon_{\text{r,GaAs}}\Delta E_{\text{BBR}}}{n_{\text{Zn}}q_e}} \quad (3.4)$$

and inserting the parameters for the permittivity of GaAs $\varepsilon_{\text{r,GaAs}} = 13$, the energy shift caused by the BBR $0.5\text{ eV} < \Delta E_{\text{BBR}} < 0.7\text{ eV}$ and a doping concentration of $n_{\text{Zn}} = 4 \times 10^{18}\text{ cm}^{-3}$, this leads to a thickness of around $d_{\text{BBR}} \approx 6\text{ nm} \dots 12\text{ nm}$ [Herr94, Hart97]. Nevertheless, E_{vac} has to be decreased further, which can be reached by vapor deposition of Cs and O_2 . The last step is very important for spin-polarized as well as unpolarized electrons.

Semiconductor photocathodes have some properties that should be taken into account. Close to E_g , it is possible to create spin-polarized electrons with circularly polarized photons^e. If this is desired, the stimulated electrons can occupy the lowest levels in the conduction band. When these electrons travel to the surface and are emitted, the energy distribution is very sharp. However, when operating in this mode, one suffers from low QE and reduced cathode lifetime. If high currents but no spin-polarization are desired, it is advantageous to use higher photon energies since the QE is almost an order of magnitude larger and the lifetime is longer. At around 400 nm, the photocathodes can have a QE of 18% $\triangleq 50\text{ mA/W}$ (see Fig. 3.6). For higher photon energies, not only the QE increases, but the thermal emittance does as well. This is due to the fact that the stimulated electrons can occupy higher states in the conduction band, and if they are produced close to the surface, they do not have enough time to thermalize while they travel through the semiconductor and end up with a broader energy distribution. This additional energy spread is transferred into larger transverse momenta, which leads to a higher thermal emittance. This property was investigated among others by [Baza08] and can also be seen on the right side of Fig. 3.8. The influence of the thermal emittance $\epsilon_{\text{th}} = k_B T$ on the laser spot size σ_L dependent normalized emittance ϵ_n can be expressed as

$$\epsilon_n = \sigma_L \sqrt{\frac{k_B T}{E_0}} = \sigma_L \sqrt{\frac{\epsilon_{\text{th}}}{E_0}}. \quad (3.5)$$

E_0 describes the rest mass energy of an electron. The results published in [Baza08] are summarized in Tab. 3.1 and visualized on the left side of Fig. 3.8. For the photocathode sample used in [Baza08], the wavelength dependence of the thermal emittance can be expressed via a linear function with the following parameters

$$\epsilon_{\text{th}} (\text{meV}) = 309.2 - 0.3617\lambda_{\text{ph}} (\text{nm}).$$

^ephoton wavelength: $\lambda_{\text{ph}} \simeq 780\text{ nm}$

3. Building blocks of the experiments and their physics background

Table 3.1.: Results of the thermal emittance ϵ_{th} for different wavelength λ_{ph} . [Baza08]

λ_{ph} (nm)	ϵ_{th} (meV)
458	146 ± 10
532	113 ± 8
633	81 ± 6
710	53 ± 4
860	30 ± 2

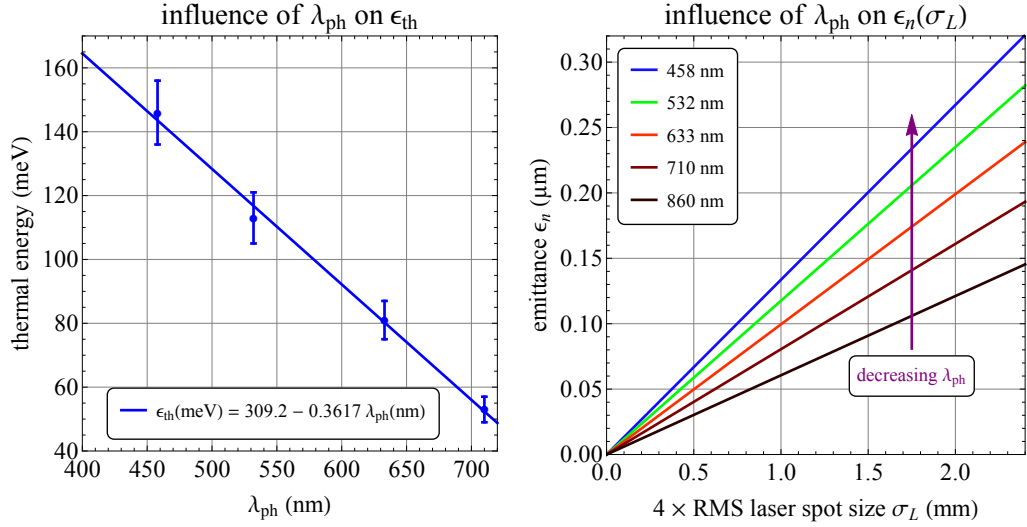


Figure 3.8.: The graph on the left illustrates the data of Tab. 3.1 with an additional linear fit. The graph on the right shows the evolution of the normalized emittance ϵ_n as a function of the laser spot size σ_L . The different lines indicate the influence of the photon wavelength λ_{ph} on the thermal emittance. The results presented here are calculated with Eq. 3.5 and with the values of Tab. 3.1. [Baza08]

Inserting the values of the thermal emittance from Tab. 3.1 into Eq. 3.5 leads to the results presented on the right side of Fig. 3.8.

Comparing the statements of Eq. 3.2 and Eq. 3.5 indicates that the aim of reaching a low-emittance high-current electron beam is contradictory since Eq. 3.2 states that the extractable current increases with increasing laser spot size on the photocathode, but this will also increase the normalized emittance at the same time. Furthermore, it is recommended to use a laser system that provides a high QE by small wavelength, which in turn leads to an increase in the thermal emittance. Thus, a compromise must be found.

3.2.1. Photocathode response time

An additional and important property of the photocathode used is the response time. This time should be very short ($\mathcal{O}(\text{ps})$) to ensure the production of the necessary electron pulse structure.

Results for the response time from published measurements:

- $\tau_{\text{pc,FWHM}} = (20 \pm 3) \text{ ps}$ for 840 nm and GaAs [Hart97]
- $\tau_{\text{pc}} = 1.87 \text{ ps}$ for 400 nm and GaAs [Dehn13]
- $\tau_{\text{pc}} = 2.37 \text{ ps}$ for 800 nm and GaAs [Dehn13]
- $\tau_{\text{pc},90} = (14.0 \pm 0.2) \text{ ps}$ for 800 nm and transmission GaAs/GaAsP SLSL [Yam+16]
- $\tau_{\text{pc},90} = (4.6 \pm 0.7) \text{ ps}$ for 850 nm and $0.2 \mu\text{m}$ GaAs [Aul+02]
- $\tau_{\text{pc},90} = (15 \pm 2) \text{ ps}$ for 850 nm and $0.4 \mu\text{m}$ GaAs [Aul+02]

The symbol $\tau_{\text{pc},90}$ corresponds to the time which includes 90% of the extracted charge. This measure was introduced by [Aul+02] due to the strongly asymmetrical shape of the pulse response. All published results for the response time indicate that an influence of the “cathode internal” response time would be negligible for a laser pulse length of several 100 ps. The difference in the response time for the photon wavelengths used is caused by the wavelength dependence of the photon absorption length $d_{\text{abs}}(\lambda_{\text{ph}})$. In Fig. 3.9, the calculated absorption length for two different doping concentrations of GaAs is shown [Kar+13]. It can be extracted from the calculations shown in Fig. 3.9 that p-doped GaAs is almost transparent for photons with an energy near $E_{\text{ph}} = E_g = 1.4 \text{ eV}$ corresponding to $\lambda_{\text{ph}} \simeq 890 \text{ nm}$. The absorption length is $d_{\text{abs}} \simeq 750 \text{ nm}$, $d_{\text{abs}} \simeq 150 \text{ nm}$ and $d_{\text{abs}} < 15 \text{ nm}$ for the wavelengths 780 nm, 520 nm and 405 nm, respectively. Thus, photons with a wavelength around 405 nm will be absorbed within the BBR, which can cause a significant decrease in the response time.

3.2.2. Photocathode preparation

The GaAs photocathodes have to be coated with a CsO layer to increase the QE. This procedure is called “preparation” and has to be repeated from time to time. The preparation is carried out in the preparation chamber, which is connected to the source chamber via an all-metal valve. The arrangement of the preparation chamber to the source chamber can be looked up in Fig. 3.10. The first step in the preparation process is to heat up the photocathode to a temperature of $(550 - 580)^\circ\text{C}$ and to keep it at this temperature for 30 min. This step is necessary to clean the cathodes before they are coated with a CsO layer. The cathode heating is followed by a break of $\sim 45 \text{ min}$ to improve the vacuum conditions. During this

3. Building blocks of the experiments and their physics background

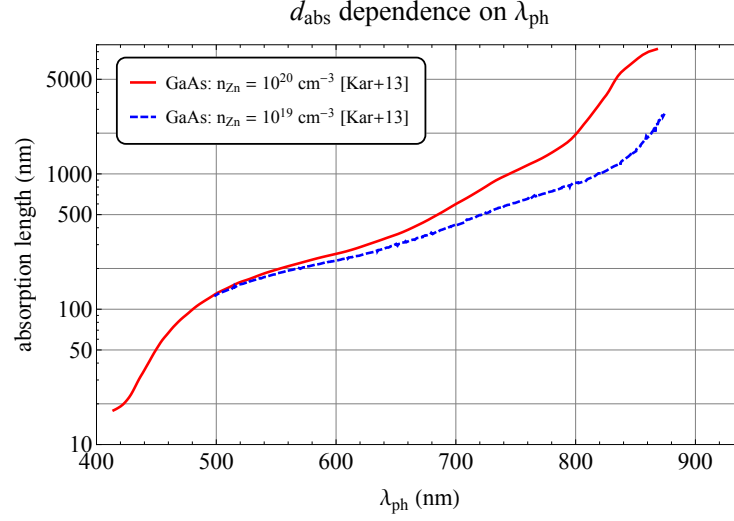


Figure 3.9.: Wavelength dependence of the photon absorption length in p-doped GaAs for two different doping concentrations. The trend of the absorption length for a doping concentration of $n_{\text{Zn}} = 1 \times 10^{18} \text{ cm}^{-3}$ is very similar to that for $n_{\text{Zn}} = 1 \times 10^{19} \text{ cm}^{-3}$ and is omitted for clarity.

break, the photocathode is placed in a mask and positioned above a Cs dispenser^f, which is illustrated in Fig. 5.2. Between this Cs dispenser and the photocathode, an annular electrode is mounted, which enables to establish a small accelerating voltage of several hundred volts. When the vacuum has recovered to around 1×10^{-10} mbar and better, the coating process can be started. Ultra high vacuum conditions are essential for a successful preparation because GaAs is very sensitive to oxygen, water, and carbon dioxide [Aule07]. The Cs is evaporated from the Cs dispenser by applying a few amperes. During the whole preparation process, the QE evolution is observed by measuring the electron current which is produced by illuminating the photocathode with a laser. The QE starts to rise after a few minutes of Cs evaporation and reaches its first maximum. If this first maximum is exceeded, the QE starts to fall, and at this point O_2 is admitted into the preparation chamber via a leak valve^g. The amount of O_2 is adjusted to deliver the highest increase of the QE and is observed with a residual gas analyzer^h. The partial pressure of O_2 in the chamber can reach 2×10^{-7} mbar during the preparation of the photocathode. Although this is a fairly high partial pressure of O_2 , the preparation provides high QE values. The partial pressure is typically 10^{-9} mbar for O_2 . The Cs coating generally takes (15 – 25) min and is finished if no further increase in the QE can be reached. New bulk GaAs photocathodes can easily reach a QE of around 20% at a wavelength of 405 nm (see Fig. 3.6), but the QE will decrease from preparation to

^fSAES Getters S.p.A. - Cs dispenser type: Cs/NF/??/25/FT 10 + 10

^gVACGEN LTD - all metal right angle leak valve: ZLVM940R

^hAMETEK - Dycor LC-D

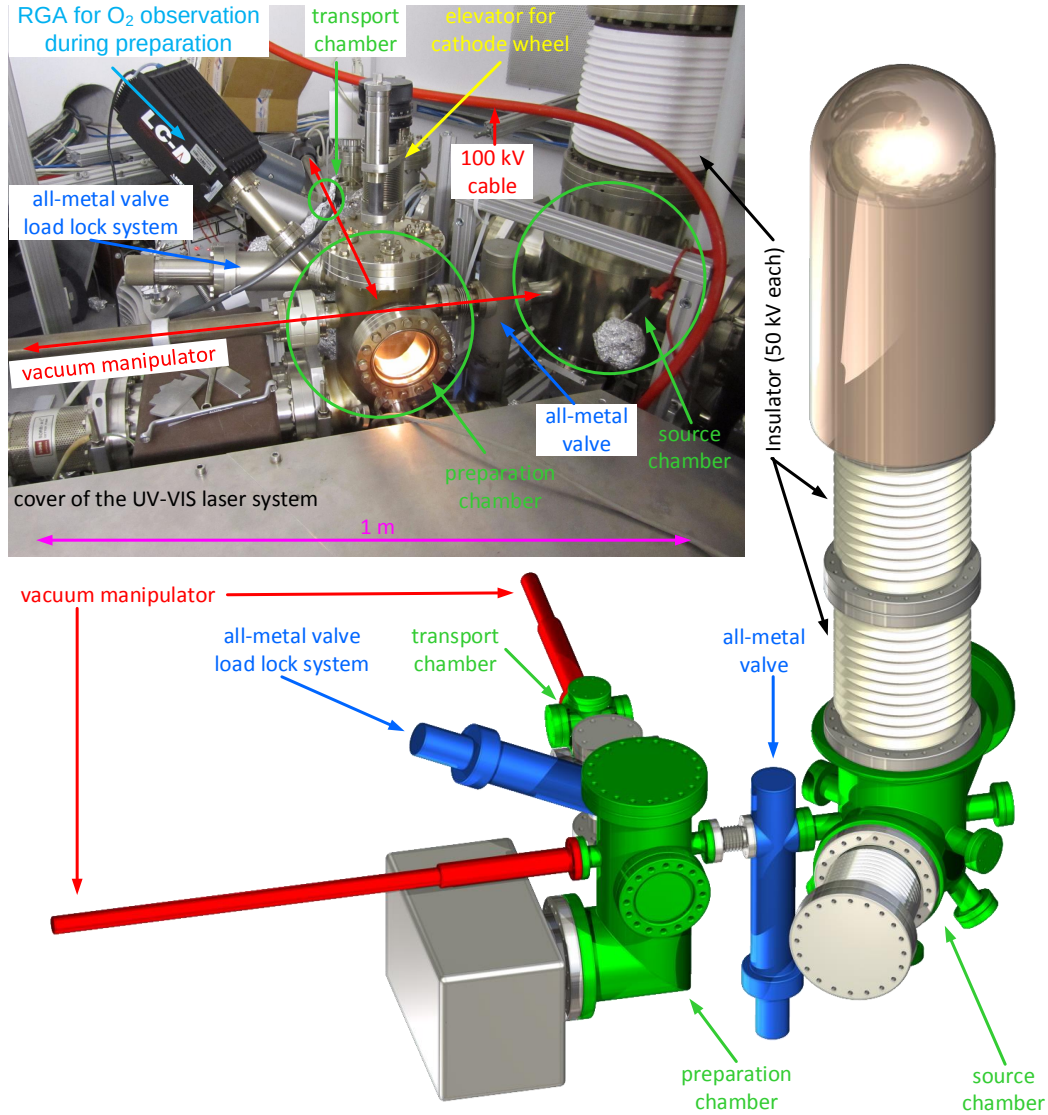


Figure 3.10.: Picture and CAD drawing of the photoelectron source (PKA2) and the preparation chamber. An all-metal valve enables to insert new photocathodes into the preparation chamber without breaking the vacuum (load lock). After the cathode preparation, these are transported under vacuum conditions into the source chamber. The preparation chamber and the source chamber are connected to each other via an all-metal valve to keep the vacuum in the source chamber during the photocathode preparation at the same level as during operation. (CAD drawing courtesy of M. Schwartz)

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preparation (illustrated on the right side in Fig. 6.1). This is caused by collecting impurities during the operating time which cannot be removed through the heating procedure.

3.3. Laser system

3.3.1. Requirements of the laser system

MESA will be a continuous wave (c.w.) accelerator in which the accelerated electrons are packed in bunches that occupy a small fraction of the RF phase. In Fig. 3.11, the phase acceptance of the buncher system is visualized. The first example on the left side shows electron bunches which would deliver a high transmission T_e through the accelerator because the whole bunch will lie within the accepted RF phase which can be captured by the buncher system. The electron bunches in the example on the right side of Fig. 3.11 will have a reduced transmission through the injector. Thus, for a high transmission through the injector, the electron bunches should occupy an RF phase of less than 160° because electrons outside this phase interval will not be captured by the buncher system and get lost. On the other hand, the length of the electron bunches transported through the MELBA system should not be too small either ($< 45^\circ$). Short electron bunches will result in a faster increase of the bunch length during the transport through the low-energy section. An acceptable compromise would be a bunch length of around 100° (shown in Fig. 3.4). This assumption is based on experience at MAMI.

The laser system used has two different laser diodes (see Fig. 5.5) with different pulsing behavior and wavelength (405 nm & 520 nm). To produce the desired electron current of MESA stage-1, at least the following parameters have to be taken into account.

- the wavelength dependent responsivity S_{GaAs} of the photocathode
- the laser power P_L on the photocathode
- the electron transmission T_e through the beam line with an RF phase acceptance of 100°

Multiplying all these values should lead to an electron current $I_{\text{beam}} > 1 \text{ mA}$. Better would be a factor $e \simeq 2.7183$ times more current to be able to compensate for life time effects of the photocathode. Thus, the following equation should be fulfilled:

$$I_{\text{beam}} = T_e P_L (W) S_{\text{GaAs}} (\text{mA/W}) > 1 \text{ mA} \quad (3.6)$$

The typical shape of the responsivity S_{GaAs} can be looked up on the right side of Fig. 3.6. Generally, it can be assumed that S_{GaAs} for a blue laser is 1.5 times as much as for a green one. Typical results for S_{GaAs} of the photocathodes used in this thesis are 60 mA/W and 40 mA/W for blue and green, respectively. As depicted in Fig. 3.8, not only the responsivity changes with wavelength, also the emittance

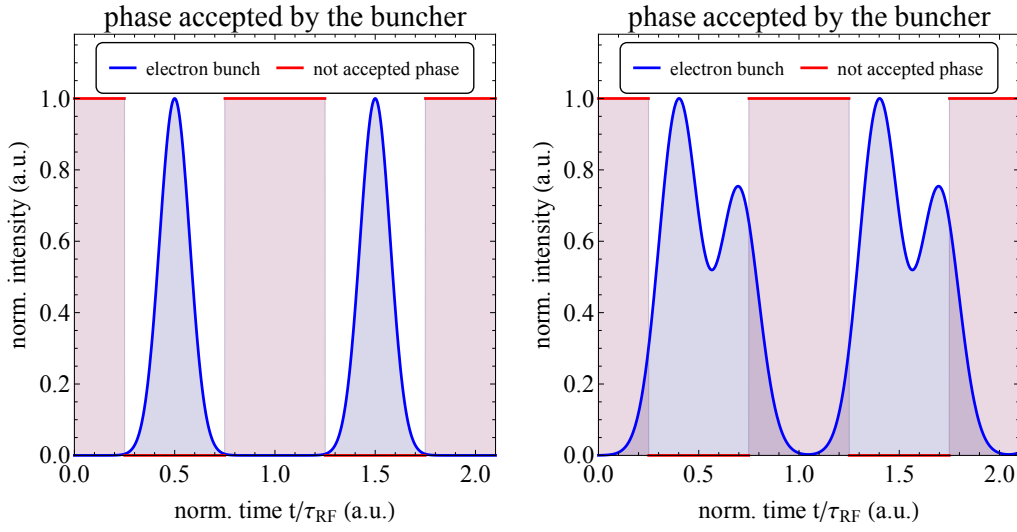


Figure 3.11.: RF phase acceptance of the injector. The example on the left side shows electron bunches which would deliver a high transmission through the accelerator. Only electrons which arrive during the positive part of the RF wave will be accelerated through the injector. The electron bunches in the example on the right side will have a reduced transmission through the injector. Thus, for a high transmission through the injector, the electron bunches (blue) should be produced synchronous to the accelerator frequency and lie within a phase interval of 160° .

3. Building blocks of the experiments and their physics background

does. But this effect is neglected in the following consideration. The laser system used consists of several optical components that reduce the photon transmission T_{ph} to the photocathode. Thus, P_L takes into account only the transmitted portion of the laser power. Another important point is the electron transmission T_e through a beam line of several meters. T_e is mainly influenced by the electron pulse length in combination with the RF phase acceptance of the buncher system. The initial temporal and spatial shape of the electron bunch is defined by that of the laser pulse. After the electron bunch is generated, its shape is influenced by the electron source (see Fig. 3.3) and the beam line (see Fig. 3.4). Both influences are bunch charge-dependent. Experiences have shown that the temporal laser pulse shape depends on the laser diode current (I_{LD}) (see Fig. 3.15). By changing I_{LD} , an optimized pulse shape can be set that promises a high electron transmission. This means if a suitable laser pulse shape is found, the laser power should not be varied by changing the laser diode current, but by an external attenuator. Nevertheless, the influence of the bunch charge will cause a diminution of the electron transmission, especially at the position of the chopper system where the phase acceptance is adjusted. The working principle of the chopper system is described in Fig. 3.19. The electron current behind the buncher system is calculated via Eq. 3.6 including the properties of both laser diodes. The results are presented in Fig. 3.12. Both laser diodes enable investigations of the beam dynamics in the desired electron current region. In this first estimate, 100% transmission through the beam line and the buncher system is assumed. What it looks like if the electron transmission T_e depends on the bunch charge will be given in Fig. 6.30. Since the length of the beam line used for the investigations in this thesis is comparable to that of MELBA (see Fig. 1.2), the findings about the electron bunch behavior (Fig. 6.30) can be seen as clues for MESA.

3.3.2. Realization of the requirements of the laser system

Different methods are available to create RF-synchronous laser pulses. The most promising one for a simple laser system is the “gain switching” method of laser diodes.

To reach the goal discussed in Fig. 3.11, it is necessary that the laser system is able to produce light pulses synchronous to the accelerator frequency ν_{MESA} with a pulse length of less than 160° with respect to the RF phase. Experience collected within the operation of MAMI has shown that it is possible to produce these light pulses with a laser diode by a superposition of a dc current with additional RF power [Aul+98]. To determine if this technique is also applicable for laser diodes working in other wavelength regions than infrared, a system of differential equations can be solved. These differential equations are known as rate equations. The rate equations describe the temporal evolution of the charge carrier number (electron number) $\frac{dN_{\text{ec}}}{dt}$ within the active laser medium and the resulting photon number

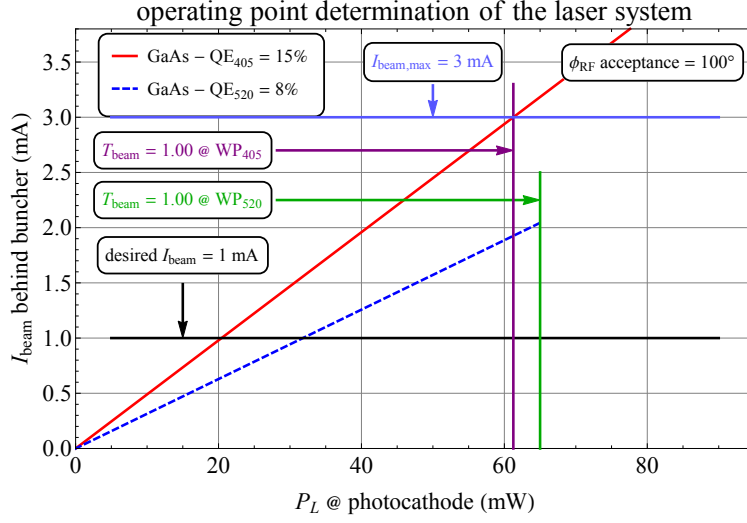


Figure 3.12.: The plot shows the operating point determination of the laser system used. The initial laser pulse is set in such a way that it promises a high electron transmission (T_e). Both laser diodes enable investigations of the beam dynamics in the desired electron current region. The line at $I_{\text{beam,max}} = 3 \text{ mA}$ denotes the maximum current of the HV power supply.

$\frac{dN_{\text{ph},p}}{dt}$ in the cavity. One attempt is given in [Mey+08] and the rate equations are as follows:

$$\frac{dN_{\text{cc}}}{dt} = \eta_{\text{LD}} \frac{I_{\text{LD}}}{q_e} - \frac{N_{\text{cc}}}{\tau_{\text{sp}}} - \sum_p \tilde{g}_p N_{\text{ph},p} \quad (3.7)$$

$$\frac{dN_{\text{ph},p}}{dt} = (\tilde{g}_p - \tilde{g}_{\text{th}}) N_{\text{ph},p} + \beta_{\text{sp},p} \frac{N_{\text{cc}}}{\tau_{\text{rad}}} \quad (3.8)$$

These rate equations are multi-mode equations with the mode number p . They are taken because the laser diodes used—working at 405 nm and 520 nm—establish multiple modes during high-power operation. An additional aspect is that these equations enable a larger parameter variation compared to the much simpler single-mode rate equations presented in [Aule07]. The parameter I_{LD} describes the laser diode current with the efficiency η_{LD} because not all electron-hole pairs will recombine within the active area. q_e is the charge of an electron, and τ_{sp} stands for the spontaneous carrier lifetime, which is linked to the radiative recombination time constant τ_{rad} and the non-radiative recombination time constant τ_{nr} via

$$\tau_{\text{sp}}^{-1} = \tau_{\text{rad}}^{-1} + \tau_{\text{nr}}^{-1}.$$

The first term of the differential Eq. 3.7 describes the growth of the charge carrier number N_{cc} produced by the laser diode current I_{LD} . The electron number N_{cc} is decreased by spontaneous recombinations, which is taken into account by the second term. In the third term of Eq. 3.7, the produced photons $N_{\text{ph},p}$ of each mode p will cause an additional decrease of the carrier number N_{cc} .

3. Building blocks of the experiments and their physics background

All photon losses are collected by one parameter—the threshold gain $\tilde{g}_{\text{th}}$ —which contains the cavity length l_{cav} , the reflectivity of the end faces R_1 and R_2 , the internal cavity losses α_{int} , the group refractive index n_{gr} and the speed of light in vacuum c_{vac} . The threshold gain can be calculated via

$$\tilde{g}_{\text{th}} = \frac{c_{\text{vac}}}{n_{\text{gr}}} \left[\alpha_{\text{int}} - \frac{1}{2l_{\text{cav}}} \ln \left(\frac{1}{R_1 R_2} \right) \right]. \quad (3.9)$$

To get a multi-mode rate equation which takes into account the spectral properties of a laser diode, it is necessary to calculate the gain $\tilde{g}_p$ for every mode. This can be done with

$$\tilde{g}_p = \xi_p A_{\tilde{g},p} - B_{\text{sat}} N_{\text{ph},p} - \sum_{q \neq p} (D_{pq} + H_{pq}) N_{\text{ph},q}. \quad (3.10)$$

The first term includes the linear gain coefficient $A_{\tilde{g},p}$ and the gain fluctuation parameter ξ_p . The parameter ξ_p can cause a modulation in the linear gain coefficient $A_{\tilde{g},p}$ independently for every mode and is given by

$$\xi_p = 1 + d\xi \cdot r_p. \quad (3.11)$$

For the simulations presented here, the value $d\xi$ is set to zero, which ends up in a smooth gain spectrum. In general, r_p will be a random number given by the standard normal distribution. The modulation of ξ_p can be useful in investigations of properties like the current-dependent shift of the central mode of a laser diode or the current-dependent increase of the total mode number, but it has no influence on the results presented here. The second term in Eq. 3.10 takes self-saturation effects into account with the factor B_{sat} . D_{pq} and H_{pq} in the sum of the last term determine the cross-saturation effects between the longitudinal modes. The gain coefficients necessary to calculate the modal gain $\tilde{g}_p$ can be expressed as follows:

$$A_{\tilde{g},p} = \frac{a_{\tilde{g}} \Gamma}{V} \left[N_{\text{cc}} - N_{\tilde{g}} - bV (\lambda_p - \lambda_{\tilde{g}})^2 \right] \quad (3.12)$$

$$B_{\text{sat}} = \frac{9}{2} \frac{\pi c_{\text{vac}}}{\varepsilon_0 n_{\text{gr}}^2 \hbar \lambda_{0,\text{th}}} \left(\frac{\Gamma \tau_{\text{in}}}{V} \right)^2 a_{\tilde{g}} |R_{\text{CV}}|^2 (N_{\text{cc}} - N_{\text{sat}}) \quad (3.13)$$

$$D_{pq} = \frac{4}{3} \frac{B_{\text{sat}}}{\left(\frac{2\pi c_{\text{vac}} \tau_{\text{in}}}{\lambda_p^2} \right)^2 (\lambda_q - \lambda_p)^2 + 1} \quad (3.14)$$

$$H_{pq} \approx \frac{3\lambda_p^2}{8\pi c_{\text{vac}}} \left(\frac{a_{\tilde{g}} \Gamma}{V} \right)^2 \frac{\alpha (N_{\text{cc}} - N_{\tilde{g}})}{\lambda_q - \lambda_p} \quad (3.15)$$

with the volume of the active laser medium V , the characterizing slope of the gain $a_{\tilde{g}}$, and the confinement factor Γ , which describes the overlapping of the modes with the active laser medium. The next parameter in Eq. 3.12 is known as transparency

electron number $N_{\tilde{g}}$. This number denotes the amount of charge carriers at which the gain is zero and can be expressed as

$$N_{\tilde{g}} = \eta_{LD} \frac{I_{LD}}{q_e} \tau_{sp} - \frac{V}{a_{\tilde{g}} \Gamma} \tilde{g}_{th}. \quad (3.16)$$

The other necessary parameters are b , describing the dispersion of the gain spectra with its central wavelength $\lambda_{\tilde{g}}$, the vacuum permittivity ε_0 , the intraband relaxation time τ_{in} , the anti-guiding factor α and the dipole moment of the quantum wells R_{CV} .

The second term in Eq. 3.8 contains the spontaneous emission factor $\beta_{sp,p}$ and the radiative recombination time constant τ_{rad} . The factor $\beta_{sp,p}$ describes the increase of the photon number in the mode p by spontaneously emitted photons. The spontaneous emission has a Lorentzian shape and can be calculated via

$$\beta_{sp,p} = \frac{K_{en} \Gamma \lambda_p^4}{4\pi^2 n_{ref}^2 n_{gr} V} \frac{\delta \lambda_{sp}}{(\lambda_p - \lambda_{sp})^2 + \delta \lambda_{sp}^2}. \quad (3.17)$$

Here, λ_{sp} is the central wavelength of the spontaneous emission with the half-width at half-maximum (HWHM) $\delta \lambda_{sp}$, n_{ref} is the refractive index of the waveguide, and K_{en} is known as spontaneous emission enhancement factor, which depends on the waveguiding of the laser.

The last and not yet mentioned parameters are the mode wavelength λ_p and the central gain wavelength $\lambda_{\tilde{g}}$, which are both dependent on the laser diode current I_{LD} . The mode and gain wavelength can be estimated via

$$\lambda_p = \lambda_{0,th} + p \Delta \lambda + \frac{d\lambda_p}{dI_{LD}} (I_{LD} - I_{th}) \quad (3.18)$$

and

$$\lambda_{\tilde{g}} = \lambda_{0,th} + \frac{d\lambda_{\tilde{g}}}{dI_{LD}} (I_{LD} - I_{th}) \quad (3.19)$$

where the current dependence is denoted with $\frac{d\lambda_p}{dI_{LD}}$ and $\frac{d\lambda_{\tilde{g}}}{dI_{LD}}$ for the mode wavelength and the gain wavelength, respectively. $\Delta \lambda$ indicates the mode spacing, and I_{th} is the threshold current of the laser diode. All parameters which are kept fixed in the following simulations are summed up in Tab. 3.2.

As mentioned above, the laser pulses should be synchronous to the accelerator frequency ν_{MESA} , which is reached with a superposition of the dc current I_{dc} from a laser diode driver with an additional amount A_{RF} of RF power. The mathematical expression for this is:

$$I_{LD}(t) = I_{dc} + A_{RF} I_{dc} \sin(\omega_{MESA} t) \quad (3.20)$$

Solving the rate equation system (Eq. 3.7 and Eq. 3.8) with an RF-modulated laser diode current (Eq. 3.20) leads to RF-synchronous laser pulses. Fig. 3.13 shows three examples with different RF-modulated laser diode currents for the start of

3. Building blocks of the experiments and their physics background

Table 3.2.: Common parameters for GaN laser diodes [Mey+08]

Parameter	Value
center wavelength $\lambda_{0,\text{th}}$	405 nm
resonator length l_{cav}	600 μm
mirror reflectivities R_1 & R_2	17% & 98%
volume of quantum wells V	$5.4 \times 10^{-18} \text{ m}^3$
confinement factor Γ	0.017
mode spacing $\Delta\lambda$	38 pm
group refractive index n_{gr}	3.59
refractive index n_{ref}	2.53
anti-guiding factor α	3.5
dipole moment R_{CV}	$2.8 \times 10^{-57} \text{ C}^2\text{m}^2$
spontaneous emission enhancement factor K_{en}	1
wavelength of spontaneous emission λ_{sp}	416 nm
HWHM of spontaneous emission $\delta\lambda_{\text{sp}}$	3.5 nm
spontaneous lifetime τ_{sp}	4.5 ns
non-radiative emission constant τ_{nr}	9 ns
intraband relaxation time τ_{in}	25 fs
electron characterizing self-saturation N_{sat}	$0.8 \times N_{\tilde{g}}$
slope coefficient of linear gain $a_{\tilde{g}}$	$9.8 \times 10^{-13} \text{ m}^3\text{s}^{-1}$

the pumping process of a semiconductor laser. The left side shows the increase of the charge carrier concentration, which speeds up with increasing current. The wavy structure at the beginning is caused by the RF modulation. If the charge carrier density has reached a specific amount above the laser threshold, which depends on the internal losses, the laser starts to pulse. Now the charge carriers are depleted as a result of stimulated emission faster than they can be built up by the laser diode current. Thus, the photon number decreases rapidly and the laser pulse stops. By keeping up the laser diode current, the charge carrier density is refilled until it overcomes the laser threshold, which results in the generation of another laser pulse. If the conditions are not changed, this results in a continuous process of RF-synchronized laser pulse generation. The right side of Fig. 3.13 shows the evolution of the photon number.

Not only the laser diode current influences the pulsing behavior, also the amount of RF power does. This situation is visualized on the left side of Fig. 3.14 for the charge carrier density and on the right side for the resulting photon number. Both plots are for an laser diode current close above the threshold current. An increasing amount of RF power has a shortening effect on the pulse length. In general, if the RF modulation is chosen below $A_{\text{RF}} = 0.5$, this results in a sinusoidal modulation of the photon number instead of RF-synchronized laser pulsing.

Some additional examples are depicted in Fig. 3.15 to Fig. 3.17 on the left side and compared with real performed measurements on the right side. The comparison

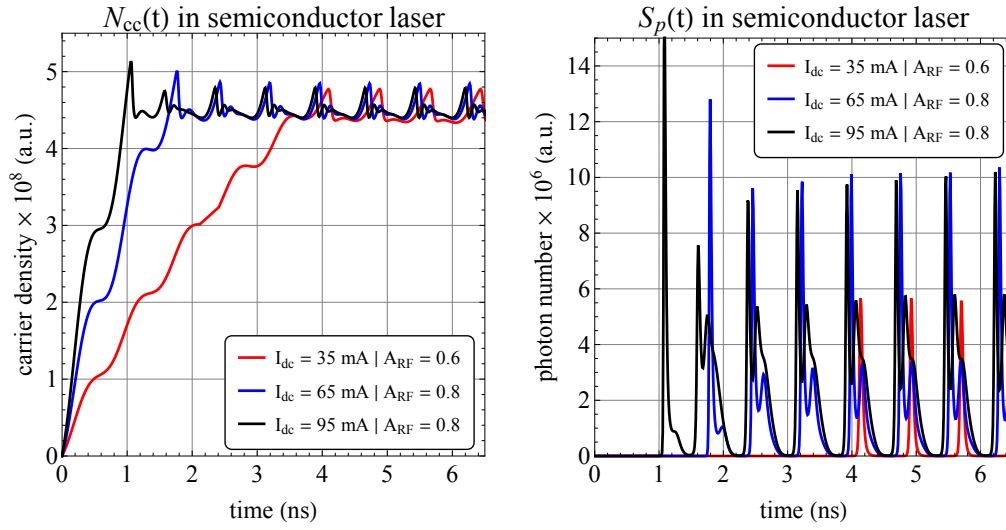


Figure 3.13.: Visualization of the pumping process of a semiconductor laser for three different laser diode currents. The left side shows the charge carrier concentration and the right side the evolution of the photon number.

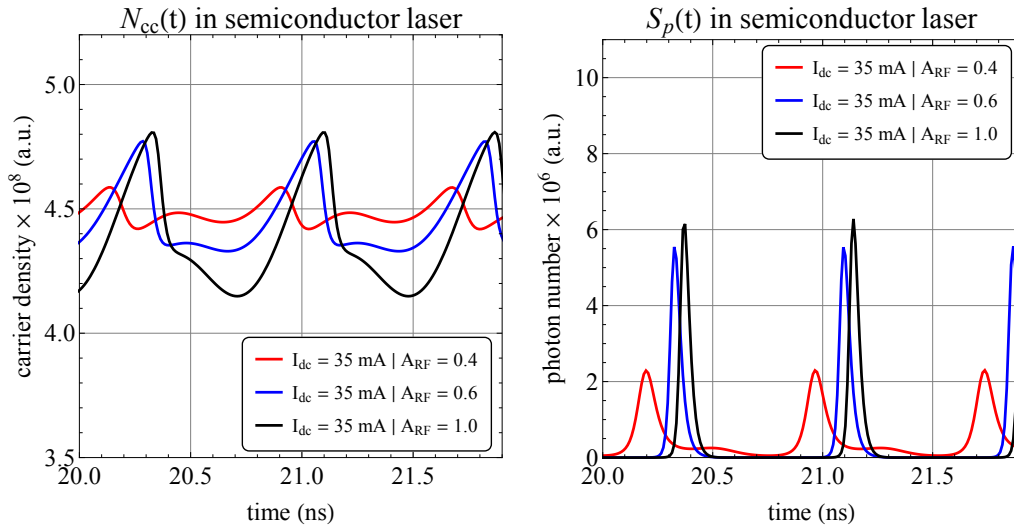


Figure 3.14.: Influence of the amount of RF modulation on the charge carrier density and pulse structure after reaching the steady state conditions. The laser diode current is chosen such that it is located closely above the threshold current. For higher laser diode currents, an RF modulation below $A_{RF} = 0.5$ leads to a sinusoidal modulation of the photon number instead of RF-synchronized laser pulsing.

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includes different laser diodes with different operating conditions. Depending on the ratio between the dc current I_{dc} and internal losses α_{int} , it takes (10 – 15) ns to reach the steady state conditions if the dc current is above the threshold current. The results shown in Fig. 3.15 to Fig. 3.17 introduce three different cases. The laser diode current as well as the internal losses increase in the plots from Fig. 3.15 to Fig. 3.17. The lowest amount of RF power is set to $A_{\text{RF}} = 0.5$, which is generally not enough to generate a sufficient modulation. RF powers above $A_{\text{RF}} = 0.75$ can produce short RF-synchronous single pulses close above the threshold current. By increasing the laser diode current, also the number of intensity peaks within one RF period increases.

Since the parameters presented in Tab. 3.2 are unknown for the laser diodes used, it is difficult to predict the pulsing behavior by solving the rate equation system. In addition, the modulation amplitude A_{RF} used in the rate equation system cannot be determined even if the RF power in the laser system can be measured. Thus, the observed pulse shapes of the laser diodes investigated can be reproduced by solving the rate equation system represented by Eq. 3.7 and Eq. 3.8, but the parameters used for the solution do not necessarily represent the laser diode properties. However, the rate equations can be a helpful tool to investigate whether more or less RF power can improve the pulse shape.

A comparison between Fig. 3.11 and Fig. 3.15 to Fig. 3.17 leads to the conclusion that a semiconductor laser is able to produce RF-synchronous single pulses with the desired time structure if it is operated closely above the threshold current. Results obtained are presented in Sec. 6.3.

3.4. RF system

To produce operating conditions similar to those used at MESA, an RF system working at $\nu_{\text{MESA}} = 1.3 \text{ GHz}$ is needed. This system must be able to provide several hundred watts of power for the deflecting cavity and around two watts of power for the laser system. Fig. 3.18 gives an overview of the RF system used.

The RF signal is produced by a signal generatorⁱ which is set to $\nu_{\text{MESA}} = 1.3 \text{ GHz}$, and this signal is fed through a directional coupler to branch the signal to the laser system. The main part of the RF signal which passes through the directional coupler is fed via a step attenuator to the input of an amplifier cascade. The amplifier cascade is able to deliver a maximum output power of 300 W, which can be used to serve the deflecting cavity in the beam line.

The part of the RF power coupled out for the laser system via the directional coupler close to the output of the signal generator is increased by a pre- and a main-amplifier. The amplified RF signal is guided to the PKA2 lab where it has to pass through a step attenuator followed by a directional coupler. This coupler couples out –20 dB of the forward and reflected RF power, respectively. The forward power

ⁱHewlett Packard: E4421E - ESG Series Signal Generator

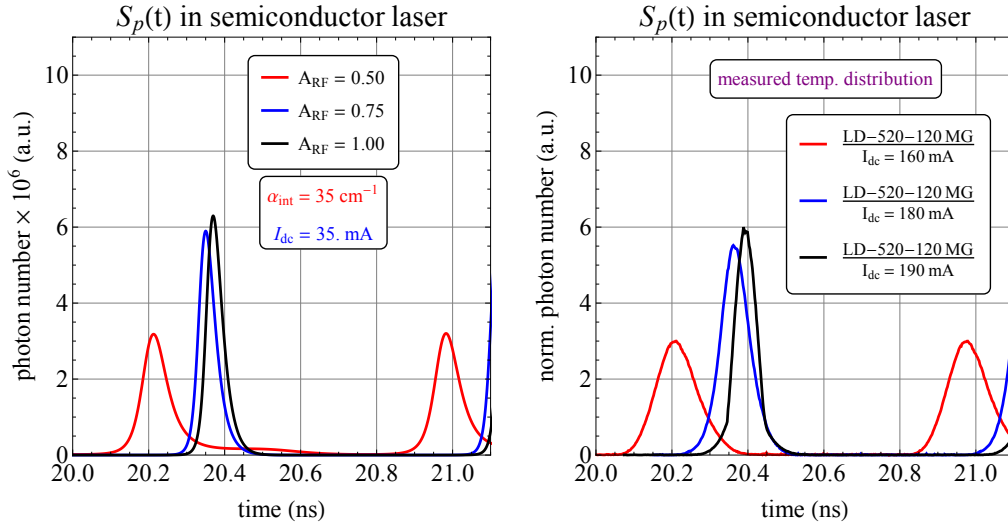


Figure 3.15.: The plot shows a comparison between a selection of solved rate equations at steady state conditions on the left side with some measured temporal pulse profiles on the right side (diff. laser diodes with diff. operation conditions). The lowest amount of RF power is set to $A_{RF} = 0.5$, which is generally not enough to generate a sufficient modulation. RF powers above $A_{RF} = 0.75$ can produce short RF-synchronous single pulses close above the threshold current. By increasing the laser diode current, also the number of intensity peaks within one RF period increases.

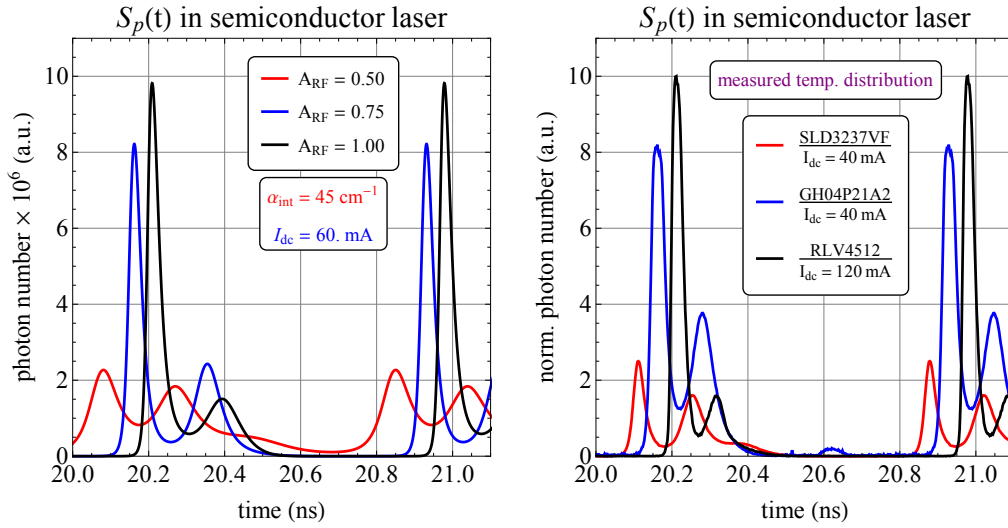


Figure 3.16.: The plot shows a comparison between a selection of solved rate equations at steady state conditions on the left side with some measured temporal pulse profiles on the right side (diff. laser diodes with diff. operation conditions).

3. Building blocks of the experiments and their physics background

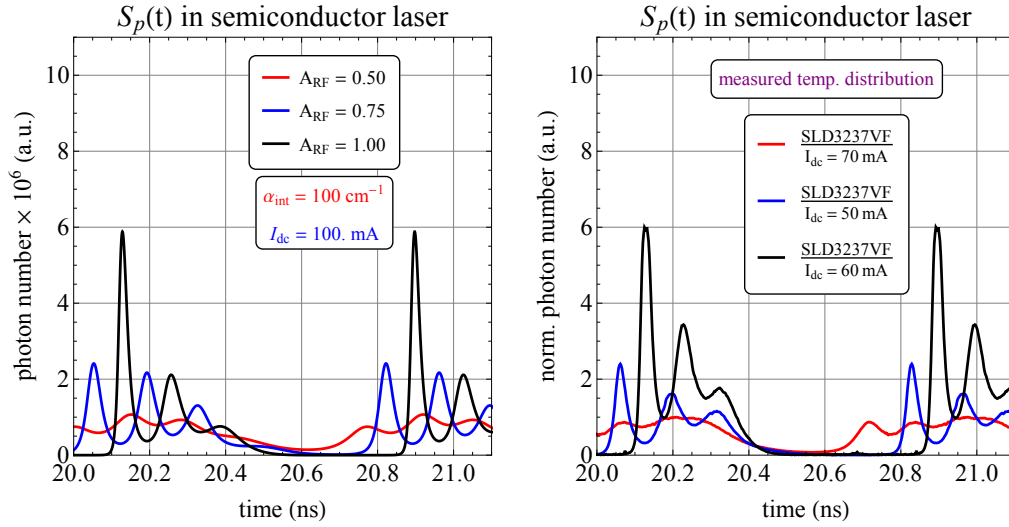


Figure 3.17.: The plot shows a comparison between a selection of solved rate equations at steady state conditions on the left side with some measured temporal pulse profiles on the right side (diff. laser diodes with diff. operation conditions).

is used to monitor the input RF power into the laser system via a powermeter^j. The reflected RF power is also monitored by the powermeter and used to optimize the performance of the laser diode. The directional coupler is followed by a double stub-tuner to perform an impedance matching for different laser diodes and to adjust the amount of RF power used. The maximum RF power available in this setup is 1.7 W. The last element in front of the laser diode is a bias-tee to superimpose the RF power with an additional dc current from a laser diode driver.

3.5. RF cavities

RF cavities have a wide range of applications in accelerator facilities. They are used to accelerate the electron bunches, to determine their position or to change their direction. The RF cavities used in the MESA facility will fulfill all three mentioned tasks, and two types of them are introduced in the next sections. The first one is a deflecting cavity, which is used to investigate the longitudinal electron distribution within the bunch, and the second one is a buncher cavity, which enables a longitudinal emittance matching to the MAMBO section.

3.5.1. RF deflecting cavity

In accelerator facilities clearly defined and background-free electron bunches are needed. This can be reached by different techniques, one of which is to combine

^jRohde & Schwarz: Powermeter NRVD

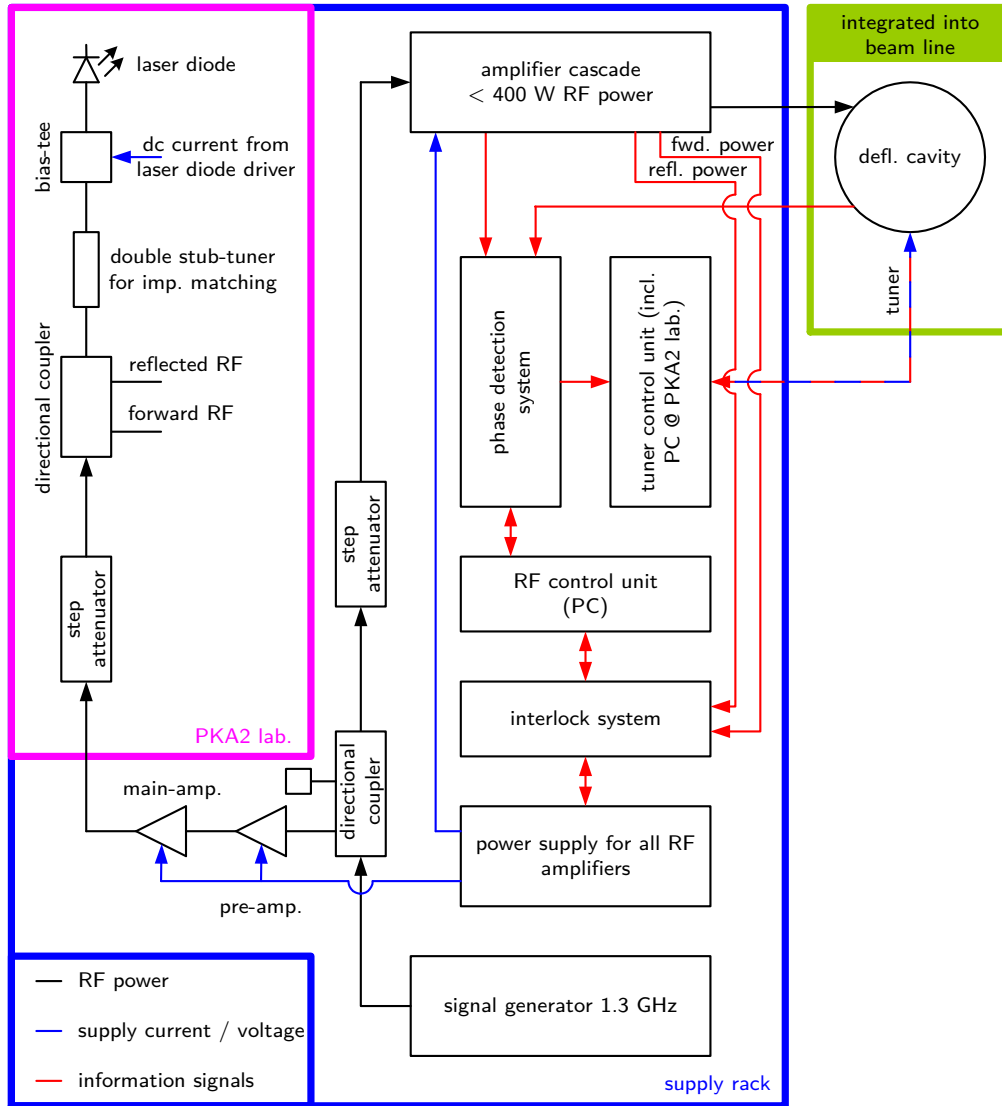


Figure 3.18.: Schematic sketch of the RF parts to provide the necessary RF power for the laser system and the deflecting cavity. The signal generator (lower right corner) produces a low power signal which is divided by a directional coupler. The main fraction of the RF signal is guided to the amplifier chain of the deflecting cavity and can be adjusted via a step attenuator. The amplifier chain is monitored via an interlock system to prevent damage. The signal coupled out by the directional coupler is guided to an additional amplifier chain to produce the RF power needed by the laser system. The double stub-tuner and the bias-tee are two important parts of the RF system related to the laser system. The stub-tuner is used to adapt the impedance of different laser diodes to the RF system. With the bias-tee, a superposition of the RF power and the dc current of the laser diode driver is performed.

3. Building blocks of the experiments and their physics background

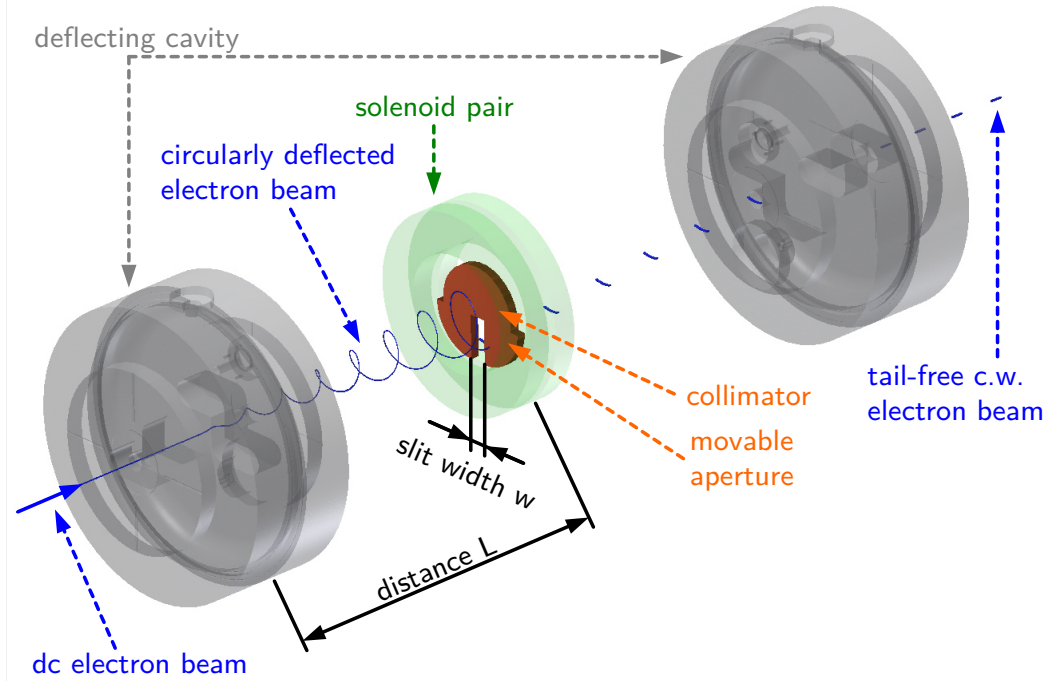


Figure 3.19.: Illustration of the working principle of the chopper system [Bech13]. From the left side, the electron bunches reach the first deflecting cavity and are bent on a cone surface. Each period of the spiral corresponds to one RF period. After a distance, the electrons hit an adjustable aperture surrounded by a pair of solenoids. The adjustable aperture is used to optimize the RF phase range occupied by electrons. Through the solenoid pair, the exit of the first cavity is projected onto the entrance of the second cavity. The imposed temporal-directional modulation is removed again by the second resonator. Thus, behind the chopper system the electrons move on a straight orbit again. (courtesy of V. Bechthold; modified)

an RF deflecting cavity with some additional components to the so-called “chopper system”, which will be explained in more detail in this section. The components of [Bech13, Ledr16, Stol16] are adapted for the use at MESA from the MAMI chopper [Brau88].

To ensure that no electron is located outside the phase acceptance of the MAMBO system, the electron bunches should look as illustrated on the left side of Fig. 3.11. In Fig. 3.19 an illustration of the working principle of the chopper system is presented. From the left side, the electron bunches reach the first deflecting cavity and are bent on a cone surface. Each period of the spiral corresponds to one RF period. After a distance L , the electrons hit an adjustable aperture which is surrounded by a pair of solenoids. The adjustable aperture is used to optimize the RF phase occupied by electrons. This element is called “chopper-collimator”, was designed by [Ledr16] and tested at the beam line which is introduced in Sec. 5. Through the solenoid pair, the exit of the first cavity is projected onto the

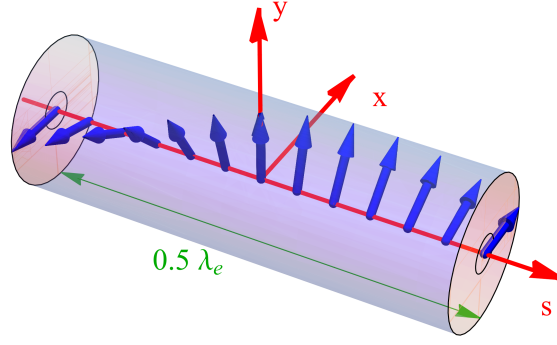


Figure 3.20.: Schematic sketch of an ideal force field to realize a circular deflection of the electron beam. Here the spatial force field distribution is shown at a fixed time in a cylindrical resonator.

entrance of the second cavity. This is realized by choosing the focus length f_{sole} of the solenoids as $f_{\text{sole}} = 0.5L$. This results in a 1 : 1 projection. The design and the manufacturing of the solenoids was done by C. Stoll [Stol16]. Afterwards, the solenoids have been tested in combination with the chopper in the beam line of the PKA2. An important point why the focusing magnets around the aperture are designed as a solenoid pair is that this configuration can avoid a rotation of the electron spin direction if spin-polarized electrons are used. The temporal-directional modulation imposed by the first deflecting cavity is removed again by the second resonator. Thus, behind the chopper system the electrons move on a straight orbit again. If dc beams are injected, the output is a c.w. beam corresponding to the phase acceptance defined by the slit. If a c.w. beam is injected, only the bunchtails exceeding the acceptance are cut away.

As cavity mode a modified TM_{110} -mode is used. Modified means that the cavity deflects the electron beam circularly on a cone surface instead of only in the horizontal or vertical direction. This kind of deflection is realized by a force field that changes the direction along the longitudinal cavity axis s . Such a force field can be described in the following way

$$\left. \begin{aligned} B_x &= \hat{A}_{\text{RF}} \sin(\omega_{\text{MESA}} t) \cos\left(\frac{2\pi}{\lambda_e} s\right) \\ B_y &= \hat{A}_{\text{RF}} \sin(\omega_{\text{MESA}} t) \sin\left(\frac{2\pi}{\lambda_e} s\right) \end{aligned} \right\} \text{ for } s \in \left[-\frac{\lambda_e}{4}, \frac{\lambda_e}{4}\right] \quad (3.21)$$

$$B_x = B_y = 0 \quad \text{otherwise}$$

Here, $\hat{A}_{\text{RF}}$ is the amplitude of the RF field, $\omega_{\text{MESA}} = 2\pi\nu_{\text{MESA}}$ is the angular velocity, t is the time, and λ_e is the distance an electron travels during one RF period. The spatial distribution for such a force field is shown in Fig. 3.20 for a fixed time. To ensure that the modified TM_{110} -mode creates the desired force field, the deflecting cavity is equipped with two additional “S” shaped recesses. In each case, one of the recesses is located at the entrance side or the exit side of the cavity.

Since the complete chopper system for MELBA is currently under design, the prototype is still part of the diagnostic equipment at the PKA2 beam line. In

3. Building blocks of the experiments and their physics background

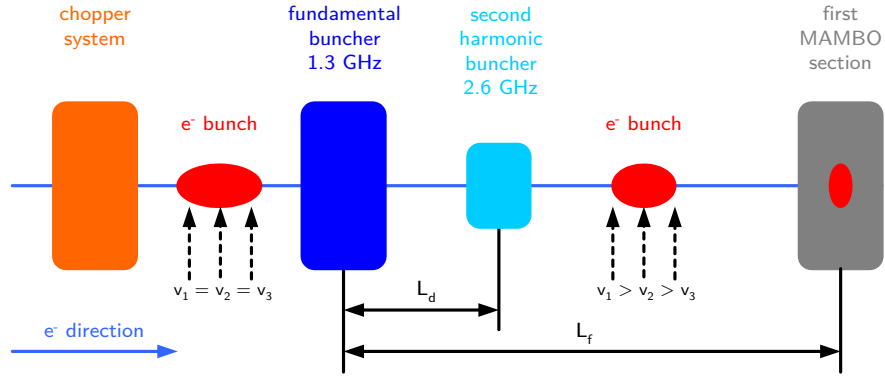


Figure 3.21.: Schematic sketch of the working principle of the buncher system. Behind the chopper system, the velocity distribution of the electrons within a bunch is very sharp. By passing through the buncher cavities, the electrons get a velocity modulation. The velocity modulation is realized in such a way that the first electrons are decelerated and the last electrons are accelerated. Thus, the longitudinal dimension shrinks and reaches a minimum after the distance L_f . The longitudinal focus is placed in the first MAMBO section where the electrons are accelerated close to the speed of light, which suppresses a further drifting apart.

the case of the diagnostic beam line, only a deflection of the electron bunches is necessary in order to investigate their temporal structure; the collimator is therefore replaced by a screen.

3.5.2. RF buncher cavities

The buncher cavity described here is not used in this thesis, but it might be helpful for understanding why bunch lengths up to an RF phase of 160° are acceptable in the MELBA system. A more precise description is given in [Heil15].

Due to the fact that space charge forces scale with γ_L^{-2} , they are a low-energy problem in electron machines. Thus, to avoid emittance growth, the produced electron bunches are kept long with respect to the RF phase until they are focused longitudinally into the MAMBO system after they have passed the MELBA system. The longitudinal focusing is realized via a velocity modulation by means of an RF cavity. This type of cavity is called buncher cavity. A schematic sketch of the working principle is shown in Fig. 3.21.

The result presented in Fig. 3.22 shows the velocity modulation and explains why bunch lengths up to 160° are acceptable in the MELBA system.

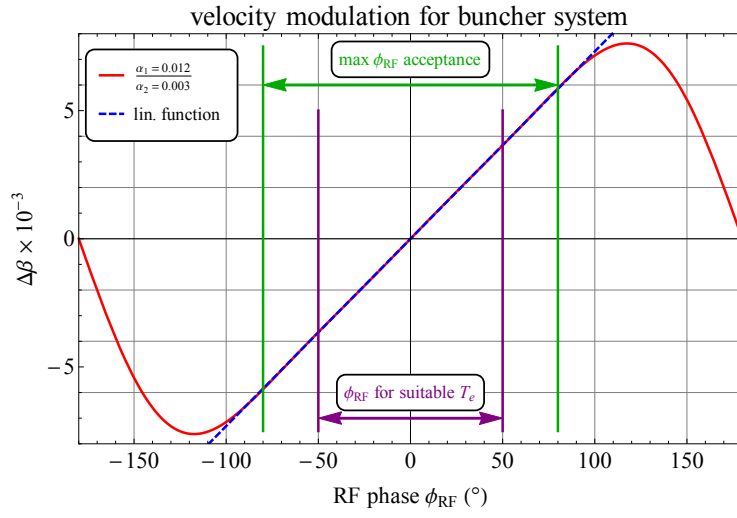


Figure 3.22.: The resulting velocity modulation for a system of two buncher cavities is plotted over the RF phase ϕ_{RF} . To assess the quality of the harmonic approach, an additional linear function is included in the plot. The velocity modulation is symmetric around zero and linear for RF phases between $\phi_{RF} \pm 80^\circ$. In addition, two regions are marked in the plot. The first shows the maximum phase acceptance, and the second one indicates an area that proposes a high beam transmission through the accelerator. Continuous operation requires a safety margin, which is why 100° is chosen. This decision is based on the experience gained during the operation of MAMI.

4. Physical background of beam diagnostic equipment

In this chapter, an introduction to the physical basis of the beam diagnostic equipment will be given. First, the scanner devices used will be introduced, followed by the properties of the scintillator material used as a screen and for X-ray counting detectors. Regarding the X-ray counting detectors, a closer look at the wires used in the analyzing stages and their abilities for bremsstrahlung production will be taken. These wires are also used to determine the beam dimensions during the quad scans. Moreover, some uncertainties which can occur during the optical beam size determination will be discussed.

4.1. Scanner devices

The so-called scanner devices are the main analyzing elements at the PKA2 apparatus. These devices are modeled after the “Dombo scanner” [Domb91]. A scanner device can move targets (screens, wires, masks, etc.) inside the vacuum to certain positions. The targets are mounted on a sled which typically can accommodate three targets and an empty position. It contains a remote-controlled drive unit, and the position is read back via a resistor with an accuracy $< 100\text{ }\mu\text{m}$. The rotation from the drive unit is transformed into a linear movement by a ball screw drive to reduce friction and the stick-slip effect. In addition, this reduces backlash and influences the accuracy in a positive way. The total length of travel is 150 mm. The scanners used are modified according to the new tasks and to get a fully bakeable device to fulfill the specification of the vacuum. The modifications include lower dimensions in the direction of the electron beam, a housing completely made of stainless steel and all vacuum connections in compliance with the CF standard. This enables to bake out the scanner device up to a temperature of 180°C . The drive and control system is the same as before. One of the three scanners is shown on the bottom of Fig. 4.2. The three scanners are located 1 m, 2.3 m and 3 m along the beam line as depicted in Fig. 5.1.

4.1.1. Occupancy of the sleds

All analyzing stages have different occupancies for specific tasks. A general arrangement of the sled occupancy is depicted in Fig. 4.1. All sleds can be seen in Fig. 4.2. The first one has a Ce:YAG screen with a diameter of 25 mm and a tungsten wire with a diameter of $\sigma_{\text{wire}} = 40\text{ }\mu\text{m}$ for the quadrupole scans. Furthermore, there are

4. Physical background of beam diagnostic equipment

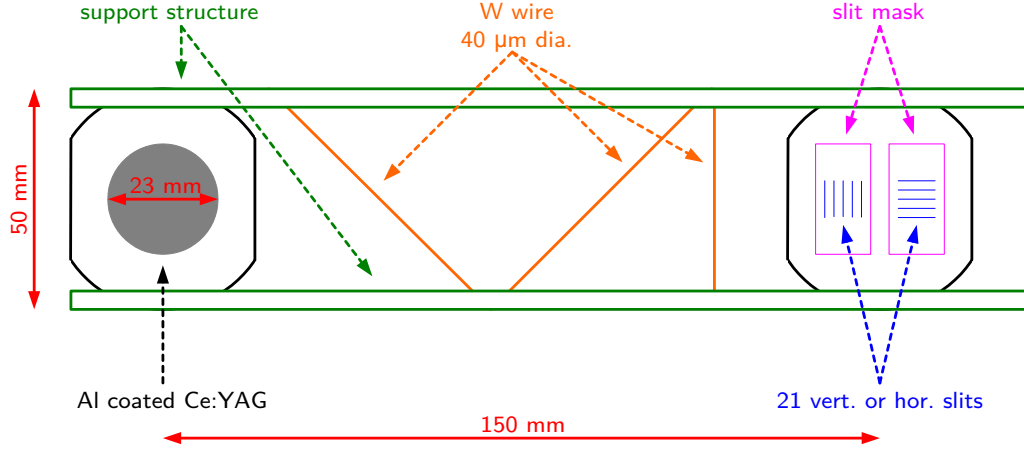


Figure 4.1.: Schematic sketch of the sled occupancy. The sled, in general, comprises two Ce:YAG screens with a diameter of 25 mm and a twice folded W wire with a diameter of 40 μm . One screen (left side) is for quad scan emittance measurements, and the other one is used to image the intensity pattern caused by the slit masks mounted (right side). The side of the screens facing towards the electron beam is Al coated to conduct away the charge, and the overall dimension of the mask pattern is $(5 \times 5) \text{ mm}^2$. The whole sled can be moved by 150 mm.

two slit masks with 21 slits each with a spacing of $d_{\text{slit}} = 250 \mu\text{m}$ and a width of $\sigma_{\text{slit}} = 25 \mu\text{m}$. So each of them has a dimension of $(5 \times 5) \text{ mm}^2$. A drawing of the slit mask including all necessary dimensions is illustrated in Fig. 4.3. The difference between the two masks is that the slits are oriented perpendicular to each other to measure the horizontal and vertical emittance of the electron beam. After the electrons have passed through the mask, they hit a Ce:YAG screen, and the light is coupled out by a mirror which is mounted at an angle of 45° and a CF40 view-port. The same applies to the Ce:YAG screen without mask. There is a drift space between the mask and the Ce:YAG screen of $d_{\text{drift}} = 19.6 \text{ mm}$. The reason for the length of the drift space is mainly the lack of space in the existing beam line, and the calculations for this measure will be described in Sec. 6.2.2. To measure the emittance with the masks, it is not necessary to make a quadrupole scan (see Sec. 2.5).

The following part of the beam diagnostic equipment is optional and was mainly used for beam alignment optimization to operate the double scattering polarimeter (DSP) and the deflecting cavity. Furthermore, it offers further possibilities for investigations with respect to beam dynamics studies.

The occupancy of the second sled is almost the same as the first one with the difference that there is a hole mask (pepper pot) with 21×21 holes instead of the slit masks. All 441 holes have a diameter of $\sigma_{\text{hole}} = 25 \mu\text{m}$ and a spacing of

all components are UHV suitable

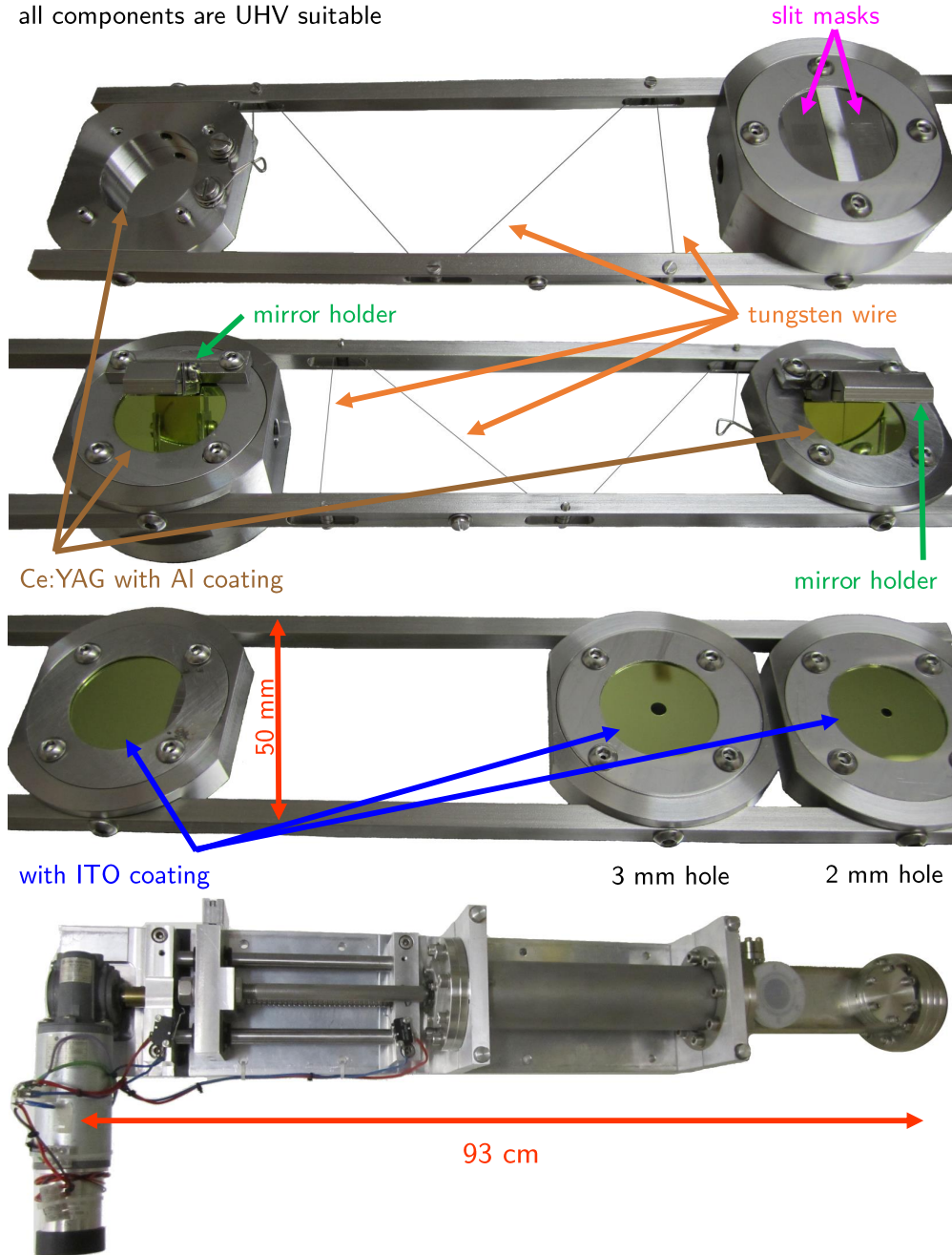


Figure 4.2.: Photo of the sleds for the scanner devices. At the top, the occupancies of all three scanner sleds are illustrated in the order of their installation. The upper one shows the side of the sled facing towards the beam mounted in scanner one. On the second picture, the back side of the second sled is visualized to show how the mirrors are oriented with respect to the screens, and on the third picture, the third sled is depicted with its perforated screens for halo investigations. At the bottom of the picture, the complete scanner device is presented including the vacuum chambers and the motorized drive.

4. Physical background of beam diagnostic equipment

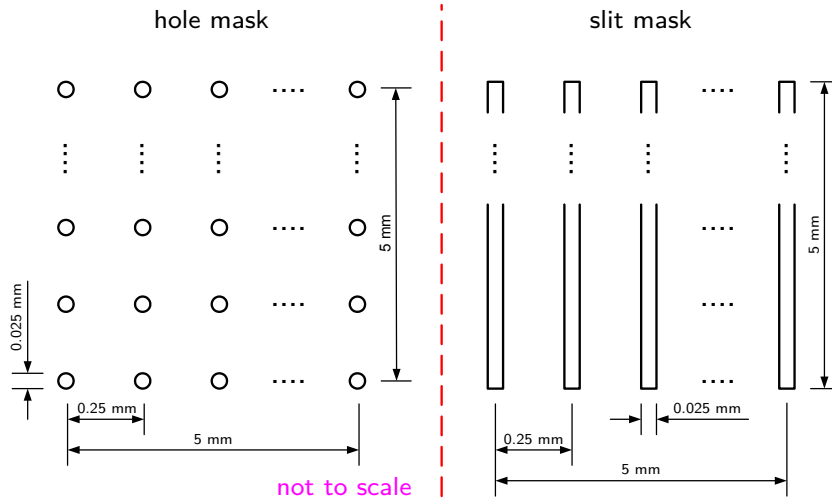


Figure 4.3.: Sketch of the hole mask and slit mask dimensions. The overall dimension of the mask pattern is $(5 \times 5) \text{ mm}^2$. The spacing between the slits or holes is 0.25 mm, and the width or diameter is 0.025 mm. All masks are made of 50 μm thick stainless steel.

250 μm . Thus, this mask also has a dimension of $(5 \times 5) \text{ mm}^2$. All masks are made of stainless steel with a thickness of $d_{\text{mask}} = 50 \mu\text{m}$.

The targets in the third sled differ a lot from the other two. In this sled three Ce:YAG screens are mounted, each with a diameter of 25 mm. Two of them are perforated with a 2 mm or a 3 mm hole, respectively. These holes are for investigations of the beam halo distribution because the main part of the electron beam can pass through these screens without interactions. The Ce:YAG screens have a thickness of 100 μm and the side facing towards the beam is coated with Al to take the charge of the incoming electrons away. Here also the third sled represents an exception because the viewing direction of the CMOS camera is parallel to the direction of the incoming electrons, and thus, the front of the screen is coated with ITO. The additional coating with ITO was chosen because this conductive material is transparent in the visible range of light.

4.2. Properties of Ce:YAG and why it was selected

For the determination of the emittance, it is necessary to analyze the transverse electron beam distribution. This can be done with screens where the stopped electrons create an amount of light proportional to their number. The produced light is imaged on the photosensor of a CMOS camera afterwards. Another way to determine the beam distribution is to move a thin wire target through the beam. The electrons stopped by the wire create bremsstrahlung photons that can be measured with a scintillator photomultiplier tube (PMT) configuration. The bremsstrahlung

Table 4.1.: Basic physical properties for different scintillator materials

	ρ_{mat} (g/cm ³)	λ_{peak} (nm)	$\frac{\text{photons}}{\text{keV}}$	α_m (cm ² /g) @ 60 keV	α_m (cm ² /g) @ 80 keV	α_m (cm ² /g) @ 100 keV
Tl:NaI	3.67	415	38	6.35	2.97	1.65
BaF	4.88	310	10	6.71	3.14	1.75
Ce:YAG	4.57	550	35	1.64	0.79	0.48
Ce:YAP	5.37	370	25	1.93	0.92	0.54
BGO	7.13	480	8.2	3.89	1.88	3.97
LuAG	6.73	535	25	2.12	4.48	2.55
CRY018	4.5	425	30	2.69	1.07	0.62

photon intensity is proportional to the dumped electron current, i.e. it is important to find a screen and scintillator material that fits the experimental needs best.

There are different scintillating materials available on the market, and Tab. 4.1 displays a selection of them with some of their physical properties. The properties are the density of the material ρ_{mat} , the peak emitting wavelength λ_{peak} , the photon yield per deposited MeV of energy, and the mass attenuation coefficient α_m for different energies. The peak emittance wavelengths of LuAG and Ce:YAG fit the peak QE of most standard PMTs. But LuAG has the disadvantage that Lu has a natural radioactivity, necessitating precautions during handling and creating an additional background. Another candidate would be BGO, but in this case, the photon yield is not as high compared to Ce:YAG.

The other materials have additional disadvantages, e.g. being hygroscopic or having a long decay constant. Thus, Ce:YAG was selected for the screen material as well as for the X-ray scintillator. An overview of additional physical properties of Ce:YAG is given in Tab. 4.2. Positive properties are the central wavelength λ_{YAG} , which fits in the region where the most standard PMTs and CMOS cameras have a high QE, as well as the short decay constant τ_{YAG} . A short decay constant is—among others—important for phase-resolved macro pulse investigations if these are desired and to prevent saturation effects during quadrupole scans. Furthermore, the light output per deposited MeV of energy will ensure a low threshold electron current in the performed experiments. Measurements in which the electron beam hits a tungsten wire (as presented in Fig. 4.4) have shown that in the existing configuration at the PKA2, currents down to $I_{\text{beam}} \simeq 10$ pA can be measured with a signal-to-noise ratio of $\text{SNR} \simeq 1$ with a scintillator PMT configuration.

4.3. Wires and X-ray detector

One method to measure the beam profile during a quadrupole scan is to move a wire through the beam and detect the generated bremsstrahlung photons. Here, the signal is collected with a scintillator PMT configuration. The purpose of this section is to determine an optimum position which delivers a high count rate. A

4. Physical background of beam diagnostic equipment

Table 4.2.: Selection of physical properties of Ce:YAG

property	value
stoichiometric formula	$\text{Y}_3\text{Al}_5\text{O}_{12}$
density	$\rho_{\text{YAG}} = 4.57 \text{ g/cm}^3$
integrated light output (% Tl:NaI)	40
index of refraction	1.82
central wavelength	$\lambda_{\text{YAG}} = 550 \text{ nm}$
decay constant	$\tau_{\text{YAG}} \simeq 80 \text{ ns}$
photon yield	$30 \times 10^3 \text{ photons/MeV}$
doping concentration with respect to Y mass fraction	$w_{\text{Ce}} = 0.18\%$
Ce concentration	$N_{\text{Ce}} = 2.5 \times 10^{19} \text{ atoms/cm}^3$

sketch of the wire position inside the chamber and the PMT alignment is given in Fig. 4.4.

The parts used for the scintillator PMT configuration are shown in Fig. 4.5. The left side shows the Ce:YAG cylinder with its dimensions and the PMT. In the middle picture, the scintillator is mounted on top of the PMT, and a part of the cylinder surface is already covered with a reflective foil to increase the amount of photons detected by the PMT. Before the scintillator and the PMT are mounted inside the housing, all sides of the scintillator are covered by the reflective foil. On the right side of Fig. 4.5, the complete assembled X-ray detector is depicted including an optional bracket to mount it on a CF40 flange.

One attempt to calculate the angular distribution of the X-rays produced by the electrons stopped in the tungsten wire is given in [Scot67]. The resulting formula is very complex. Another approach is to use a Monte Carlo program^a to simulate the setup. The results of the simulations are presented in Fig. 4.6. At the top, the FLUKA result for the X-ray production via a tungsten wire (black circle) and incident electrons with an energy of 100 keV is visualized. It can be seen that the 40 μm thick tungsten wire must be treated as a thick target for the photons because the attenuation is not negligible. On the bottom, the photon flux inside and outside the scanner chamber is depicted. The beam line is located in the center of the picture and extends horizontally. The cones above and below the beam line correspond to the side walls of the scanner chamber. Thus, these locations promise a high signal rate for the X-ray detector. The scintillator PMT configuration is mounted beside the scanner chamber.

^aFLUKA: a multi-particle transport code [Fer+05, Boe+14]

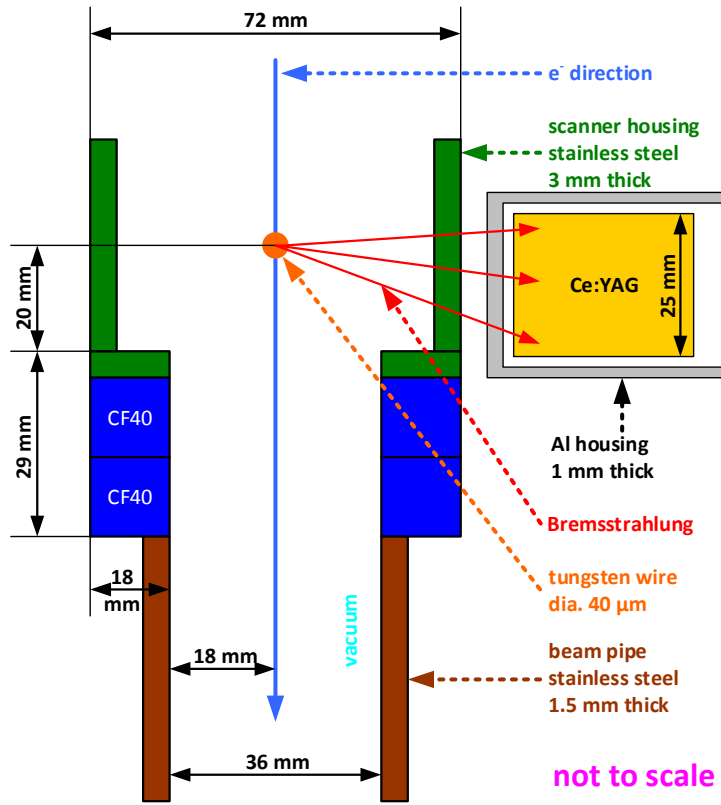


Figure 4.4.: Sketch (not to scale) of the wire position with respect to the vacuum chambers and the PMT alignment outside the vacuum chambers. The sketch includes the most important measures for the following simulations of the photon flux.

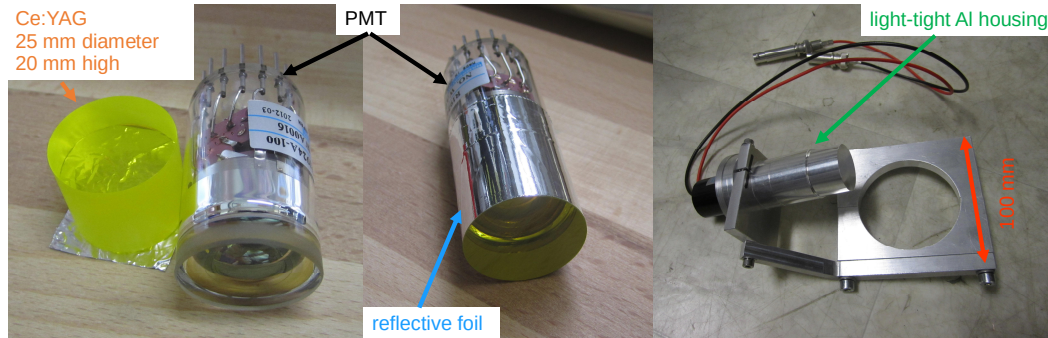


Figure 4.5.: Introduction of the parts used for the scintillator PMT configuration. The left side shows the Ce:YAG cylinder with its dimensions and the PMT. In the middle picture, the scintillator is mounted on top of the PMT, and a part of the cylinder surface is already covered with a reflective foil to increase the amount of photons detected by the PMT. On the right, the complete assembled X-ray detector is depicted including an optional bracket to mount it on a CF40 flange.

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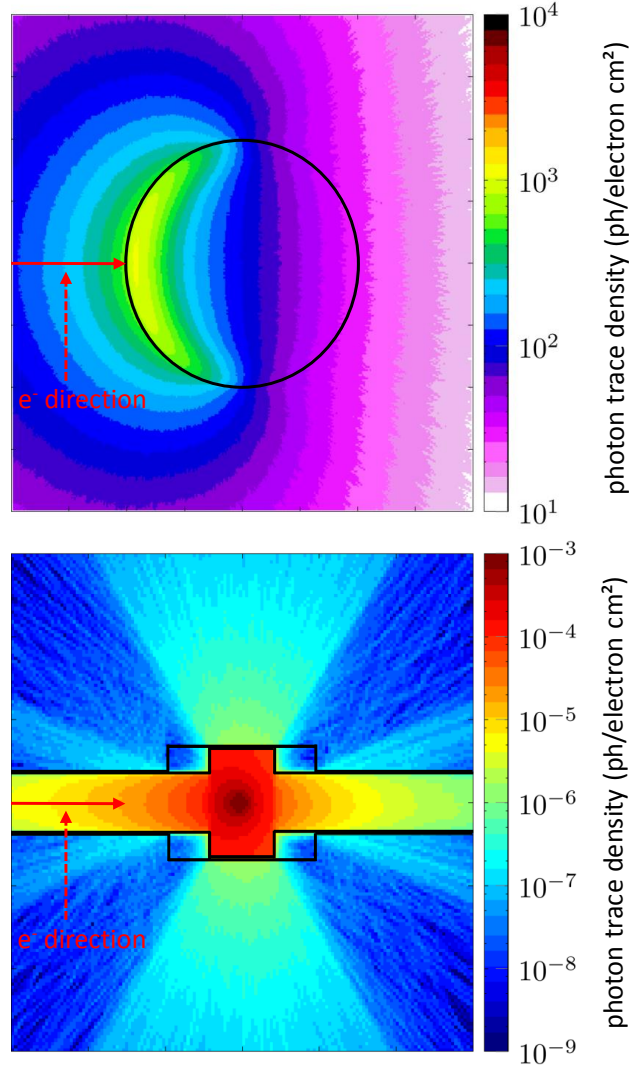


Figure 4.6.: At the top, the FLUKA result for the X-ray production via a tungsten wire (black circle) and incident electrons with an energy of 100 keV is visualized. The electrons arrive from the left side, and the color code represents the total flux of photons in both pictures. It can be seen that the 40 μm thick tungsten wire must be treated as a thick target for the photons because the attenuation is not negligible. On the bottom, the photon flux inside and outside the scanner chamber is depicted. The beam line is located in the center of the picture and extends horizontally. The cones above and below the beam line correspond to the side walls of the scanner chamber. Thus, these locations promise a high signal rate for the X-ray detector. (courtesy of S. Heidrich; modified)

4.4. Uncertainties

4.4.1. Camera system

A large fraction of the results presented in Sec. 6 is obtained from digital pictures, which is why some properties of the CMOS cameras used should be taken into account. One of these properties is the shutter type of the CMOS sensor. At the PKA2, there are two different types of cameras in use. Some have a pixel size of $4.5\,\mu\text{m}$ or $6.6\,\mu\text{m}$ and a global shutter (VC4067^b and VC6215^c). The other ones have a pixel size of $2.2\,\mu\text{m}$ and a rolling shutter (VC4012^d and BA2500-14^e). The cameras with the global shutter are used as a virtual cathode in the laser system and to investigate the longitudinal distribution of the electron bunches. This stems from the fact that the observed structures are large ($\mathcal{O}(1 - 10)$ mm). The camera with the $2.2\,\mu\text{m}$ pixels is used during the quad scans and the slit mask measurements. Both features are measured with scanner 1 (see Fig. 5.1). The number of pixels is necessary because the intensity distribution of a beamlet on the screen during a slit mask emittance measurement should expose enough pixels, while the image of the whole mask should fit onto the CMOS sensor. During the hole and slit mask measurements, the sizes of the observed structures are tiny ($\mathcal{O}(20 - 50)$ μm) and the pattern of the mask is (5×5) mm².

Since all beam dynamics studies were performed with macro pulse lengths of $\tau_{\text{pulse}} \ll \tau_{\text{mains}} = 20$ ms, beam position fluctuations caused by the mains frequency can be neglected.

The rolling shutters of the BA2500-14 and VC4012 cause a restriction during the measurements, namely that the exposure time τ_{exp} for these cameras should not be below 200 ms. If the exposure time is set $\tau_{\text{exp}} < 200$ ms, only a fraction of the picture contains information about the beam distribution. These fluctuations increase the observed beam dimensions. The vertical size of this fraction depends on the exposure time, whereas the horizontal dimension of this fraction is not affected by the exposure time and stays constant. Changing the delay between the laser pulse trigger and the camera trigger shifts the vertical position of this fraction. A visualization of this phenomenon is given in Fig. 4.7.

A possible explanation would be that the rolling time of the shutter—which is unknown—is longer than the exposure time if the latter is set below 200 ms [Tech14]. Also the temporal structure of the observed object plays a role because during each picture there is only a short flash with the duration of the macro pulse τ_{pulse} . This is typically in the order of 0.3 ms to 1 ms. Thus, it is not possible to adjust the picture

^bVision Components - VC4067, 1280×1024 pixel, pixel width and height: $6.6\,\mu\text{m}$, sensor type: CMOS, global shutter

^cVision Components - VC6215, 1600×1200 pixel, pixel width and height: $4.5\,\mu\text{m}$, sensor type: CMOS, global shutter

^dVision Components - VC4012, 2592×1944 pixel, pixel width and height: $2.2\,\mu\text{m}$, sensor type: CMOS, rolling shutter

^eBasler - acA2500-14, 2592×1944 pixel, pixel width and height: $2.2\,\mu\text{m}$, sensor type: CMOS, rolling shutter

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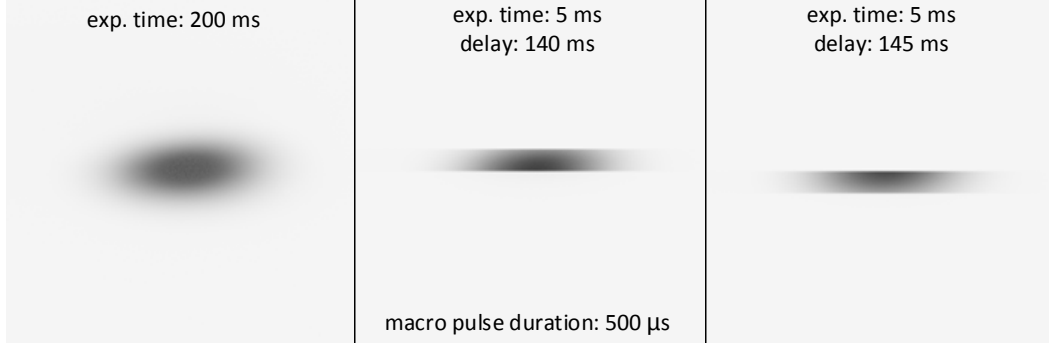


Figure 4.7.: Visualization of how the exposure time affects the obtained picture (inverted color). The length of the electron pulse is $500\text{ }\mu\text{s}$ for all three pictures. On the left, the complete intensity distribution is depicted. The pictures in the middle and on the right show what happens if the exposure time is reduced to 5 ms . A reduction of the exposure time results in a portion of the picture being black. A comparison of the center picture to the right one illustrates the influence of the delay between the macro pulse and the camera trigger. Thus, the exposure time affects the height and the delay the position of the intensity distribution within the picture taken.

brightness by decreasing the exposure time to $\tau_{\text{exp}} < \tau_{\text{pulse}} = 0.3\text{ ms} \ll 200\text{ ms}$. Instead, the brightness adjustment is done with additional attenuators in front of the camera lens, which cover a dynamic range up to 10^3 in five steps (OD06, OD13, OD20, OD25 and OD30)^f. The global shutter in the other two cameras does not cause this restriction.

Other uncertainties are mainly the background in the pictures and the stability of the beam position due to current fluctuations through the magnets (steerer and focusing elements) or the laser spot stability on the photocathode. Fluctuations that occur slowly do not affect the measurements because either the exposure time or the macro pulse length ($0.3\text{ ms} - 1\text{ ms}$) is shorter. Beam position fluctuations are suppressed by synchronizing the data taking to the mains frequency.

The VC6215 camera is mounted behind the deflecting cavity to investigate the temporal structure of the micro and macro pulses. This camera model was selected since it has a fast electronic shutter which enables to examine the macro pulses in steps of $1\text{ }\mu\text{s}$. This kind of measurement has been performed to check if the micro pulses are stable along the macro pulse. Unfortunately, the CMOS sensor has only an electronic shutter with an extinction ratio r_{ext} of around $200 - 400$ [LaLe11]. The extinction ratio is defined as

$$r_{\text{ext}} = \frac{\text{Int}_{\text{open}}}{\text{Int}_{\text{closed}}}.$$

This leads to an adulteration of the measurement results since the CMOS sensor is still light-sensitive after closing the shutter [Priv15]. A schematic illustration of this

^fOD - optical density is defined as: $\text{OD} = 10 \log(1/T_{\text{ph}})$ with the transmission T_{ph}

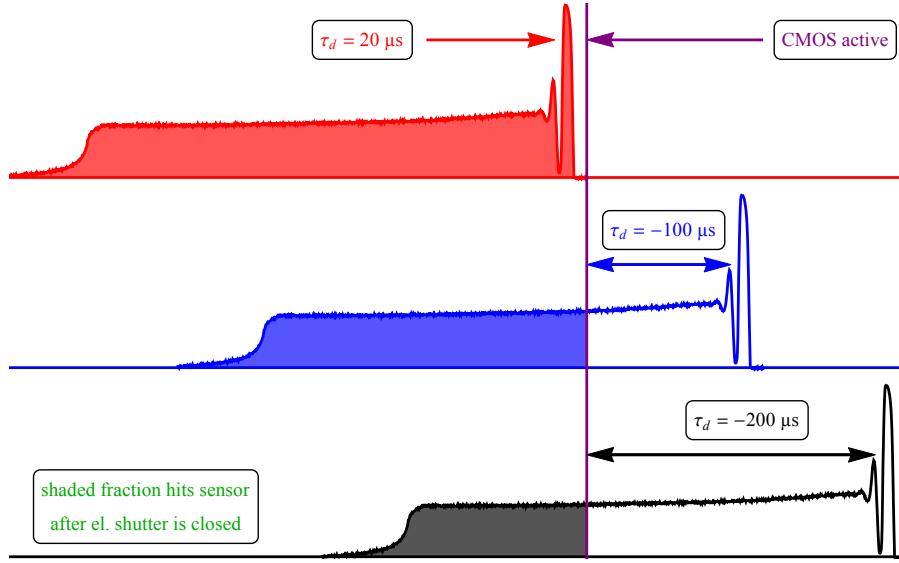


Figure 4.8.: The plot illustrates the light fraction hitting the CMOS sensor for different trigger delays in the case of short exposure times $\tau_{\text{exp}} = 1 \mu\text{s}$. Due to the electronic shutter—which causes an extinction ratio of about 200 – 400—the sensor is still light-sensitive after a picture was obtained.

is depicted in Fig. 4.8. While this may cause some restrictions in the interpretation of the data, it is still possible to perform measurements on a short time scale.

Not only the camera causes restrictions, but also the imaging lens^g does. The properties of the optical setup are summarized in Tab. 4.3. Using the data in Tab. 4.3, the region to be imaged can be calculated. Within this region the image has an acceptable sharpness. In the field of photography this region is known as “depth of field” (DoF). The imaging lens has an internal variable aperture, the size of which is defined by $f/\#$. Since each aperture causes a diffraction of light, it affects the properties of the imaging system. If the aperture size is decreased, $f/\#$ will increase. Thus, the following values are calculated as function of $f/\#$ and refer to the object space. To determine the depth of field, the hyperfocal length f_{hyper} is needed, which is defined as

$$f_{\text{hyper}} = \frac{f_{\text{optic}}^2}{f/\#\text{CoC}} + f_{\text{optic}}. \quad (4.1)$$

The hyperfocal length f_{hyper} is the nearest focus where the far distance d_{far} reaches infinity. The near distance d_{near} results as $0.5f_{\text{hyper}}$. An additional meaning of f_{hyper} is that if the focus is at infinity, the closest object appearing sharp lies at the distance f_{hyper} [King63]. With the working distance d_{object} , the region in front of the focus is defined by

$$d_{\text{near}} = \frac{d_{\text{object}}(f_{\text{hyper}} - f_{\text{optic}})}{f_{\text{hyper}} + d_{\text{object}} - 2f_{\text{optic}}} \quad (4.2)$$

^gEdmund Optics - 50mm FL Ultra High Resolution Fixed Focal Length Lenses

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Table 4.3.: Properties of the camera lens and experimental set up

property	value
magnification	0.5
focal length f_{optic}	50 mm
min. working distance	100 mm
working distance d_{object}	130 mm
resolution, full field ν_{optic}	160 lp/mm
resolution, on-axis	200 lp/mm
circle of confusion CoC	0.013 mm
range of aperture size $f/\#$	2.8 – 16
central wavelength of YAG λ_{YAG}	550 nm

and the region behind the focus is defined by

$$d_{\text{far}} = \frac{d_{\text{object}} (f_{\text{hyper}} - f_{\text{optic}})}{f_{\text{hyper}} - d_{\text{object}}}. \quad (4.3)$$

The circle of confusion CoC determines the area of acceptable sharpness and includes the Rayleigh criterion as well as the pixel size of the CMOS sensor used. The results for the depth of field are depicted on the left side of Fig. 4.9.

Since the depth of field is less than 0.4 mm in the setup given, the requirements for the assembling accuracy are very high. To stay within the depth of field, the camera must be aligned with an accuracy better than $\pm 2^\circ$. The plot on the right of Fig. 4.9 visualizes the necessary accuracy for three different circles of confusion.

Apart from the calculations of the depth of field, this has also been experimentally investigated. When determining the emittance via the beam diagnostic equipment, mainly two different object sizes can be observed. The electron beam can be focused down to an RMS width of about 50 μm within a quad scan. In contrast, in the defocusing plane, the electron distribution can quickly reach an extent of a few mm. Thus, the quad scan represents the large objects within this comparison. In the case of the slit mask, the width of the distribution obtained by the CMOS camera can shrink down to 10 μm . However, not more than a doubling, possibly a tripling, is to be expected. The dimensions of the screen used during the quad scans are four times that of the slit mask. For this reason, the depth of field determination is repeated at three different locations. These are schematically illustrated on the left in Fig. 4.10. The camera system can be moved 25 mm by means of a remote-controlled translation desk. By sufficiently accurate scanning of the range of motion, the so-called Rayleigh length z_R can be determined. In each step, an image of the electron beam distribution is taken. The data can be fitted by applying the following equation to them:

$$\sigma_x(s) = w_0 \sqrt{1 + \left(\frac{s}{z_R}\right)^2} \quad (4.4)$$

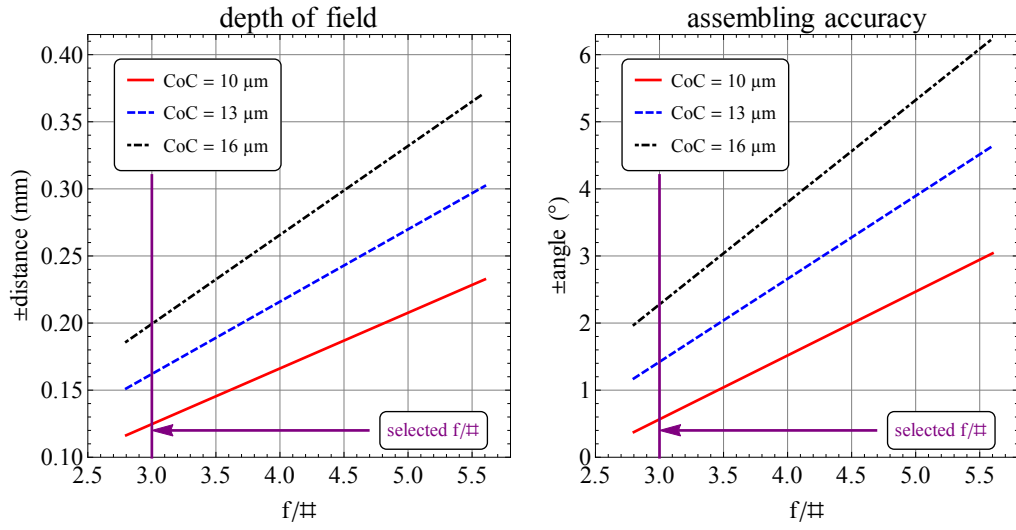


Figure 4.9.: The plot on the left illustrates the depth of field as a function of $f/\#$ in the case of the setup used. On the right, the necessary assembling accuracy is shown, which results from the depth of field.

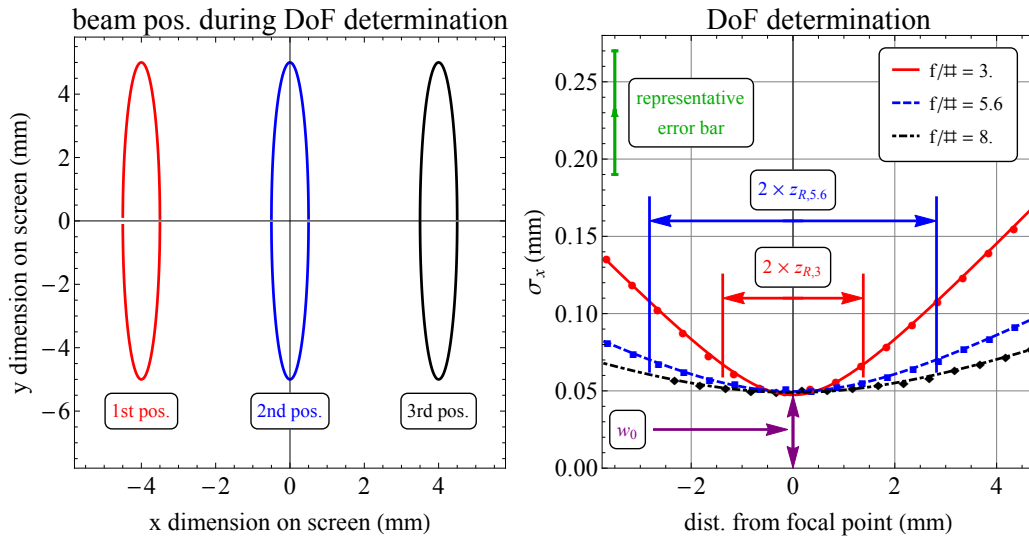


Figure 4.10.: The plot on the left shows the electron beam positions on the screen that are used to determine the DoF of the camera imaging lens system. At each position the distance between the camera and the screen is varied via a remote-controlled translation stage. On the right, the collected data and their corresponding fit functions are depicted. As the $f/\#$ increases, the course of the data becomes flatter, resulting in a larger Rayleigh length z_R . The numbers in z_R indicate the $f/\#$ used.

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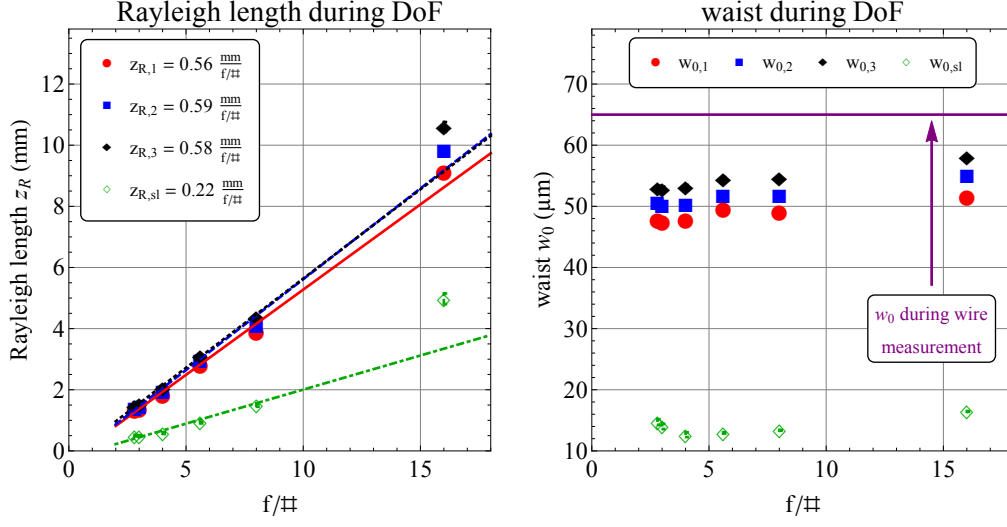


Figure 4.11.: Depth of field measured with the setup given. The plot on the left shows the Rayleigh length for the three positions on the screen examined for different $f/\#$ of the imaging lens. Between the three positions, there is only a slight difference in the resulting Rayleigh lengths. This can be attributed to the fact that the camera was not aligned perfectly perpendicular to the screen. Furthermore, a result for the slit mask is also included. On the right, the minimum observed spot sizes are compared with the results obtained by the scintillator PMT configuration. $f/\#$ larger than four causes an increase of w_0 .

The equation consists of two parameters, namely the Rayleigh length z_R and the waist w_0 . The latter describes the RMS dimension of the smallest observable beam size. This means that the object to be imaged is located in the focal plane. The Rayleigh length z_R refers to the distance to the focus, in which the surface doubles when rotated around the propagation direction. Both parameters are determined by the fit. An example of such a measurement is illustrated in the right plot of Fig. 4.10.

As illustrated on the left side of Fig. 4.9, the calculated depth of field shows a linear dependence with respect to an increasing $f/\#$. The left plot in Fig. 4.11 summarizes the Rayleigh lengths for the three different locations on the screen examined for different $f/\#$. Between the three positions, there is only a slight difference in the resulting Rayleigh lengths. This can be attributed to the fact that the camera was not aligned perfectly perpendicular to the screen. A result for the slit mask is also included in the comparison. Due to the different object sizes, the Rayleigh length of the slit mask increases more slowly than that of the screens.

The smallest beam sizes w_0 associated with the Rayleigh lengths are illustrated in the right part of Fig. 4.11. Especially with regard to the slit mask measurements, an $f/\#$ in the range of four should be selected. Here the smallest beamlets are observed. For both object sizes imaged at the camera sensor, an increase of w_0 is

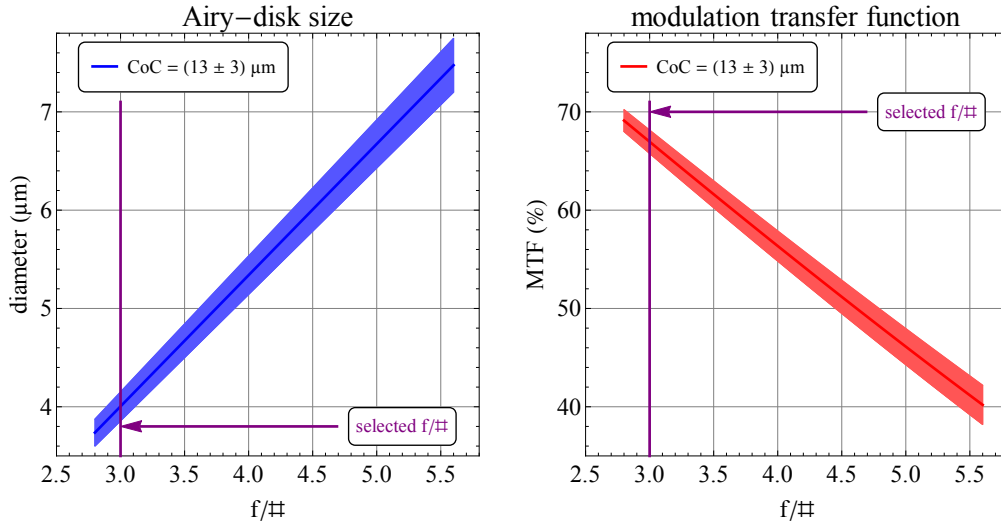


Figure 4.12.: The left side visualizes the dependence of the diameter of the Airy disk on the $f/\#$. Larger apertures cause less diffraction, and thus, the resulting Airy disk size decreases. The plot on the right shows the probability of the optical system to transfer the contrast information from the object to the image.

visible for an increasing $f/\#$. This is an indication of the increasing influence of diffraction effects. But nevertheless, careful adjustment of the camera allows the observed beam sizes to be comparable to those obtained by the scintillator PMT configuration. If the aperture size only affected the depth of field, a small aperture would be preferable. But smaller apertures cause an increase in diffraction.

Each point-like source is transferred into an Airy disk by an optical system. An Airy disk is defined via

$$g_{\text{Airy}}(x) = E_0 \left(\frac{2J_1 \left(\frac{\pi x}{f/\# \lambda_{\text{YAG}}} \right)}{\frac{\pi x}{f/\# \lambda_{\text{YAG}}}} \right)^2, \quad (4.5)$$

and thus, the diameter results as

$$d_{\text{Airy}} = 2.44 f/\# \lambda_{\text{YAG}}. \quad (4.6)$$

The first zero of an Airy disk is located at $1.22 f/\# \lambda_{\text{YAG}}$, which corresponds to its radius. The left plot in Fig. 4.12 depicts the trend of the Airy disk size, which increases with increasing $f/\#$.

An additional important property of an optical system is the ability to transfer the contrast information of an object to the image, which is called modulation transfer function (MTF). This function can be expressed as

$$\text{MTF} = \frac{2}{\pi} \left(\arccos(\xi) - \xi \sqrt{1 - \xi^2} \right) \quad (4.7)$$

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with

$$\xi = f/\# \lambda_{\text{YAG}} \nu_{\text{optic}}.$$

The results of the modulation transfer function are presented on the right of Fig. 4.12. For the presented results, an optical frequency of $\nu_{\text{optic}} = 160 \text{ lp/mm}^{\text{h}}$ is used. For the sake of completeness follows the definition of the contrast C :

$$C = 100 \frac{\text{Int}_{\text{max}} - \text{Int}_{\text{min}}}{\text{Int}_{\text{max}} + \text{Int}_{\text{min}}}. \quad (4.8)$$

A comparison between Fig. 4.9 and Fig. 4.12 shows that an opened aperture increases the image contrast and improves the imaging properties of the optical system used. A disadvantage is, however, a smaller depth of field. During the emittance measurements with both techniques an f-number around $f/\# \simeq 3$ was used.

4.4.2. Electron scattering in the Ce:YAG screens

To determine the uncertainties due to scattering of the electrons inside the scintillator material, some simulations with a Monte-Carlo program and experiments at the PKA2 have been done. Knowing this value is very important for the results from the slit mask emittance measurements because the dimensions of the mask perforations are $25 \mu\text{m}$. The determined value for the scattering width will be taken into account in the emittance calculations presented in section 6.2.2.

4.4.2.1. Simulations

For the simulations of the uncertainties due to scattering in the screen material, a Monte Carlo programⁱ was used. This program was developed as a modeling tool for scanning electron microscopy [DCJ+07]. The Ce:YAG screen is designed as follows. At the surface, the electrons see a 10 nm thick Al layer followed by a $100 \mu\text{m}$ thick YAG layer with a proportion of 0.18% Ce atoms with respect to the Y mass fraction. In the simulation, the energy of the incident electrons is varied from 65 keV to 100 keV in steps of 5 keV , and the electron beam diameter is chosen to be $25 \mu\text{m}$, which corresponds to the hole diameter and the slit width of the masks. The simulation program only allows a Gaussian distribution for the incident electrons. Since the electron beam dimensions are much larger than the perforations in the mask, it could be assumed that the electron distribution behind the mask is flat-top shaped. But this would only be valid under the assumption of idealized conditions (parallel beam). Thus, the results can be used to analyze the spatial distribution of the luminescence light inside the screen material. The presented results contain 500000 simulated electrons, and there is no energy spread included in the beam properties. The mono-energetic beam depicts the reality in a reliable way because in general, the energy spread caused by the photocathode

^hThe unit lp/mm denotes line pairs per millimeter.

ⁱCASINO V2.42: improved at the Electrical Engineering Department of the Université de Sherbrooke, Québec, Canada

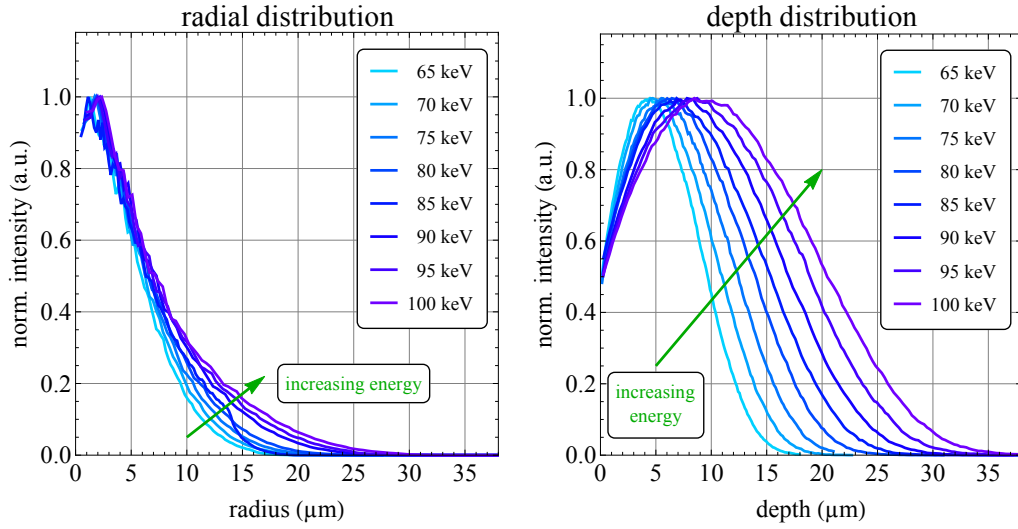


Figure 4.13.: Radial distribution (left) and penetration depth (right) of the luminescence light caused by the incident electrons at different energies as indicated in the legend.

and the electron gun is less than 10^{-5} in the case of negligible space charge. If high bunch charges are produced, the energy spread can increase to 10^{-3} (see Fig. 3.3). On the left side of Fig. 4.13, the radial distribution of the luminescence light for the different electron energies is illustrated. The most intense part of the light is produced close to the center of the incoming electron beam, which is mainly caused by the initial distribution. The right side of Fig. 4.13 shows the depth in which the luminescence light is produced. For increasing electron energies, the most intense part is shifted further inside the screen material. The simulations confirm that all 100 keV electrons are stopped inside the 100 μm thick Ce:YAG screen. On the basis of the results presented in Fig. 4.13, it becomes clear that the screen must be thinner than 25 μm if it is desired to reduce the influence of electron scattering on the resulting image. This is due to the fact that the major fraction of the incident electrons are stopped within a depth of 25 μm. While thinner Ce:YAG screens are available, it is not necessary to exchange the 100 μm thick ones since the influence of electron scattering can be determined and taken into account in the data analysis.

The results for the diameter and the penetration depth of the simulations are displayed in Fig. 4.14. The resultant values contain $\sim 100\%$ of the distribution. The results are summarized and compared with experimental results in Tab. 4.4.

4.4.2.2. Experiments

To take a closer look at the uncertainties, several experiments have been performed to determine the scattering width of the electrons inside the Ce:YAG screens and to make a cross-check against the simulated width. These experiments were done

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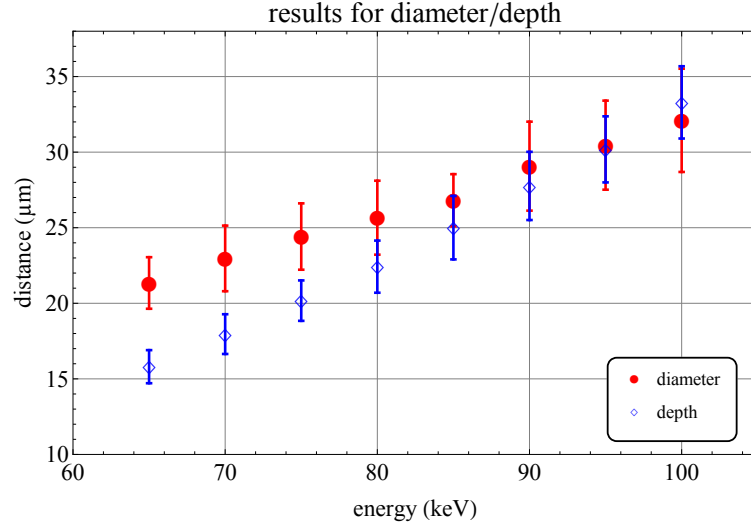


Figure 4.14.: The graph shows the diameter and the penetration depth from where the luminescence light is produced plotted over the electron energy.

because the hole diameter and the slit width are only $25\mu\text{m}$ and the simulations (summarized in Tab. 4.4) show that the scattering width is bigger than these dimensions. It is very important to know this kind of uncertainty since the beamlet size on the pictures plays a major role in the calculation of the emittance (see Eq. 2.26 and Eq. 2.27). Once the scattering width is determined, it will be taken into account by deconvolution in the emittance calculations afterwards. For the investigations of the scattering width, a mask mount was constructed where the hole mask is located directly in front of a Ce:YAG screen without a drift space. The recess for the mask is $25\mu\text{m}$ deeper than its thickness in order to avoid damage to the screen due to too much contact pressure. The influence of this tiny drift space on the scattering results can be neglected ($25\text{ nm @ }1\text{ mrad}$). This mask mount is illustrated in Fig. 4.15, and the shape of the mount is similar to those used for the quadrupole scan with the difference that there is a recess for the hole mask. This holder is mounted inside the scanner behind the second α -magnet (see Fig. 5.1). A picture of the sled is shown on the bottom of Fig. 4.2. The incoming electrons first hit the hole mask. Those which can pass through the holes create scintillation light inside the Ce:YAG screen. This light is then coupled out by a mirror similar to the other stages.

The performed experiment includes a variation of the electron energy from 100 keV down to 65 keV in steps of 5 keV and different electron currents. The various energies are chosen to induce a visible effect on the scattering width, and to control the measuring method. Due to the fact that the electron energy plays a role in the scattering width inside the screen material, the measuring method must be able to resolve a changing spot size by changing the energy. The examined energy region was sufficient to demonstrate an effect on the scattering width. The different cur-

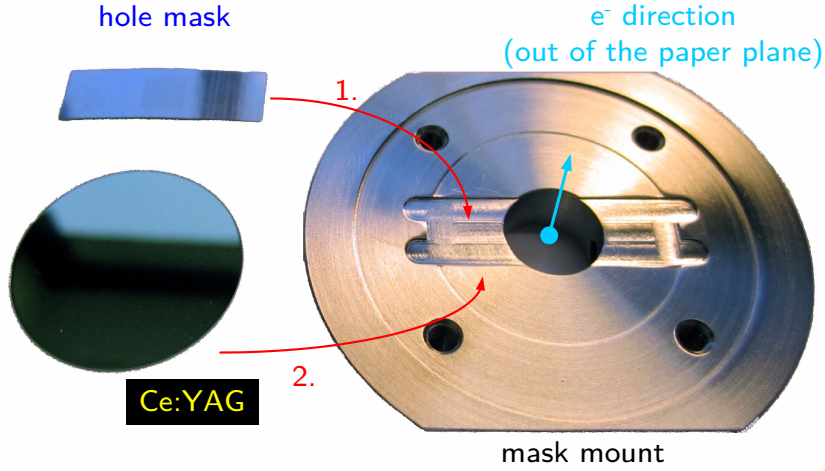


Figure 4.15.: Picture of the mask mount for the investigations of the scattering behavior inside the Ce:YAG screens. First the hole mask is inserted and then the Ce:YAG screen. Afterwards, they are fixed by a ring. The direction of the electrons is facing out of the paper plane. The diameter of the Ce:YAG is 25.4 mm, and the diameter of the mask mount is 50 mm.

rents were chosen to check if the exposure time of the CMOS camera affects the results, and the investigated exposure times are 50 ms, 20 ms, 10 ms, and 5 ms.

In order to check for systematic drifts not related to the expected decrease of the light emitting volume, the hole by hole distance was checked. The dimensions of the hole mask are well known, allowing calibrations of the pixel resolution based on the spacing between the adjacent holes. This calculation has been done with the majority of the holes and the result is presented in Fig. 4.16. It can be seen that the spacing between the holes is quite stable, and for the determination of the hole width and the scattering width, the average over all distances is calculated. In Fig. 4.16, the distances for the x and y axis are illustrated in red and blue, respectively. Furthermore, it is shown that the difference of the values for both axes is $\simeq 0.3$ pixels. This difference results in a hole displacement of $\simeq 1.5 \mu\text{m}$, which is within the specifications of the manufacturer^j. The weighted mean results in $d_x = (51.46 \pm 0.03)$ pixels and $d_y = (51.22 \pm 0.03)$ pixels for the x and y axis, respectively. Thus, one pixel on the CMOS sensor corresponds to $\sim 5 \mu\text{m}$ on the screen. Fig. 4.16 also shows that the distance is independent of the electron energy and the exposure time used.

For the calculation of the beamlet width, the picture is divided into small parts to locate the maxima and to fit a 2D Gaussian function to the data. Examples of these data are presented in Fig. 4.18 for three different energies (70, 85, 100) keV. This analysis enables to check if any holes in the area of the electron beam are missing, which is not the case. On the right side of Fig. 4.18, the width of each beamlet is

^jmanufacturer of the hole and slit masks: LaserJob GmbH

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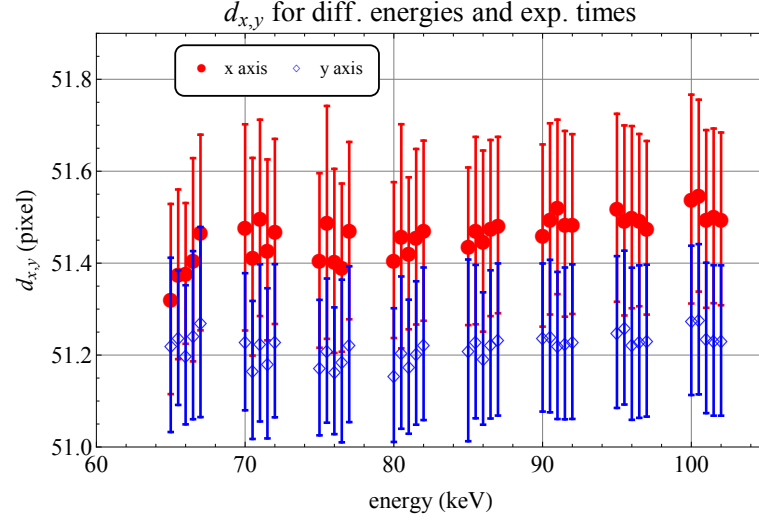


Figure 4.16.: Results of the calibration of the pixel resolution of the optical system. In the graph, the hole distance is plotted over the beam energy. Different electron energies and exposure times are included. The electron energy is varied in steps of 5 keV and the blocks of data points belong to the same electron energy but have different exposure times. The hole distance of $250\text{ }\mu\text{m}$ is resolved by ~ 51 pixels, which corresponds to a resolution of $\sim 5\text{ }\mu\text{m}/\text{pixel}$ on the screen.

plotted over the amplitude of the fit function for the x and y direction. It can be seen that the values for both axes differ by $\sim 0.5\%$, the y values being bigger. This could be caused by the laser beam profile of the laser system used to drill the holes. But the standard deviation of the average is almost the same. Furthermore, the graphs illustrate an increasing width of the beamlets with increasing energy, which is expected and a trustworthy sign for the working principle of the method. The scattering width is calculated with

$$\sigma_{\text{scat}} = \sqrt{\sigma_{\text{meas}}^2 - \sigma_{\text{hole}}^2}$$

where σ_{meas} is the measured width of the beamlets in the obtained picture and $\sigma_{\text{hole}} = 25\text{ }\mu\text{m}$ is the width of the holes in the mask.

Fig. 4.19 summarizes the results for the extracted scattering width. The resulting value does not only represent the scattering inside the material because the influence of the optical system used (vacuum viewport, lens and camera) is also included here. Fig. 4.19 shows a linear function fitted to the data with the parameter

$$\sigma_{\text{scat}}(E_{\text{kin}}) = AE_{\text{kin}}.$$

A comparison of the slopes indicates that the resulting scattering widths for the selected exposure times do not differ significantly. The resulting slopes are presented in the legend, and it can be seen that the slopes for the y axis are 3% larger

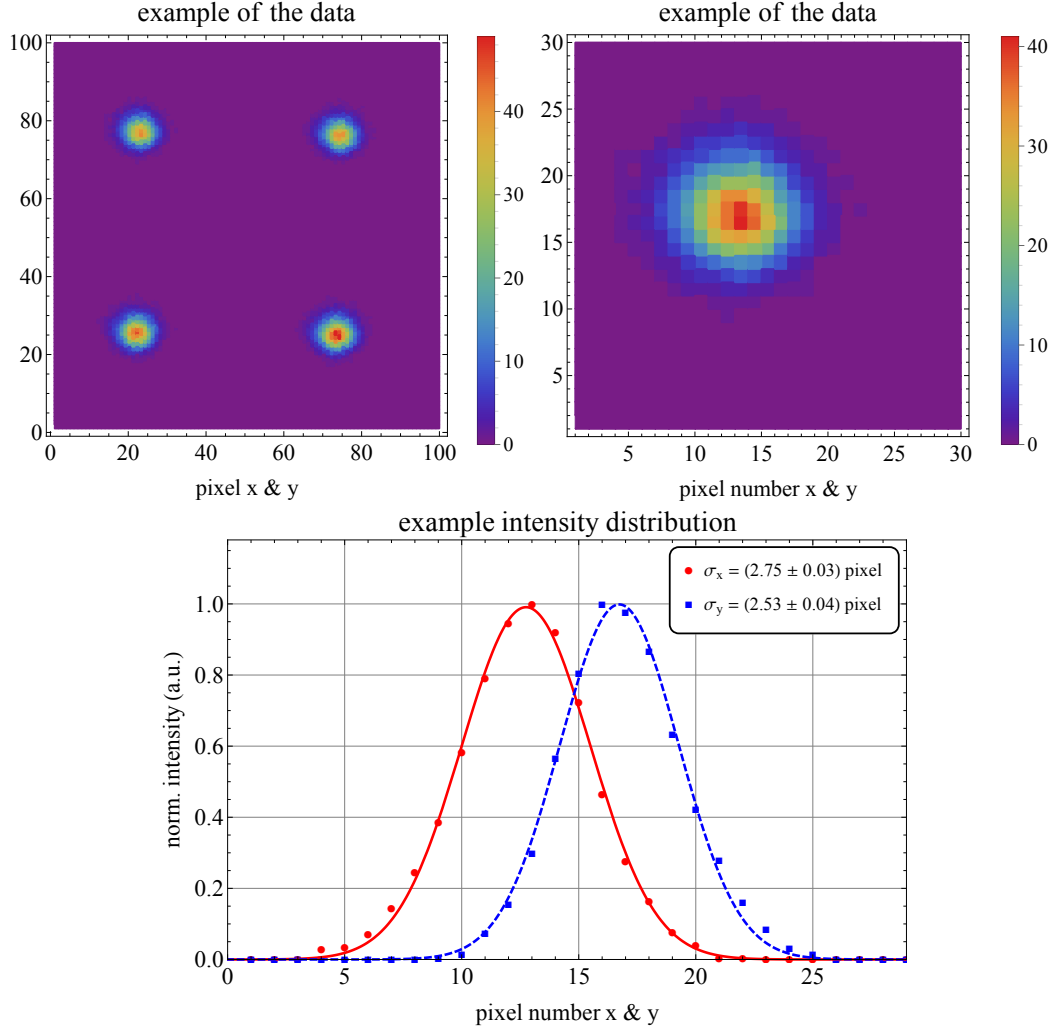


Figure 4.17.: On the upper left, an example of the intensity distribution of four holes is visualized. The individual intensity distributions are clearly separated from each other. The upper right plot shows a single spot. Taking this data and fitting a Gaussian function leads to the graph visualized on the bottom of the figure.

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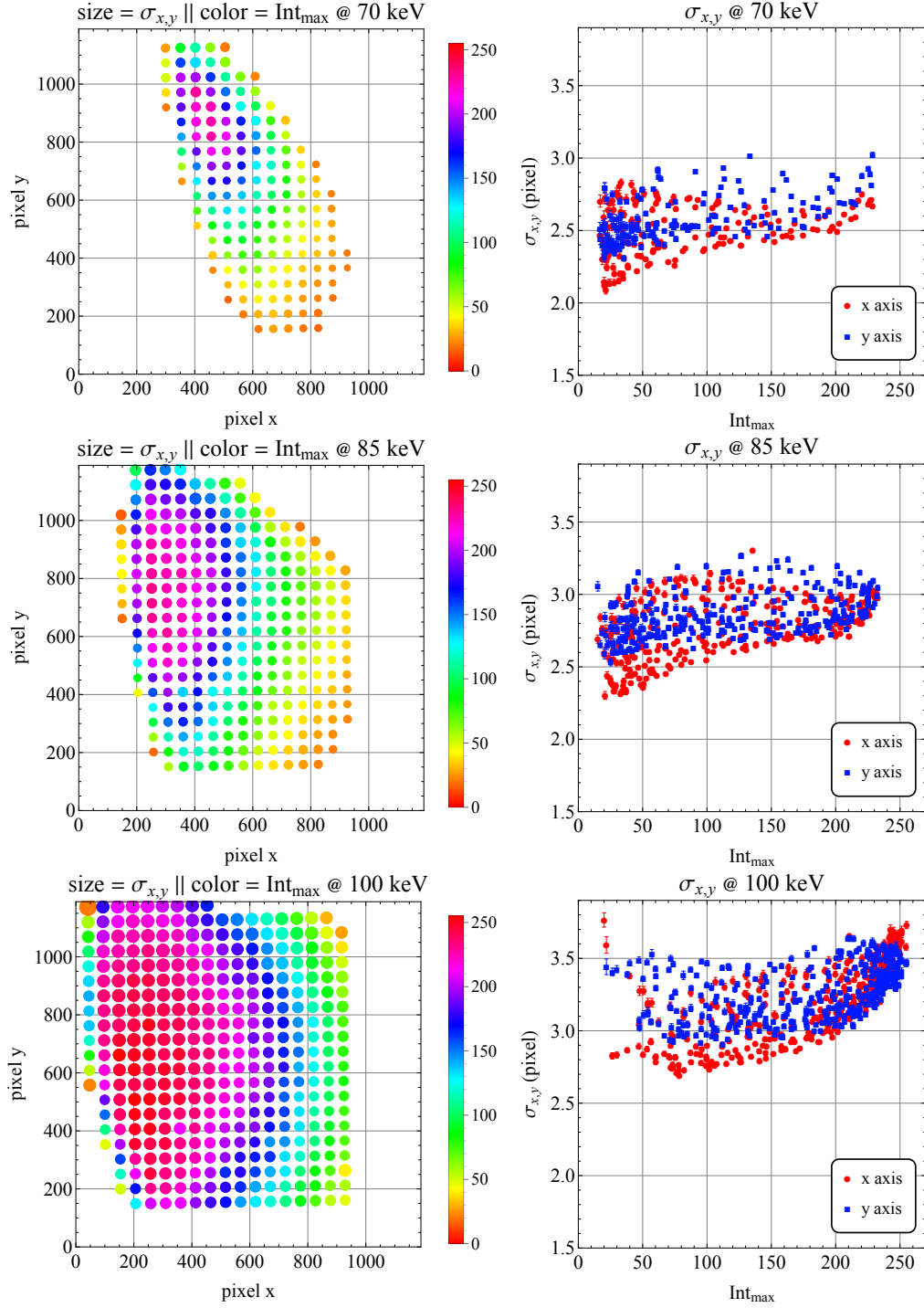


Figure 4.18.: The left side gives an example of the data taken to estimate how the electron scattering inside the Ce:YAG screen influences the apparent hole width for three different energies (70, 85, 100) keV. The point size indicates the width of the distribution of each hole (not to scale) and the color is linked to the amplitude of the 2D Gaussian function. On the right, the width of each hole is plotted over the amplitude of the 2D Gaussian function. (1 pixel $\simeq 5 \mu\text{m}$)

Table 4.4.: Summarized results of the scattering width/depth of the electrons inside the Ce:YAG screens from the experiments, a simulation, and the manufacturer. All data are given in μm .

E	experiment	simulation	Crytur Inc. (depth)
100 keV	32.74 ± 0.88	32.10 ± 3.41	37.50
95 keV	31.36 ± 1.01	30.46 ± 2.95	33.84
90 keV	28.59 ± 0.62	29.07 ± 2.94	30.38
85 keV	27.46 ± 0.71	26.82 ± 1.73	27.10
80 keV	25.67 ± 0.41	25.66 ± 2.45	24.00
75 keV	24.70 ± 0.77	24.42 ± 2.19	21.09
70 keV	23.79 ± 0.86	22.97 ± 2.17	18.38
65 keV	22.65 ± 0.74	21.34 ± 1.71	15.84

than for the x axis, which lies within the precision of the measurement. In addition, an overall fit is included in the plots that takes all data points into account and is represented with the dashed line. The slope of the overall fit results in $(0.32 \pm 0.002) \mu\text{m}/\text{keV}$ and $(0.33 \pm 0.003) \mu\text{m}/\text{keV}$ for the x and y axis, respectively.

In Tab. 4.4 a comparison of the scattering results is presented. The results from the experiment, the simulations, and the data from the manufacturer are close to each other. Therefore, in all subsequent emittance measurements (see Sec. 6.2.1 and Sec. 6.2.2) a scattering value of $(32.74 \pm 0.88) \mu\text{m}$ (experiment)—i.e. the calculated value for a beam energy of 100 keV—is deconvoluted from the beam distribution.

4.4.3. Saturation effects of the Ce:YAG screens

Saturation effects can disturb the emittance calculation with a quadrupole scan because the beam spot is varied and has a focus in x and y direction on different quadrupole settings. The focus spots are the most important data points in such a measurement and will create the highest electron density. Also, if only one direction is focused and the other one is defocused, the defocusing does not change the fact that the smallest area is at the focus. To ensure that these focal spots are not flattened out, the maximum charge density is calculated in this section.

A comparison between the length of the RF period $\tau_{\text{MESA}} = \nu_{\text{MESA}}^{-1} = 0.77 \text{ ns}$ for $\nu_{\text{MESA}} = 1.3 \text{ GHz}$ and the response time of Ce:YAG $\tau_{\text{YAG}} \simeq 80 \text{ ns}$ (taken from Tab. 4.2) shows that approximately 100 bunches arrive before the first τ_{YAG} has passed. Thus, it is expedient to introduce an integrated charge density Ξ [MRY+00] with

$$\Xi = \sum_{i=1}^{n_{\text{bunch}}} \frac{q_{\text{bunch},i}}{A_{\text{beam}}} = \frac{n_{\text{bunch}} q_{\text{bunch}}}{A_{\text{beam}}}. \quad (4.9)$$

The parameter

$$n_{\text{bunch}} = \nu_{\text{MESA}} \tau_{\text{YAG}}$$

4. Physical background of beam diagnostic equipment

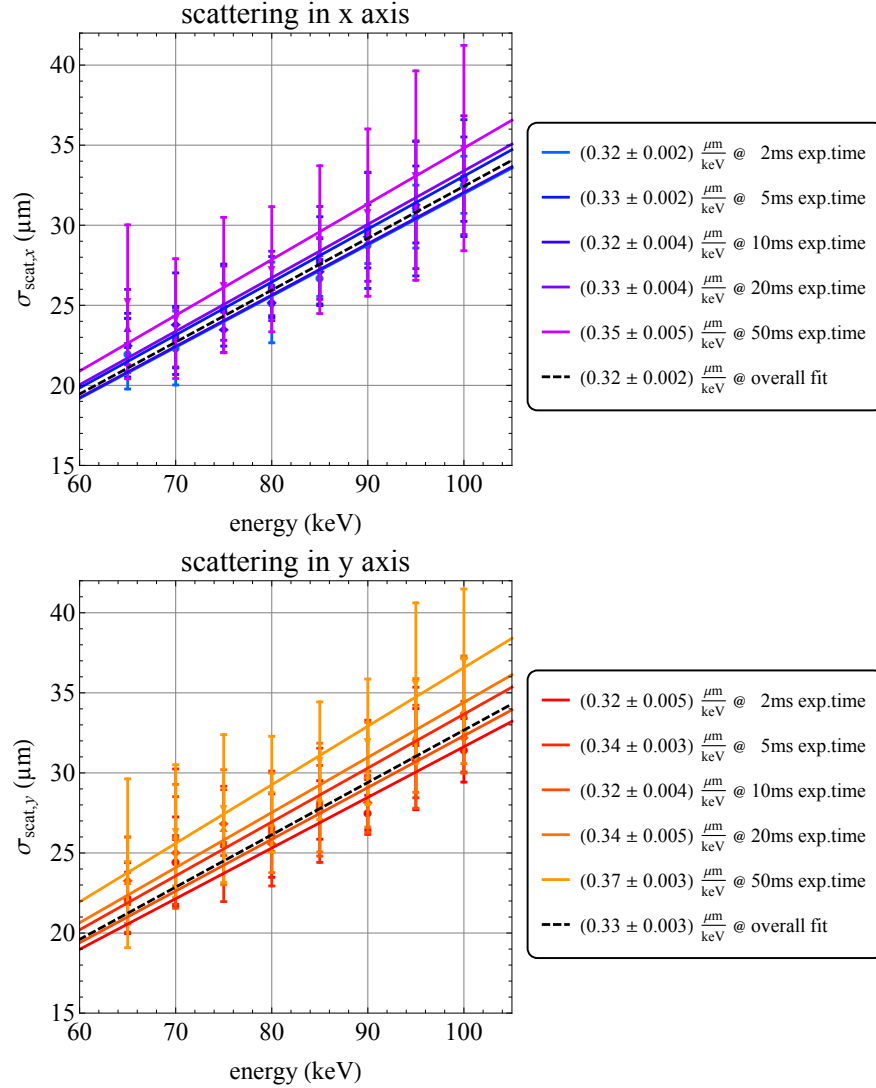


Figure 4.19.: Illustration of the results for the scattering width. The width is plotted over the electron energy and for different exposure times of the CMOS camera. The upper plot shows the results for the x axis and the lower one the results for the y axis. Apart from the fitting of each exposure time, an overall fit is included, and the slopes are presented in the legend. The uncertainty of the slopes is between $\pm 0.002 \mu\text{m}/\text{keV}$ and $\pm 0.005 \mu\text{m}/\text{keV}$.

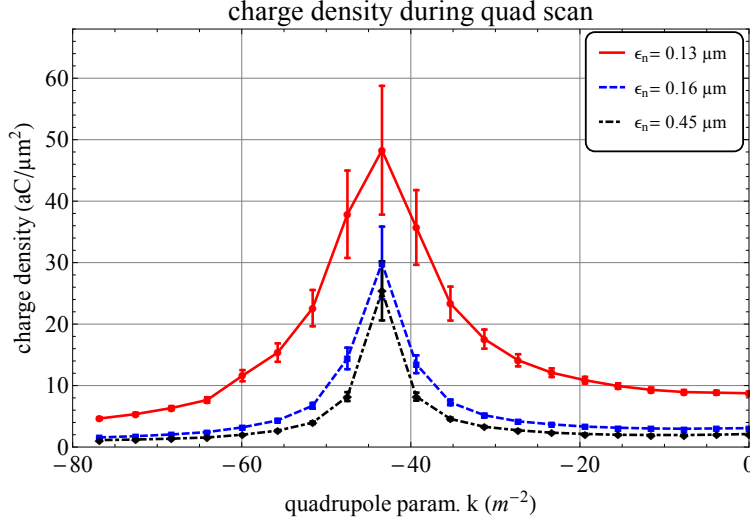


Figure 4.20.: Maximum charge density during a quadrupole scan for a bunch charge of $q_{\text{bunch}} = 0.8 \text{ pC}$. The beam dimensions to calculate the area on the screen are experimental values from three actual quad scans with different emittances. The lowest emittance causes the highest charge density on the screen.

represents the number of bunches, $q_{\text{bunch},i} = 0.8 \text{ pC}$ is the charge of the i -th bunch and

$$A_{\text{beam}} = \pi \sigma_x \sigma_y$$

is the area of the beam. During the operation of MESA, each bunch must contain the same charge. To calculate Ξ during a quad scan, the beam dimensions of such a scan are inserted into Eq. 4.9. The result of this calculation is illustrated in Fig. 4.20 for three different emittances. The highest value of the charge density Ξ is reached at the waist of the beam with the lowest emittance and stays below $\Xi = 0.060 \text{ fC}/\mu\text{m}^2$ for a bunch charge of $q_{\text{bunch}} = 0.8 \text{ pC} \triangleq I_{\text{beam}} = 1 \text{ mA}$. As presented in Fig. 6.4, the observed beam spot size increases with increasing bunch charge. This results in a larger area occupied by the electrons inside the bunch and in a larger emittance. Thus, this behavior will avoid that charge densities as high as the calculated maximum ($\Xi = (0.048 \pm 0.010) \text{ fC}/\mu\text{m}^2$) are reached during a quad scan with bunch charges around $q_{\text{bunch}} = 0.8 \text{ pC}$.

Saturation effects will occur if the energy deposited by the electrons inside the crystal is larger than that required to create as many electron hole pairs as there are Ce atoms N_{Ce} available. The YAG is doped with $w_{\text{Ce}} = 0.18\%$ of Ce atoms with respect to the Y fraction $w_{\text{Y}} = 0.449$, and the Ce concentration can then be calculated with

$$N_{\text{Ce}} = w_{\text{Ce}} w_{\text{Y}} \rho_{\text{YAG}} N_{\text{A}} A_{\text{Y}}^{-1} \approx 2.5 \times 10^{19} \text{ cm}^{-3}.$$

The symbols N_{A} and A_{Y} are the Avogadro number and the atomic mass of yttrium, respectively. The number of electron hole pairs generated per MeV of deposited

4. Physical background of beam diagnostic equipment

energy is $N_{eh} = 6 \times 10^4 \text{ MeV}^{-1}$, and ρ_{YAG} is the density of YAG. The energy loss of the first incident electron is calculated with the Bethe-Bloch formula including the extension that makes it suitable for electrons [Leo87] to be $-\frac{dE_{\text{kin}}}{dx} = 13.8 \text{ MeV/cm}$. To determine the saturation charge density, the inverse of the saturation constant

$$\alpha_{\text{sat}} = \frac{\beta_{\text{trans}}}{q_e N_{\text{Ce}}} N_{eh} \frac{dE_{\text{kin}}}{dx} \quad (4.10)$$

can be taken [Spes07]. The parameter q_e represents the charge of the electron and $\beta_{\text{trans}} = 1^{\text{k}}$ is a transport factor. For electrons with an energy of $E_{\text{kin}} = 100 \text{ keV}$, the saturation charge density is $\alpha_{\text{sat}}^{-1} = 48 \text{ fC}/\mu\text{m}^2$. Even though smaller saturation charge densities have been reported [MRY+00, Spes07], the experiments at the PKA2 reach neither of these values, even with ten times the current, thereby reducing non-linearities that could be exhibited prior to the onset of saturation.

It should be mentioned that the side of the Ce:YAG screen facing towards the beam should be coated with a conductive material to drain off the charge. So the back side of the screens—with respect to the viewing direction of the camera—is Al coated. In the case of the third scanner device, the camera looks in the same direction the electrons come from, and thus, the front side of the screens is coated with ITO¹ in addition. ITO is chosen because it is transparent in the visible range of light. If these precautions were not taken, distortion of the beam profile would result (comparable with the corona of a sun).

^k $\beta_{\text{trans}} \simeq 1/3$ for a crystal with good quality [MRY+00]; $\beta_{\text{trans}} = 1$ worst case

¹ITO: Indium Tin Oxide

5. Experimental setup

All experiments and investigations took place at the PKA2 lab, the components of which are described in the following subsections. These elements are the electron gun and the beam line, the laser system, and a deflecting cavity which is used to investigate the temporal structure of the electron bunches.

5.1. Electron source and beam line alignment

At the Institute of Nuclear Physics, there are three dc photoelectron guns with an electrical potential of 100 kV. One of them (PKA1) is located at the MAMI facility dedicated to production of spin-polarized electron beams while the other two (PKAT and PKA2) are located in two adjacent labs and are used for research experiments. All experiments took place at the PKA2. All three sources are quite similar with the difference that the PKA2 has an optimized vacuum system to improve the vacuum lifetime of the photocathodes.

A sketch of the PKA2 is shown in Fig. 5.1. The diagnostic beam line in general can be divided into three sections with respect to their purpose:

- emittance and halo investigations (red frame)
- temporal pulse shape investigations (green frame)
- polarimetry (blue frame)

The source has a load lock system [Aul+97] to insert new photocathodes into the source without breaking the vacuum. The cathodes can be transported through the load lock directly into the preparation chamber. Inside the preparation chamber, a surface treatment of the photocathode has to be done, which is necessary to produce a NEA^a. The preparation technique is described in Sec. 3.2.2. All transports of the photocathodes are done under UHV conditions with magnetic linear and rotary drives (MLRD). A picture of this part of the equipment is depicted in Fig. 3.10. The preparation chamber has a cathode wheel with eight positions to allow to store a mask and up to seven cathodes inside the preparation chamber. The mask reduces the active area of the cathode to a circle of 3 mm diameter during preparation [ATWW03]. The mask and photocathode alignment during a preparation is illustrated in Fig. 5.2. This was introduced by Dr. V. Tioukine to suppress the unwanted electron beam halo which can be caused by stray light of the laser system or other light sources in the lab. Applying this technique is essential if long

^aNEA: Negative Electron Affinity

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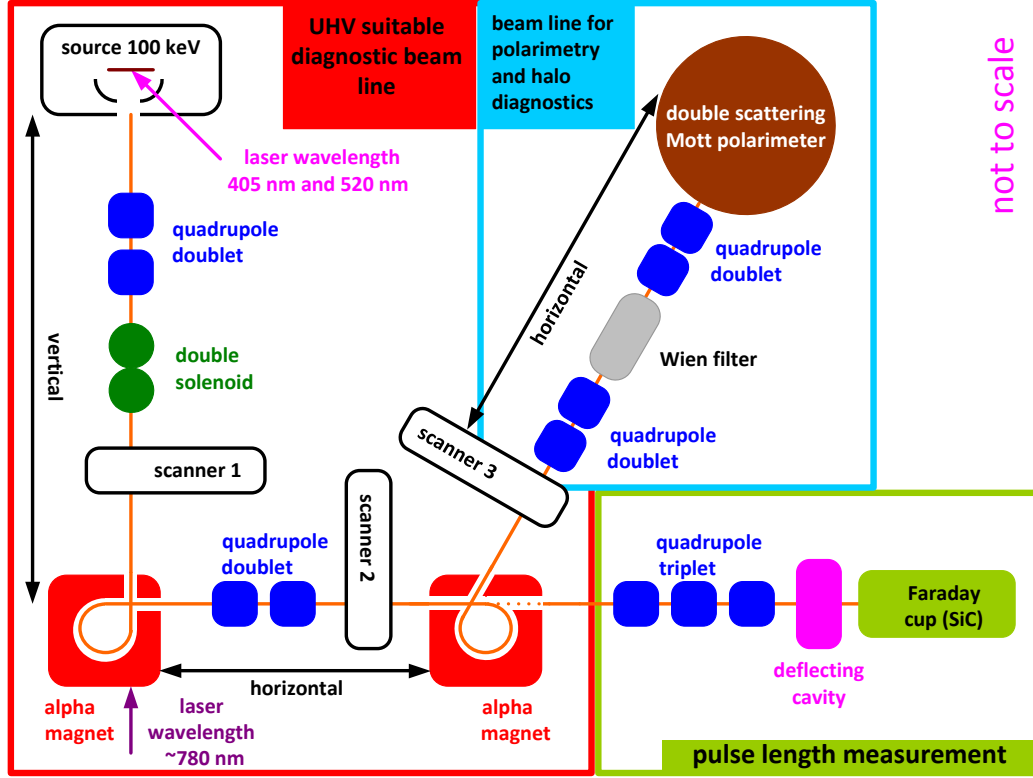


Figure 5.1.: Overview of the PKA2 apparatus and the surrounding lab. The source is located in the upper left corner of the sketch and the electrons are accelerated in the vertical direction until they are bent to the horizontal plane by an α -magnet. The second α -magnet gives the possibility to choose between two different beam lines. The PKA2 can in general be divided into three parts. red: emittance and halo investigations; green: temporal pulse shape investigations; blue: polarimetry

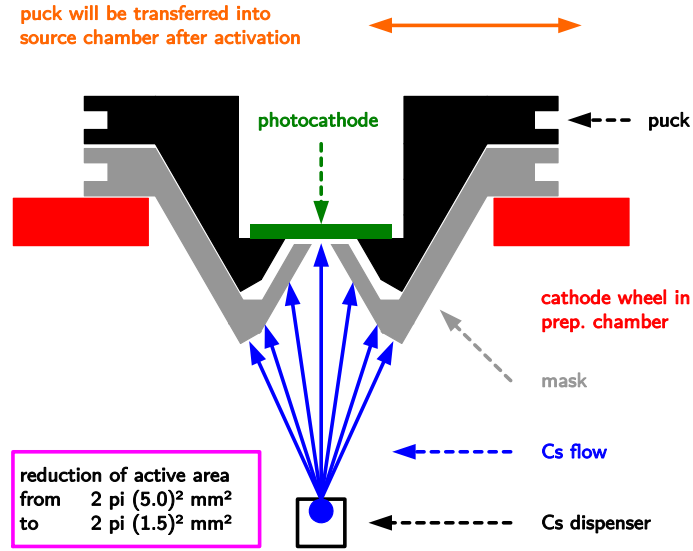


Figure 5.2.: Working principle of the mask preparation technique. The puck with the photocathode is placed in a mask after a heat cleaning procedure. The mask covers a large fraction of the photocathode surface and reduces the area with the CsO layer, which is important for the beam quality. If long operating times with high average electron currents ($I_{\text{beam}} > 100 \mu\text{A}$) are desired, this step is essential. After this surface treatment, the photocathode is transported into the source chamber.

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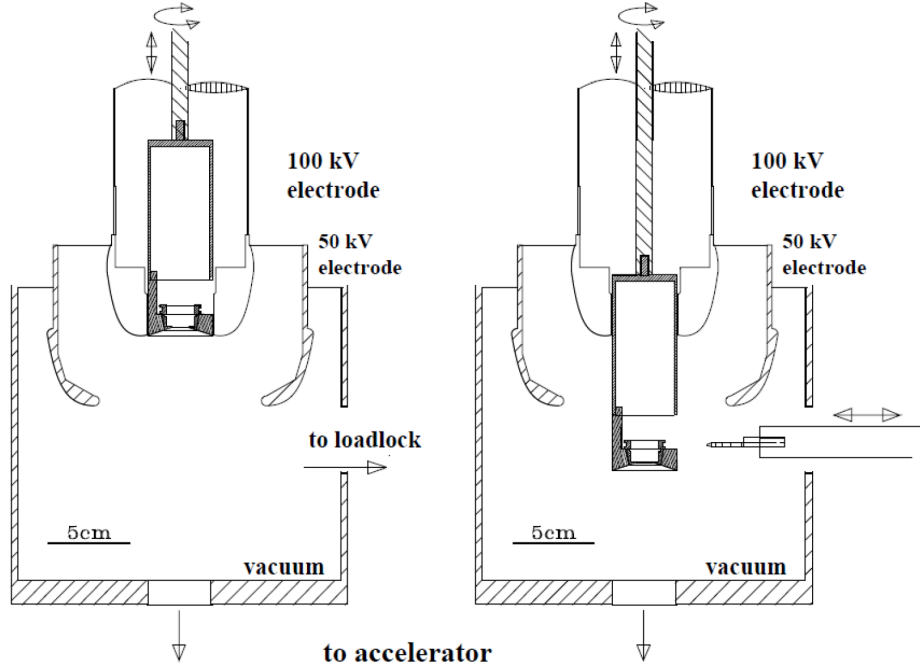


Figure 5.3.: Illustration of the working principle of the photocathode elevator inside the electron source. The picture on the left shows the elevator orientation during operation. On the right, the situation for a cathode transfer is given. The elevator is moved down and from the right side comes an MLRD to pick up the cathode and to move it into the preparation chamber. Furthermore, the main and intermediate electrodes are shown with their electric potentials. [Hart97]

operating times with high average electron currents ($I_{\text{beam}} > 100 \mu\text{A}$) are desired. A photocathode that has been prepared can be transported with an MLRD into the electron source. Inside this source, there is an elevator to pick up the cathode and lift it up to the correct position inside the electrode. An illustration of the elevator working principle is given in Fig. 5.3.

At the PKA2, there are two possibilities to get the laser light onto the cathode. The first one is through a viewport which is welded into the bottom plate of the source chamber and has an angle of 25.6° with respect to the surface normal of the cathode. Through this viewport, the laser light of the 405 nm and 520 nm laser diodes is directed onto the photocathode. The second possibility is through a viewport below the first α -magnet, which enables the laser to illuminate the photocathode perpendicularly to its surface. This is necessary to produce spin-polarized electrons since the electron polarization depends on that of the light. This laser diode has a wavelength of $\lambda_{\text{IR}} = 780 \text{ nm}$, so the photon energy is close to the band gap energy $E_g = 1.4 \text{ eV}$ of the photocathode. Due to the wavelength dependence of the photocathode QE (see Fig. 3.6), it is not recommended to use this wavelength for the high-current investigations presented in this thesis. One

reason is that the necessary laser power needed to achieve several mA of average electron current must be produced by a MOPA system to ensure the desired pulse structure (see Sec. 3.3 and [Aule07]). This kind of laser system would be much more expensive and complex than the laser system introduced in the following chapter. An additional reason is that the photocathode lifetime is sensitive to the cathode temperature [Rieh11]. An increase in temperature—caused by a high laser power, which is required due to a low QE—reduces the cathode lifetime, preventing long operating times. Additional information can be found in [Herr14].

The produced electrons can be accelerated by an electric potential of 100 kV with the direction of flight during the first 1.5 m being vertical. The first α -magnet bends the orbit by 270° , after which it continues horizontally. After a few additional meters, they reach a second α -magnet, and in this position the experimenter can choose between guiding them through a deflecting cavity (α -magnet is off) or into a polarimeter (α -magnet is on). Although polarimetry is not part of this thesis, the beam line assembly and the commissioning of the polarimeter was supported within this thesis under the guidance of Dr. V. Tioukine [AuAT12]. By means of the deflecting cavity, the longitudinal profile of the electron beam can be analyzed. As beam dump a Faraday cup made of silicon carbide (SiC)^b is used. The SiC has a diameter of 50.8 mm and scintillates when hit by electrons, which is why it can also be used as a screen. A mirror mounted inside the vacuum chamber of the Faraday cup allows to view the screen image from outside. The reason why the Faraday cup is made of SiC is explained using the electron back-scattering coefficient η_{BSC} (BSC). Following [TIO71], the BSC can be calculated via

$$\eta_{\text{BSC}} = \frac{a_{\text{BSC},1}}{1 + a_{\text{BSC},2}\tau^{a_{\text{BSC},3}}}. \quad (5.1)$$

The parameter $\tau = E_{\text{kin}}/m_e c^2$ denotes the kinetic energy of the electrons E_{kin} in units of the electron rest mass $m_e c^2$ and the $a_{\text{BSC},i}$ are dependent on the atomic number, taken from [TIO71] and calculated for the species Cu, Si and C. For the compound SiC, η_{BSC} can be calculated for each component o and weighted with the mass fraction w_o via

$$\eta_{\text{BSC,comp}} = \sum_o w_o \eta_o.$$

The calculation yields $\eta_{\text{BSC,Cu}} = 27.4\%$ and $\eta_{\text{BSC,SiC}} = 10.7\%$ at $E_{\text{kin}} = 100 \text{ keV}$. The lower BSC for SiC supports the vacuum conditions because of the lower out-gassing rate caused by electron bombardment on the chamber walls, and it decreases the uncertainty of the current measurement. Furthermore, there is a Ce:YAG screen, which can be moved in and out of the beam path. This screen has a distance of 380 mm to the center of the deflecting cavity. The Ce:YAG screen is mounted perpendicular to the beam and can be looked at with a 45° mirror. Both screen materials are needed for different tasks. The investigation of the temporal structure of the electron bunches is carried out with the Ce:YAG screen (results are

^bSemiconductor Wafer Inc. - 2" SiC, n-type, doped with nitrogen, 500 μm thickness

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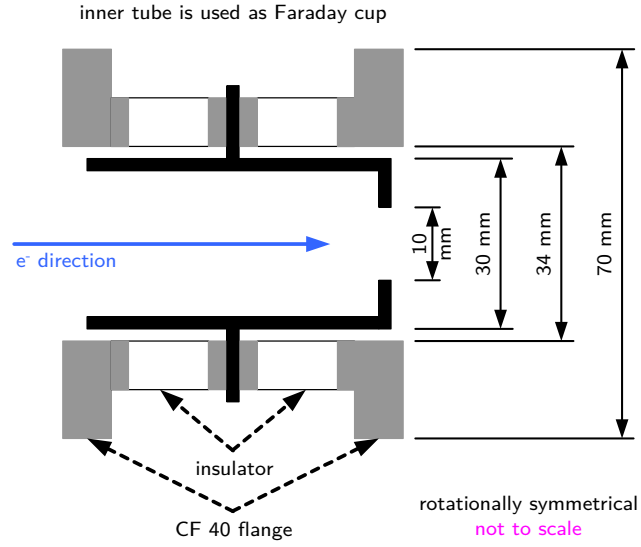


Figure 5.4.: Visualization of the perforated Faraday cup design. The inner tube is made of stainless steel and is electrically insulated by two insulators from the rest of the beam line. This enables an optimization of the beam trajectory by minimizing the measured current. In addition, this Faraday cup works as diaphragm in the differential pumping station. The gas flow to the sections with better vacuum conditions is reduced by the lower inner diameter of the hole in the endplate.

presented in Fig. 6.28), whereas in the high current experiments the SiC screen is used (results are shown in Fig. 6.2).

The beam line contains several focusing magnets such as quadrupoles (blue) and solenoids (green) and also some steering magnets, which are not shown in Fig. 5.1. Steerers are dipole magnets with two pairs of air coils to adjust the electron beam direction on two axes at the same time.

The PKA2 contains four different analyzing stages, namely three scanners with different sled occupancies (see Fig. 4.2) and the deflecting cavity. The scanners are used to analyze the transverse behavior of the electron beam and also to investigate the halo distribution, while the cavity is used for longitudinal bunch profile measurements. The first scanner is located in the vertical part of the beam line close to the electron source, the second one sits between both α -magnets, and the third one is located behind the second α -magnet on the way to the polarimeter.

At the PKA2, there are three possible ways to measure the electron current via the control system. Two of them are Faraday cups, one of which is mounted behind the deflecting cavity (the one with the SiC screen) and the other one is in the polarimeter. The one located in the polarimeter consists of two concentric cups, which are independent of each other, allowing to measure the angle at which the electrons enter the polarimeter. The third element is located between the second α -magnet and the deflecting cavity. It consists of two insulators which electrically

separate a tube from the beam line. A schematic sketch of the layout is shown in Fig. 5.4. On the downstream side of this element, a plate with a 10 mm diameter hole is attached. Thus, it looks like a mug with a hole on the bottom. The Faraday cup allows to determine and optimize the transmission through the beam line and can be used as an additional diagnostic element. Furthermore, the perforated Faraday cup also works as a diaphragm in the differential pumping stage in the vacuum system in that it reduces the gas flow to the sections with better vacuum conditions due to the lower inner diameter. All currents collected by these cups flow through Current-to-Voltage-to-Frequency Converters (IUFC)^c and can be read out by the control system. In addition, the electron current emitted by the source is measured by an amperemeter located at the 100 kV platform.

The vacuum from the electron gun up to the second α -magnet is better than 3×10^{-10} mbar. This vacuum level marks the normal operating condition (without electron beam) where all valves are opened, except the one directed to the double scattering polarimeter. Inside the source chamber, the vacuum is probably one order of magnitude lower than in the rest of the beam line. Behind the second α -magnet, there is a valve on the way to the polarimeter because the vacuum there is around 5×10^{-7} mbar. There is another one on the way to the deflecting cavity where the vacuum is around 2×10^{-8} mbar and better.

5.2. Laser system

The laser system consists of three laser diodes with different wavelengths. The 405 nm^d and the 520 nm^e laser are located on the first floor of the PKA2 lab, and so it is possible to illuminate the photocathode through a vacuum viewport in the base plate of the source chamber. The upper part of Fig. 5.5 shows this part of the laser system as a sketch while the lower part is a photograph of it, including a part of the RF supply. On the right side of Fig. 5.5, the 405 nm laser diode is mounted followed by an anamorphic prism pair^f and an aperture. The anamorphic prism pair has a variable magnification in one direction, and so it is possible to correct the astigmatism of the laser diode and to create a nearly round laser beam profile on the photocathode. The aperture reduces the stray light and beam halo. After the prism pair, a dichroic mirror^g is mounted to combine the 405 nm and the 520 nm lasers. The green laser can be seen in the middle-left, also followed by an anamorphic prism pair. Behind the dichroic mirror comes a remotely controlled shutter and attenuator. The next element is a telescope^h to achieve various beam diameters on the photocathode to research the effect of emittance growth caused by the spot size. The penultimate element—before the light is bent by a mirror

^cThe IUFCs were manufactured by the electronics workshop at the KPH, $10 \mu\text{A} \triangleq 10^6 \text{ Hz}$

^dRoithner Lasertechnik GmbH - RLV4512, $P_{\text{max}} = 200 \text{ mW}$

^eRoithner Lasertechnik GmbH - LD-520-120MG, $P_{\text{max}} = 120 \text{ mW}$

^fToptica - APPJ 390-420

^gThorlabs - DMLP425, 1", cutoff wavelength 425 nm

^hused lenses: plano convex (1") with $f = -50 \text{ mm}$ and plano concave (2") with $f = 100 \text{ mm}$

5. Experimental setup

into the source chamber—is a beam splitterⁱ which couples out $\sim 3\%$ of the laser power and reflects them onto a CMOS camera^j. This camera is used as a virtual photocathode to determine the laser spot size at the position of the photocathode (example beam profiles are shown in Fig. 5.10). In front of the CMOS camera, an OD30 attenuator is mounted to reduce the laser intensity and to suppress light from other sources.

For investigations with spin-polarized electrons and for the commissioning of the double scattering Mott polarimeter, there is a 780 nm laser system installed on the ground floor of the PKA2 lab close to the first α -magnet. The IR laser system also consists of a remote-controlled shutter and an attenuator followed by a fixed anamorphic prism pair and a mirror to bend the laser light from the horizontal into the vertical direction. Behind the mirror, there is a telescope to set the beam spot size on the photocathode. Between the telescope and the vacuum viewport of the α -magnet chamber, the elements to create and manipulate the light polarization of the laser are placed. The first element is a polarizer to get linearly polarized light with a high extinction ratio followed by a Pockels cell to produce left or right circularly polarized light. The Pockels cell is able to switch very fast (1000 Hz) between the two states of polarization. The main work on the polarization optics was done by C. Matejcek [Mate13].

5.2.1. Output power and operating mode of the laser system

In this section, the output power for c.w. operation of the laser system and the operating mode are presented. The output power can be determined with an optical power meter^k, and the results are illustrated in Fig. 5.6 for the blue and the green laser diode, respectively. The c.w. laser pulses are created by a superposition of a dc current from the laser diode driver^l with additional RF power. These RF-synchronous laser pulses will be called “micro pulses” in the further text. The superposition is realized with a bias-tee^m, which is an electrical circuit to ensure that the dc and the RF signals can combine on the way to the laser diode, but not on the way to the signal sources. The RF signal is provided by the amplifier of the deflecting cavity (details are given in Sec. 3.4) to get micro pulses in-phase with the analyzing frequency of the cavity ($\nu_{\text{MESA}} = 1.3 \text{ GHz}$). As discussed in Sec. 3.3, the technique used is called “gain switching”. The output power measured represents the average power of the laser diodes due to the high repetition rate, but they deliver a higher peak power. This can be derived from the data depicted in Fig. 3.15. At the same average power, the peak power increases with decreasing pulse length. The same applies to the electron beam. The increase of the peak power

ⁱThorlabs - BSF20-A, 2”, 0.5° wedged to eliminate interference fringes

^jVision Components - VC4067

^kThorlabs - PM200 with detector S121C

^lThorlabs - LDC 202 C

^mPicosecond Pulse Labs - Model 5575A

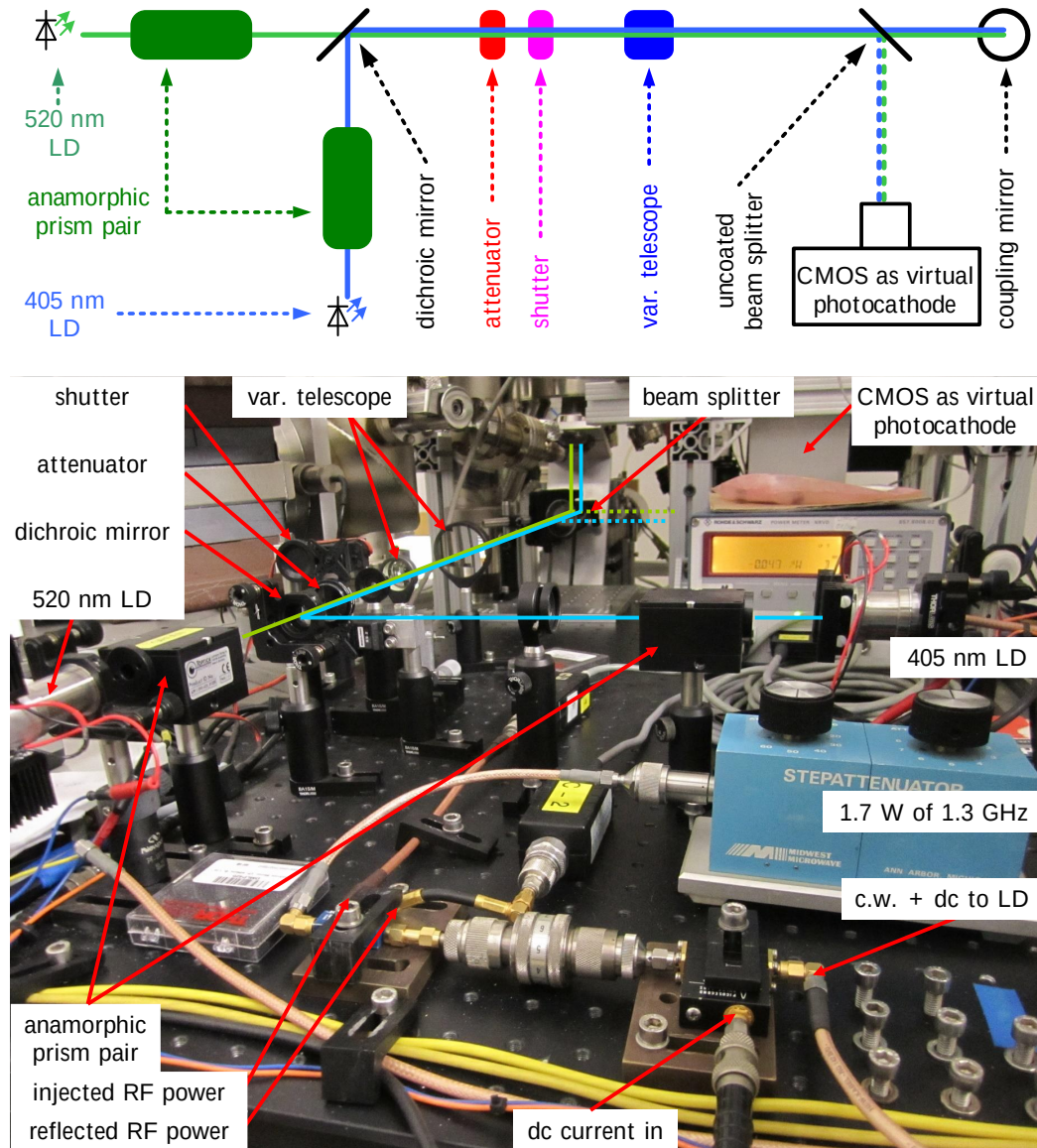


Figure 5.5.: The upper part illustrates a sketch of the laser system with the 405 nm and 520 nm laser diodes. In the lower part, a picture of the laser system with a part of the RF supply is given.

5. Experimental setup

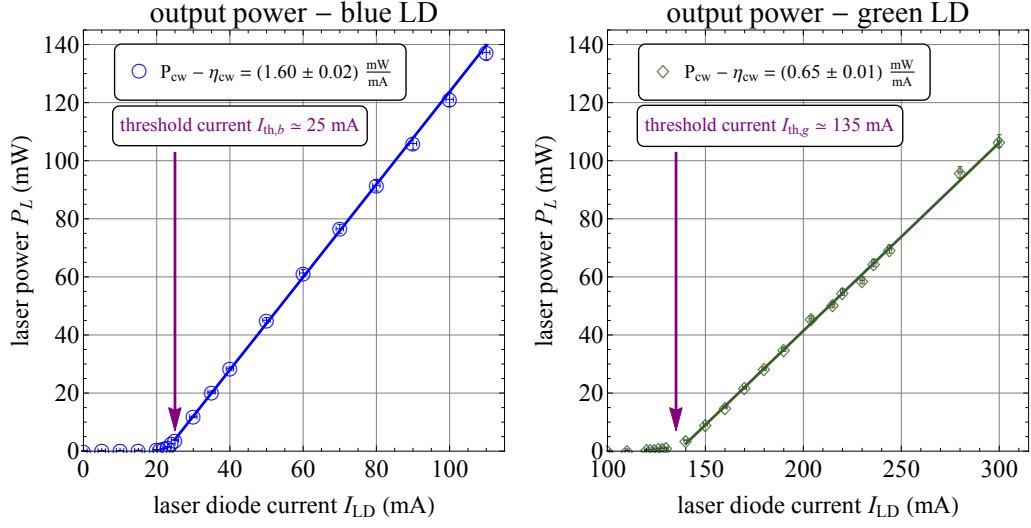


Figure 5.6.: Output power of the laser diodes in c.w. operation. Both laser diodes are able to produce electron currents above $I_{\text{beam}} = 1 \text{ mA}$ in combination with the photocathodes used.

with respect to the average power can be up to a factor of 5 – 15, which can be estimated via

$$\frac{P_{L,\text{peak}}}{P_{L,\text{avr}}} \triangleq \frac{\text{Int}_{\text{peak}}}{\tau_{\text{MESA}}^{-1} \int_{\tau_{\text{MESA}}^i}^{\tau_{\text{MESA}}^{(i+1)}} \text{Int}(t) dt}.$$

Since the emittance and the temporal structure of the electron beam are to be investigated up to an electron current of around $I_{\text{beam}} = 2.5 \text{ mA}$, the deposited power in c.w. operation would be too high for the beam diagnostic elements developed. Thus, the average power of the laser system has to be decreased. This is possible with a modulated current from the laser diode driver. A pulse generatorⁿ supplies the laser diode driver with rectangular pulses with a pulse length between $\tau_{\text{pulse}} = 300 \text{ }\mu\text{s}$ and infinity and with a variable repetition rate. In general, the repetition rate is set to $\nu_{\text{rep}} = 5 \text{ Hz}$ due to the synchronization to the mains frequency of 50 Hz. These pulse trains with a length of $\tau_{\text{pulse}} \geq 300 \text{ }\mu\text{s}$ contain more than 3.9×10^5 micro pulses and will be called “macro pulses” in the further text. Now the average c.w. power of the laser system can be decreased by 99% – 99.9%. This can be expressed by the duty cycle

$$D = \frac{\tau_{\text{pulse}}}{\tau_{\text{rep}}}.$$

The symbol $\tau_{\text{rep}} = 1/\nu_{\text{rep}}$ represents the length of the repetition period. An example of three different duty cycles is depicted in Fig. 5.7.

ⁿQuantum Composers - Model 9514

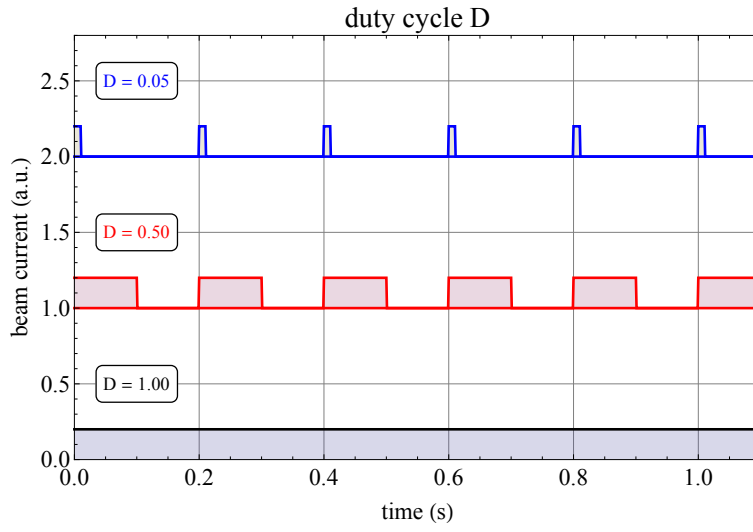


Figure 5.7.: Visualization of the duty cycle and how the average laser power/electron current is reduced due to macro pulses. The repetition rate is set to 5 Hz. A duty cycle $D = 1$ will represent the normal operation condition of MESA, but in the case of a beam parameter characterization, the average laser power/electron current has to be reduced to avoid damage on the beam diagnostic elements. If the macro pulse is half as long as the repetition period, this ends up with $D = 0.5$. The lower limit of the duty cycle will be $D = 1.5 \times 10^{-3}$ for the given laser system because the macro pulse length should not be shorter than 300 μs .

5. Experimental setup

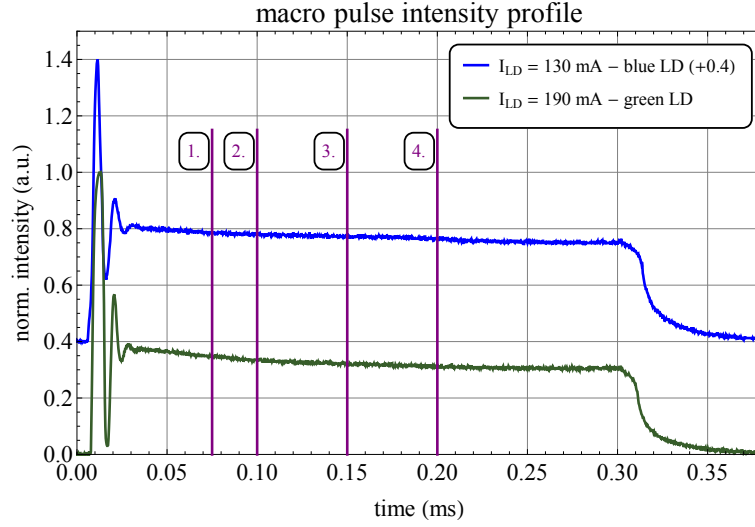


Figure 5.8.: The graph shows the normalized intensities of a 300 μ s long macro pulse for the blue and the green laser. The graph includes the laser diode current with which the emittance measurements were performed. At the beginning of the macro pulse, both laser diodes perform oscillations followed by a plateau. For a better comparability, the normalized data of the blue laser diode are increased by 0.4. The numbered vertical lines mark the different times used for the data presented in Fig. 5.9.

This enables the production of higher currents without the risk of destroying the analyzing elements because of the power/heat deposition of the electrons and enables to push forward into the desired bunch charge regime. Thus, the laser system can have a low average power with a high peak power.

5.2.2. Pulsing behavior of the laser diodes

In order to ensure that the laser diodes produce a stable output power within the macro pulses, these are examined by means of a fast photo detector^o and an oscilloscope^p. For the blue and the green laser, at the beginning of the macro pulse there is a high peak followed by a more or less stable plateau. The 3 dB modulation bandwidth of the laser diode driver is ≤ 250 kHz [Thor16] and for the laser diodes it is ≤ 100 MHz [Data14]. In the graph, depicted in Fig. 5.8, the normalized intensity signals of both lasers for a macro pulse length of 300 μ s at the maximum laser diode current used are shown. At the beginning of the macro pulse, the laser diode driver tries to push the current through the bias-tee, causing a peak in the output power. This is followed by an oscillation with a duration of approximately 20 μ s. After the oscillation follows a 270 μ s long plateau. Furthermore, the height of the plateau is comparable with the equivalent c.w. power.

^oThorlabs - DET36A/M

^pAgilent Technologies - DSO-X 3054A, 500 MHz

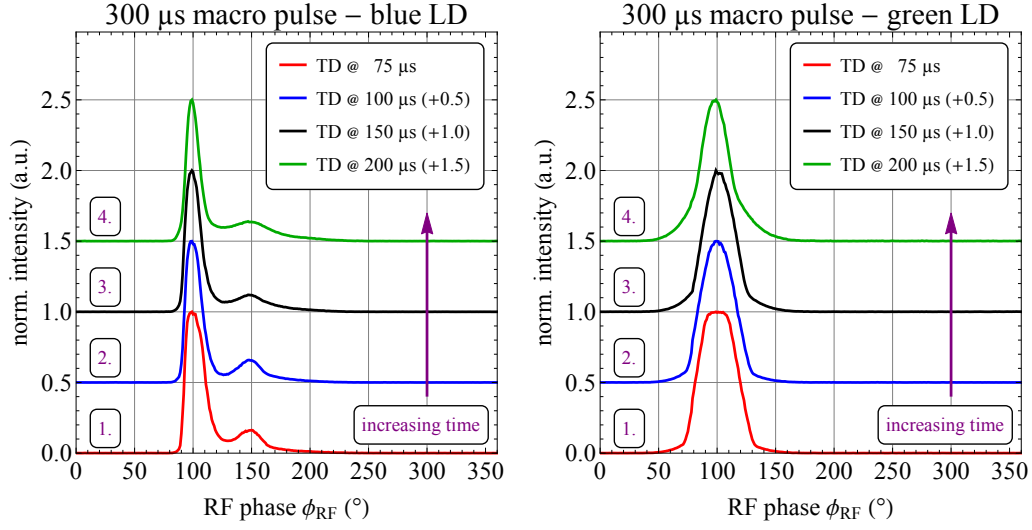


Figure 5.9.: Illustration of four example intensity profiles—obtained at different times within the macro pulse—plotted over the RF phase. These temporal distributions show that a stable micro pulse generation along the macro pulse is possible. Although the pulse shapes of each laser diode differ, their positions relative to the RF phase are stable.

In general, one would expect that the laser diode performs relaxation oscillations at the beginning of the macro pulse, which would cause an abnormal or unstable micro structure [Sieg86]. In the introduced laser system, it is a combination of both the laser diode behavior itself and the laser diode driver with the bias-tee. The solutions of the rate equation system (Eq. 3.7 and Eq. 3.8) have shown that the transient behavior of the laser diodes takes place within the first 15 ns after applying the laser diode current. This time decreases with increasing amount of current. Thus, the laser diode driver in combination with the bias-tee represents the dominant effect on the peaks appearing at the beginning of the macro pulse. This transient process has to be taken into account during the pulsed emittance measurements. At a macro pulse length of 300 μs, the first 20 μs makes up about 7% of the macro pulse.

For the investigation of the micro pulses of the laser diodes, the produced electron bunch charge is very low to avoid the influence of space charge. With the deflecting cavity behind the second α -magnet, it is possible to check whether the micro pulses are stable along the macro pulse. For this measurement, the delay between the laser pulse and the camera trigger is varied in steps of 1 μs because the shortest exposure time of the CMOS camera is 1 μs. A selection of four example micro pulses along a macro pulse with a length of 300 μs is illustrated in Fig. 5.9 for the blue laser diode (left) and the green laser diode (right), respectively. Both laser diodes are able to produce stable micro pulses, which is important for the operation of MESA if it is desired to use a comparable laser system.

5. Experimental setup

All results shown are made with a repetition rate of 5 Hz to reduce the thermal load on the screens, and a macro pulse length between 300 μ s and 1200 μ s was chosen. These times result in a duty cycle of $1.5 \times 10^{-3} \leq D = \tau_{\text{pulse}}/\tau_{\text{rep}} \leq 6 \times 10^{-3}$. Thus, in the case of a c.w. laser power of $P_{L,\text{cw}} = 100$ mW and considering the duty cycle calculated above, the average laser power will be reduced to $(0.15 \leq P_{L,\text{avr}} \leq 0.6)$ mW. In terms of electron current, this means that, using the maximum current of the HV power supply ($I_{\text{beam,max}} = 3$ mA), the average beam current is $(4.5 \leq I_{\text{beam,avr}} \leq 18)$ μ A. By multiplying these values with the acceleration voltage (100 kV), the power with which the beam diagnostic equipment has to deal can be calculated. This yields an average beam power of $(0.45 \leq P_{\text{beam,avr}} \leq 1.8)$ W. The repetition rate was selected because this enables a stable synchronization to the mains frequency of 50 Hz. The variable macro pulse length and repetition rate can also be important to optimize MESA because this mode delivers the possibility to fill the RF buckets step by step with a constant bunch charge.

5.2.3. Spot size and telescope properties

The telescope in the laser system is used to change the beam spot diameter at the photocathode, which can be checked with a CMOS camera working as a virtual photocathode. The telescope contains three elements: a variable iris to cut out a fraction of the unwanted beam distribution, a defocusing and a focusing lens. The aperture and the defocusing lens are mounted on a translation stage⁹ to change the focusing properties of the telescope.

In the middle of Fig. 5.10, the calculated four times RMS values of the projections of the beam distribution are plotted over the μ m screw setting of the translation stage. To obtain the RMS values, the intensities of each row or column are accumulated for the x or y direction, respectively. The intensities are normalized after accumulation. In the first step, the focus (CM) of the intensity distribution $\text{Int}_i(o)$ is calculated via

$$\text{CM}_i = \frac{\sum_o (o \times \text{Int}_i(o))}{\sum_o \text{Int}_i(o)}.$$

The index i represents the analyzed axis x or y , and o corresponds to the number of the pixel examined. In the next step the standard deviation, which represents the RMS value of the intensity distribution, is calculated with

$$\sigma_i = \sqrt{\frac{1}{\sum_o \text{Int}_i(o) - 1} \sum_o \left(\text{Int}_i(o) (o - \text{CM}_i)^2 \right)}$$

and the error of the standard deviation is determined via

$$\delta\sigma_i = \frac{\sigma_i}{\sqrt{2(\sum_o \text{Int}_i(o) - 1)}}.$$

⁹Thorlabs - PT1/M, 25 mm travel

The model fitted to the data is

$$\sigma_L(x) = 4\sigma_i(x) = w_0 \sqrt{1 + \left(\frac{x - x_0}{z_R}\right)^2} \quad (5.2)$$

with the waist w_0 , an offset in the x direction x_0 , and the Rayleigh length^r z_R . The blue and green laser diodes have different initial intensity distributions, causing—in addition to the influence on the dispersion—a difference in the beam diameter for the same μm screw setting. Both laser diodes show astigmatism, which is less pronounced in the blue laser diode. The minimum possible beam diameters are $(118 \pm 26) \mu\text{m}$ @ 18.37 mm for the blue laser diode and $(519 \pm 18) \mu\text{m}$ @ 22 mm for the green one.

In the upper part of Fig. 5.10, three examples of the intensity distribution of the green laser diode at different μm screw settings are given. The strongly elliptical shape of the green laser diode causes a bigger beam spot at the exit of the anamorphic prism pair in comparison with the blue one. Thus, the beam diameter is larger than the opening of the iris; combined with the fact that the laser hits the cathode at an angle, this causes an oval beam profile.

The lower part of Fig. 5.10 illustrates the beam shape of the blue laser diode for three different μm screw settings. The comparison of the beam profiles for blue and green shows that the axis ratio of the blue laser is not strongly elliptical and the intensity distribution is more Gaussian-like.

All observed intensity profiles show diffraction patterns caused by dust particles on the optical elements or the laser diode itself.

5.3. RF deflecting cavity

The deflecting cavity [Bech13] is located between the second α -magnet and the Faraday cup. This can be seen in Fig. 5.11 as a sketch (top) and a photo (bottom), respectively. The design was based on the existing chopper cavity of the MAMI accelerator, which works at a frequency of 2.45 GHz [Brau88]. The deflecting cavity at the PKA2 is designed as a prototype for the planned MESA accelerator and works at 1.3 GHz.

This cavity is used to investigate the longitudinal phase space and the pulse length growth caused by space charge. It works with a TM_{110} mode and is designed such that each period of the RF forms a circle, which can be observed with a Ce:YAG screen at a distance of 380 mm. This is possible because the deflecting cavity transfers different transverse momenta to the electrons depending on their phase with respect to the RF phase. The cavity shape is modified by two s-shaped recesses at the entrance and exit side of the cavity in order to impose a rotation on the magnetic field of the TM_{110} mode. More details can be found in [Bech13].

A normal TM_{110} deflecting cavity would deflect the electron beam only in one direction. This leads to an overlap of the intensities from the RF phase regions

^rThe Rayleigh length defines the length from the waist until the beam area has doubled.

5. Experimental setup

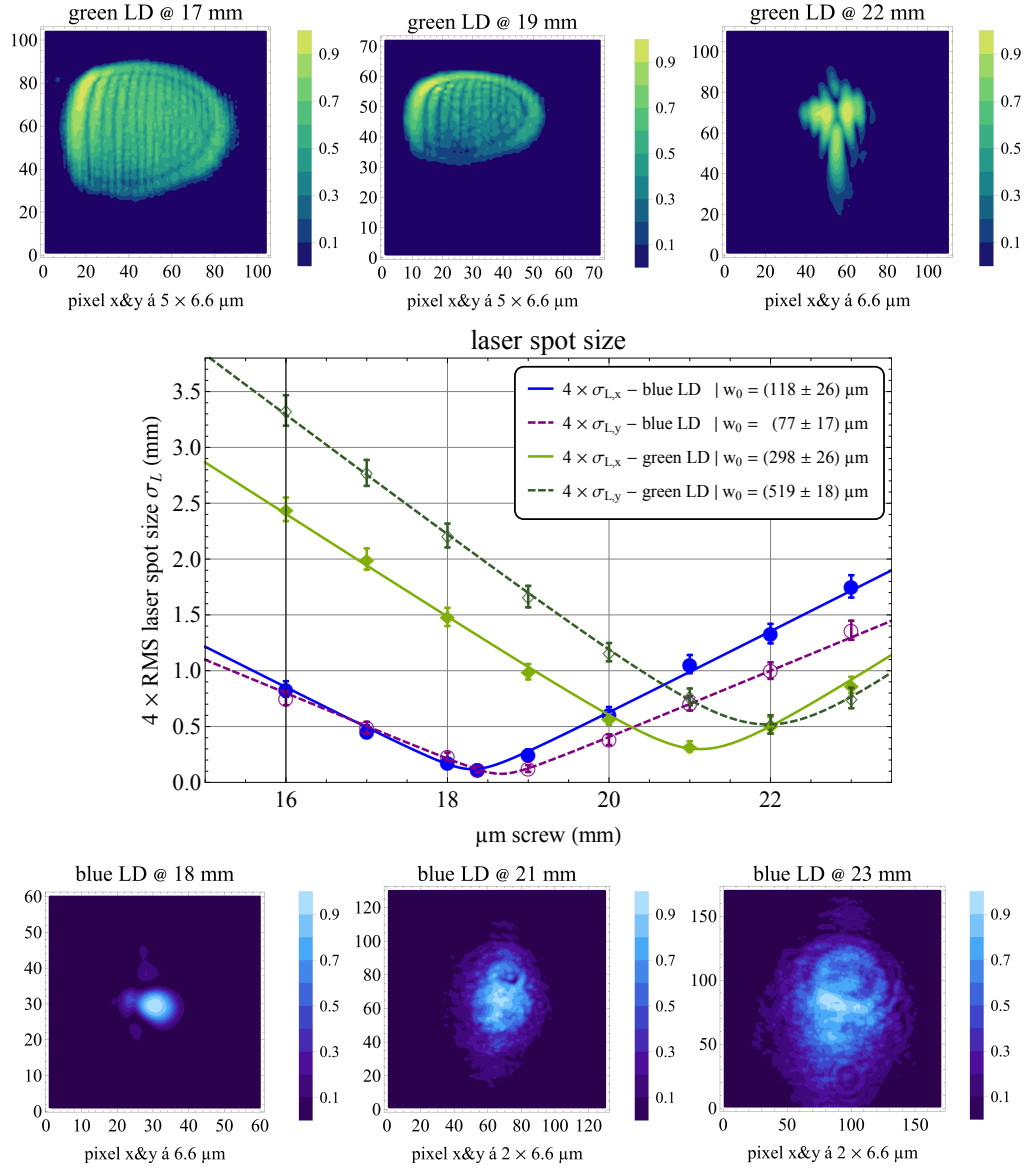


Figure 5.10.: In the middle, the four times RMS value of the beam distribution is plotted over the μm screw setting of the telescope. The upper part shows three examples of the intensity distribution of the green laser diode at the position of the photocathode, and the lower part illustrates this for the blue laser. Note that the scales of the axes are different.

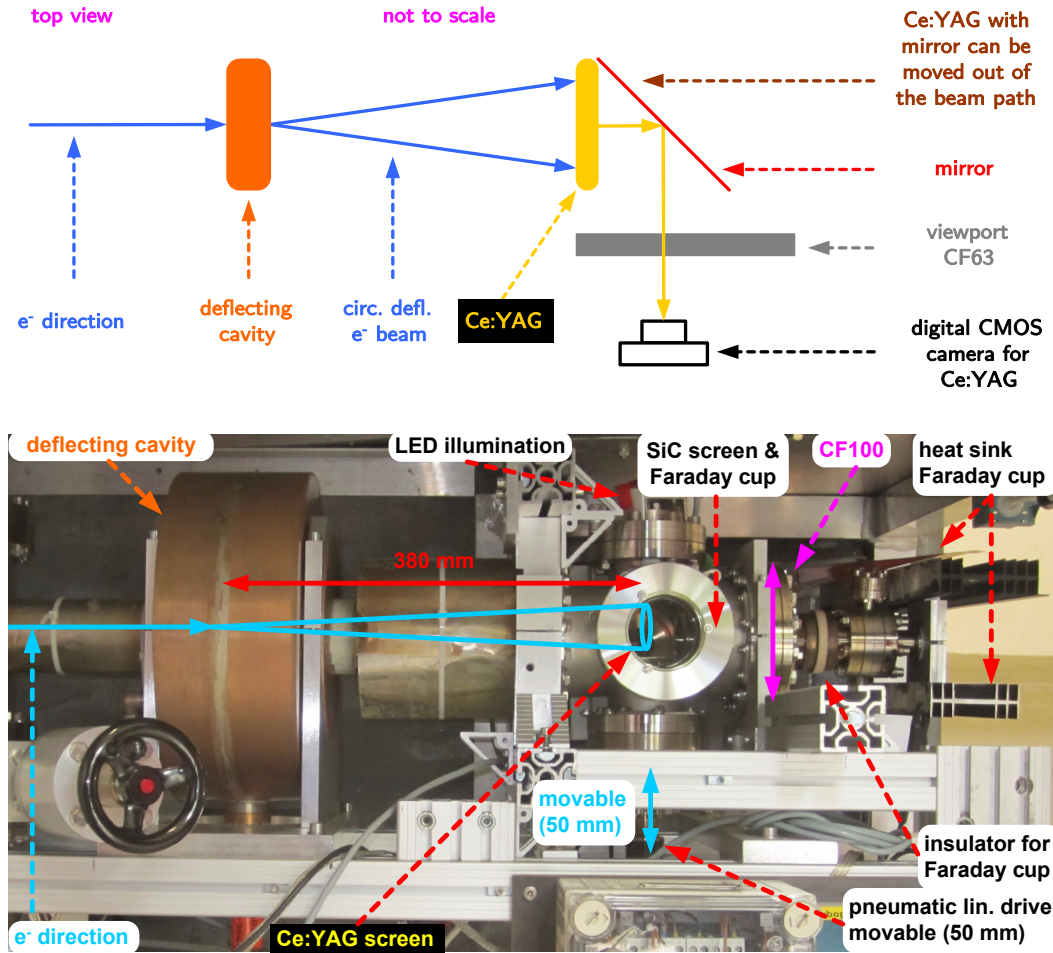


Figure 5.11.: In the upper part, a sketch of the beam line to investigate the temporal distribution of the electron bunches is depicted. The electron distribution is imaged on the Ce:YAG screen and observed via the digital CMOS camera if investigations of the temporal electron distribution are desired. If the Ce:YAG screen is moved out of the beam path, the position on the Faraday cup can be controlled via an analog CMOS camera. In the lower part, a photo of this part of the beam line is given.

5. Experimental setup

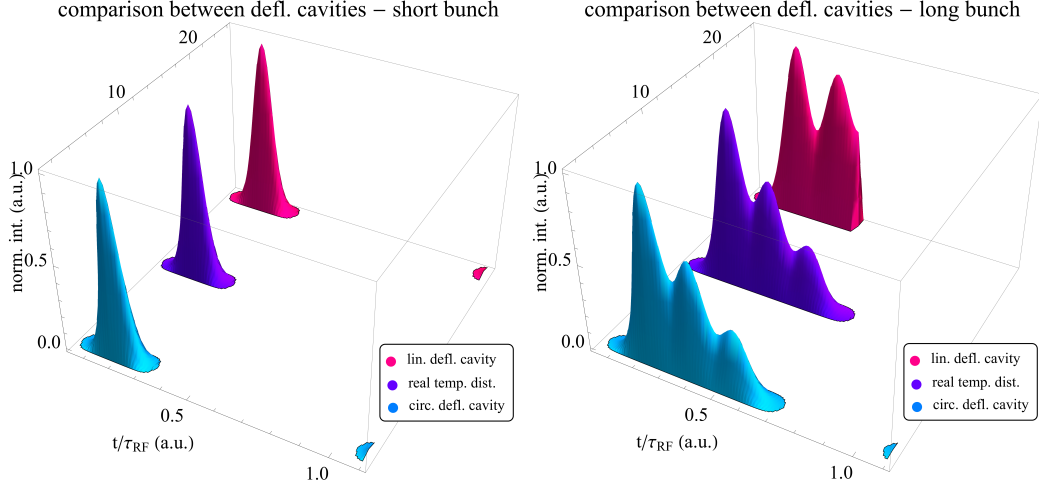


Figure 5.12.: Comparison between a linear and a circular deflecting cavity with respect to their possibilities to resolve a fraction of the RF period. For short electron bunches (left side) there is no difference between the results of the lin. and circ. deflection cavities. But if the bunches become longer than 180° , the lin. deflection cavity will superimpose the intensities of the RF phase $\phi_{\text{RF}} > 180^\circ$ with the intensities of $\phi_{\text{RF}} < 180^\circ$. Thus, the imaged temporal distribution does not correspond to reality (right side).

$0^\circ \leq \phi_{\text{RF}} \leq 179^\circ$ and $180^\circ \leq \phi_{\text{RF}} \leq 359^\circ$. Fig. 5.12 gives an impression on how a temporal distribution is imaged by a linear and a circular deflection cavity. The left side of Fig. 5.12 depicts an example for a short bunch $\phi_{\text{RF,bunch}} < 180^\circ$ and the right side for a long bunch $\phi_{\text{RF,bunch}} > 180^\circ$. In the case of a long bunch, the linear deflection cavity will superimpose the intensities of the RF phase $\phi_{\text{RF}} > 180^\circ$ with the intensities of $\phi_{\text{RF}} < 180^\circ$. Thus, the imaged temporal distribution does not correspond to reality.

If the laser system used creates electrons in the second RF phase interval, these electrons cannot be captured by the phase acceptance of the accelerating RF structures. A combination of two identical and 90° rotated linearly deflecting cavities can remedy this disadvantage. But at the same time, this will cause too many adjustable parameters to optimize the operating conditions of MESA because, as shown in Fig. 3.19, in sum four linearly deflecting cavities would be needed to build up the chopper section instead of two circular ones.

If it is desired to perform time-resolved measurements of ultra-fast phenomena, e.g. in time response investigations of photocathodes as presented in [Dehn13], a linearly deflecting cavity can also have some advantages compared to a circular one. The deflection of an electron beam with an RF cavity scales with $\sqrt{P_{\text{RF}}}$ and for investigations of very short phenomena, an increase of the cavity internal power will increase the temporal resolution. For this type of investigations, it is generally sufficient to image the region of interest on a screen. In the case of a linearly deflecting cavity, the deflection can be chosen much larger than the dimensions of

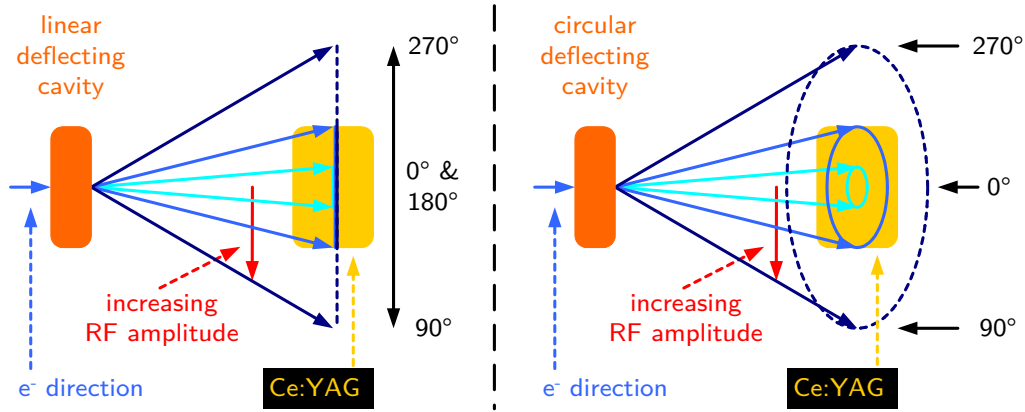


Figure 5.13.: The picture illustrates a comparison between a linearly and a circularly defl. cavity and their possibilities to increase the temporal resolution. If the electron bunch structure occupies only a few degrees of the RF phase, the linear defl. cavity is the better choice for the investigations because here it is possible to choose a larger defl. than the dimensions of the screen. If the bunch structure is more complex and distributed over more than half of the RF period, the circularly defl. cavity is the better choice because it enables to resolve the full 360° of the RF phase.

the screen if the electron distribution occupies only a few degrees of the RF phase. In addition, the deflection of the electron beam follows a sinusoidal modulation, and it has to be taken into account that a linear relationship between the RF phase and the deflection only exists in the vicinity of the zero crossing. On the other hand, in the case of a more complex electron distribution along the RF phase, a circularly deflecting cavity would be a better choice. The circularly deflecting cavity allows to resolve the full 360° of the RF phase with the restriction that the temporal resolution can only be increased until the dimensions of the screen are reached. The situation described here is depicted in Fig. 5.13.

The Ce:YAG screen mounted in the Faraday cup chamber can be moved by a pneumatic translation stage and has a diameter of 40 mm. The light signal is coupled out by a mirror, which is mounted at an angle of 45° relative to the direction of the incoming electrons. The Ce:YAG screen is movable because otherwise it would not be possible to measure the electron current.

If the electron gun works in the dc mode, a full circle appears on the Ce:YAG screen, and if the gun is operated in c.w. mode, there is only a small circular segment, the size of which corresponds to the pulse length of the electron bunches (see Fig. 6.27).

6. Experiments and results

After the introduction of the diagnostic beam line elements in Sec. 4 and Sec. 5, this chapter covers the experiments performed to determine the properties of the electron beam. It starts with the description of high-current experiments to check the photoemission stability of the PKA2, followed by the investigation of the transverse phase space with two different measurement methods. After this, the current-dependent evolution of the temporal distribution (TD) is checked with a deflecting cavity.

6.1. Lifetime measurements and high-current operation

The photoelectron source PKA2 can be a good choice to deliver the electrons for MESA. In this chapter, the properties of the source are introduced in more detail. The PKA2 has an improved vacuum system in comparison to the source of MAMI.

The data presented in the left graph of Fig. 6.1 show the evaluation of the QE in the IR region of a photocathode to check the vacuum lifetime τ_{vac} of the PKA2. The QE of 1.4% of the plateau in Fig. 6.1 corresponds to a responsivity of $\sim 9 \text{ mA/W}$. The vacuum lifetime describes the time in which the QE drops to e^{-1} of its initial value without extracting a significant amount of charge. The experiment was performed under “armed” conditions. This means that the HV was kept on and the valve between the source chamber and the beam line was kept open. To measure the QE, the laser was switched on for 2 s every 20 min, and the extracted current was measured at the PKA2 directly via a DVM^a and with a Faraday cup connected to an IUFC. During the first three weeks, the QE stayed stable before it started to decay with a lifetime of $\tau_{\text{vac}} = 26$ days. The current extracted during this experiment was kept low to prevent disturbing effects like heat-induced cathode degradation, ion back bombardment (IBB) and others. As shown in Eq. 3.6, the photoemission current is proportional to the laser power used. All photons which are not absorbed by the active area of the photocathode create heat in the substrate by depositing their energy there. Investigations of the photocathode lifetime with respect to the incident laser power have shown that the lifetime is strongly influenced by the energy deposition inside the substrate and follows an exponential decay function [Rieh11]. Thus, a large amount of laser power will shorten the lifetime. The second mentioned effect, namely IBB, is stimulated if the electrons ionize the residual gas within the acceleration structure. The positively ionized particles will be accelerated towards

^aDVM - Digital Volt Meter

6. Experiments and results

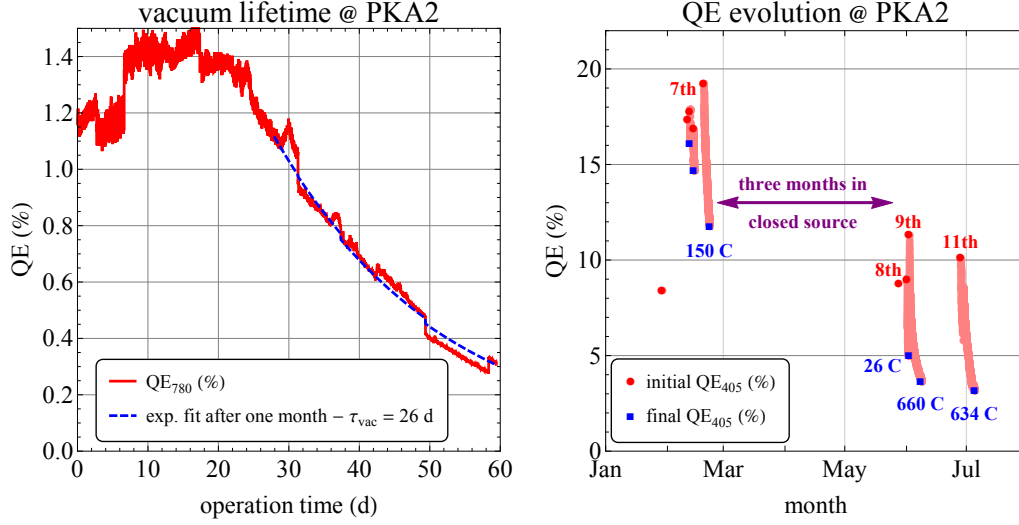


Figure 6.1.: The left graph shows the vacuum lifetime of the photocathodes with HV switched on and open valve. The QE of 1.4% of the plateau correspond to a responsivity of $\sim 9 \text{ mA/W}$ (courtesy of Dr. V. Tioukine). The right graph shows the QE development of a photocathode during operation in the PKA2. The numbers in red indicate the preparation and the numbers in blue the extracted integrated charge.

the photocathode and can sputter the CsO layer of the cathode surface. This effect is current-dependent and causes a local degradation in the QE.

To determine the reliability of the PKA2 in high-current operation, various beam tests were performed. During this time, parts of the beam line were electrically isolated from the support structure so the transmission loss I_{loss} could be directly measured with an amperemeter. In general, I_{loss} could be kept below 1 nA in all experiments. In the right graph of Fig. 6.1, the evolution of a photocathode operated in the blue region of the visible light is summarized. The QE is plotted over the time of six months with different high-current beam times and preparations. In the middle region is a break of almost three months, during which the QE dropped from 11% to 9% in a closed source chamber. These QE values correspond to a responsivity of 36 mA/W and 29 mA/W , respectively. This leads to the conclusion that the vacuum lifetime in the closed PKA2 is very long ($\tau_{\text{closed}} > 1 \text{ a}$), at least for higher photon energies. The initial and final QEs are shown with the red and blue data points, respectively, from the seventh to the eleventh preparation. A regular drop from the initial QEs depending on the number of preparations can be observed. The ability to reach a QE of $\sim 10\%$ after ten preparations indicates that the general conditions for the preparation can be controlled in a reliable way. The preparation procedure is explained in Sec. 3.2.2.

Fig. 6.2 shows two examples of high-current beam time experiments, in each of which nearly 700 C could be extracted. Several different current-dependent effects

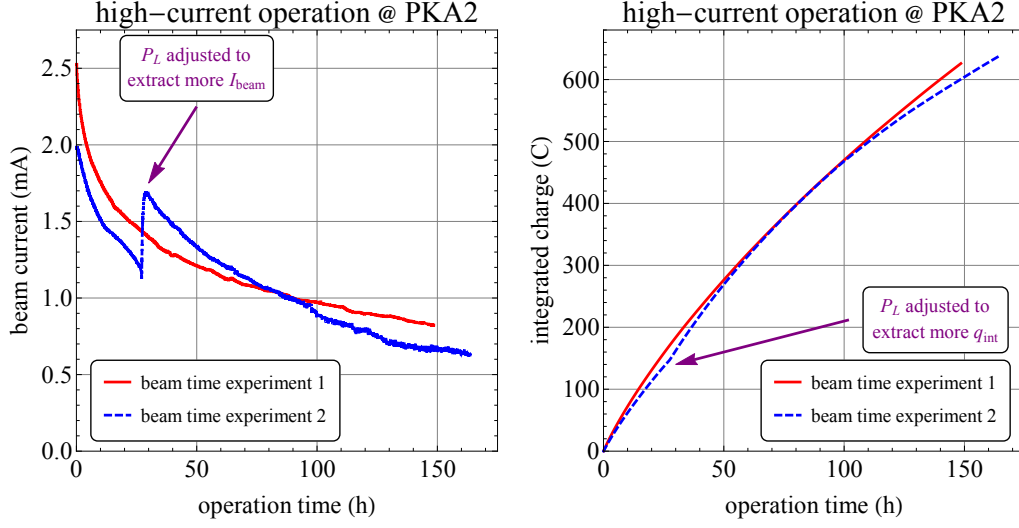


Figure 6.2.: Two examples of high-current operation at a constant laser power at the PKA2. The extracted current (left) and the integrated charge (right) are plotted as a function of time. The solid lines correspond to one dataset, the dashed lines to another. The jump in the blue dashed line is caused by the adjustment of the laser power to extract more charge. In both cases, a total charge of approximately 700 C was extracted. The solid red line decays with a time constant of $\tau_{hc} = 5.5$ d.

such as IBB cause the degradation of the QE, and so the decay of the current has a fast and a slow time constant. If the red solid line is fitted by an exponential decay function, it has a time constant of $\tau_{hc} = 5.5$ d.

The MAGIX experiment at MESA is designed to be operated at $1 \text{ mA} \triangleq 3.6 \text{ C/h}$ in stage-1 and $10 \text{ mA} \triangleq 36 \text{ C/h}$ in stage-2. With 700 C set as a start value, the PKA2 can deliver beam for 200 h in stage-1 and for almost 1 day in stage-2.

The results of high-current operation of the PKA2 lead to the conclusion that the source is able to deliver a stable and sufficient photoemission current. However, there remains the question whether the transverse beam quality fits the requirements of the accelerator, which is discussed in the next section.

6.2. Emittance measurements

The properties of the transverse phase space will be determined with two different emittance measurement techniques. The first method is a quadrupole scan, which is a standard technique at the Institute of Nuclear Physics. To check if space charge forces disturb this technique, slit mask measurements will also be performed. In all following pictures, the produced bunch charge is replaced by an equivalent average current which corresponds to c.w. operation.

6. Experiments and results

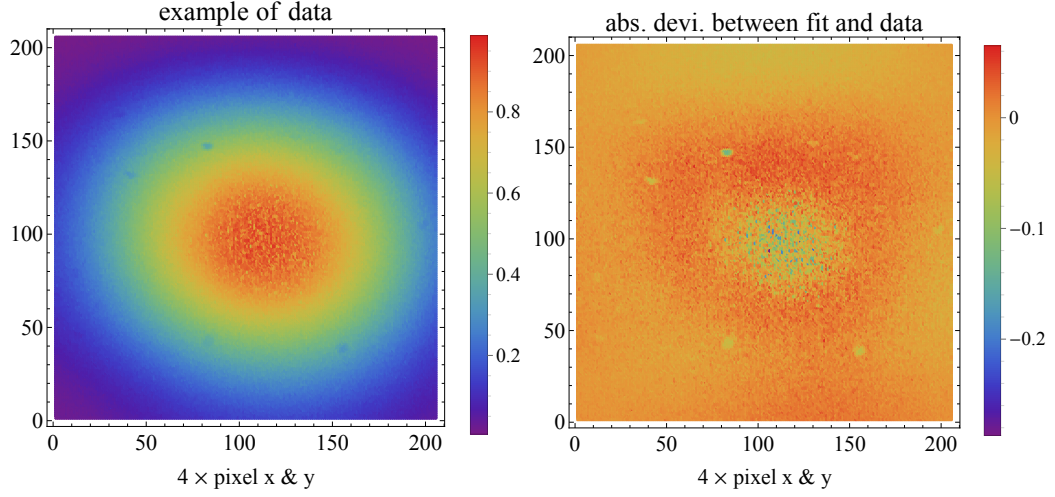


Figure 6.3.: The figure illustrates an example of the normalized intensity distribution of the electron beam obtained by a CMOS camera (left) and the absolute deviations between the normalized data and the fit function.

6.2.1. Quadrupole scan

If the squared RMS beam dimensions $\sigma_x^2 = \beta_T \epsilon_x = m_{11}$ are plotted over different k values, Eq. 2.17 and Eq. 2.18 can be fitted to these data to extract the Twiss parameters for the emittance calculation. In all quad scan emittance measurements, the k value is varied in 42 steps, and so for both planes, 21 data points are available, respectively. In Fig. 6.3, an example of the normalized electron beam intensity distribution obtained by a CMOS camera is depicted on the left. On the right, the absolute deviation between the normalized data and the fit function used is given. Most of the image shows only a slight deviation, except some spots that might be caused by dust particles on the vacuum viewport.

In Fig. 6.4, three exemplary results of the squared RMS beam dimension for electron currents of $32\ \mu\text{A}$, $110\ \mu\text{A}$, and $1005\ \mu\text{A}$ are plotted over the quadrupole parameter k . For each dataset, the beam dimensions used for the fit are obtained using a 2D Gaussian fit to the measured intensity distribution (shown on the right in Fig. 6.5), and for the sake of comparison, using a 1D Gaussian fit to the projections of the same distribution (shown on the left in Fig. 6.5). During the quadrupole scan, the attenuator in front of the CMOS camera was shifted to a higher value when the k parameter came close to a waist, and behind the waist, this change was revoked. The change in the attenuation was implemented to increase the dynamic range of the measurement. The fit functions become steeper with increasing current, but the dimension in the focus does not vary as much. The RMS dimensions calculated with the projections are about 1% to 2% larger than the ones estimated with the 2D Gaussian function.

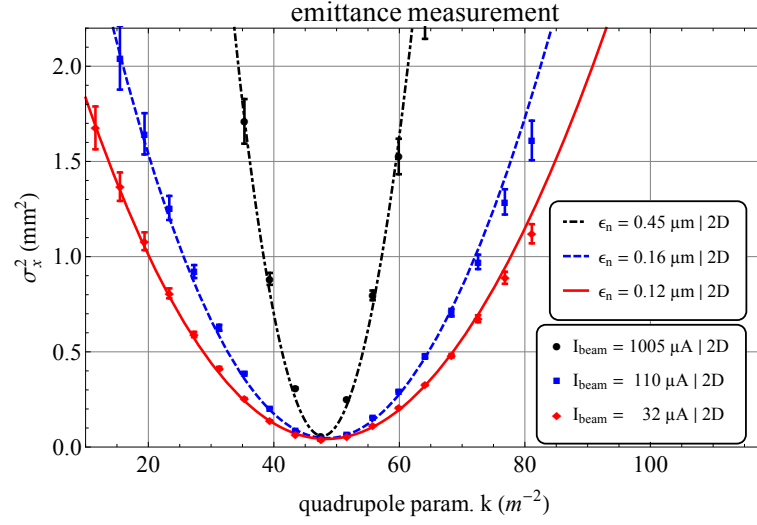


Figure 6.4.: Example of the extracted squared beam diameter in one plane for the electron currents 32 μA , 210 μA , and 1005 μA plotted over k . For each dataset, the beam diameters used for the fit are obtained using a 2D Gaussian fit to the measured intensity distribution. The resulting emittances are indicated in the legend.

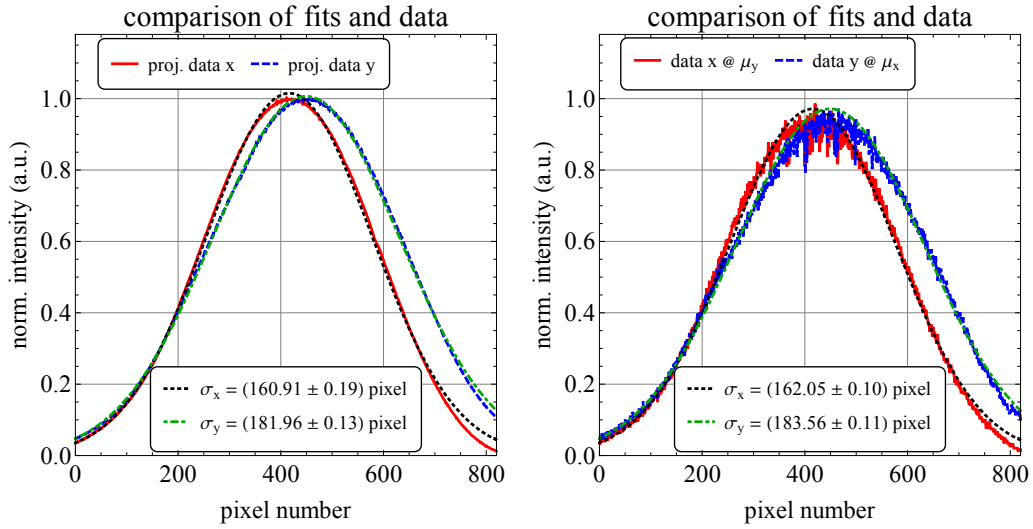


Figure 6.5.: The plot on the left shows the projected data and a comparison with the fit functions. On the right, the same is illustrated for the data presented in Fig. 6.3 with their corresponding fit function.

6. Experiments and results

Especially at higher currents, it is possible that the beam dimensions increase very fast next to the waist and become larger than the screen, distorting the determination of the dimension. The fast increase of the beam size is most likely caused by the space charge dominance presented in Fig. 2.15. Thus, the influence of the number of data points taken into account to calculate the emittance was investigated with a selection of the data sets, showing that the beam size squared should not cover more than one order of magnitude because otherwise, the fitted functions Eq. 2.11 and Eq. 2.12 do not describe the data close to the focus reliably.

6.2.1.1. Screen measurements

Before the quad scans can be performed, the scale factor ($\mu\text{m}/\text{pixel}$) on the screen has to be determined. This is done by moving the sled in defined steps and observing a significant structure such as an edge. For each step, a picture is taken and subsequently analyzed. Fig. 6.6 shows on the left side an example of how the pixel position of the edge moves for each step of the sled. By fitting a linear equation to the data, the optical resolution of the camera system can be extracted. This is done for each available attenuator (none, OD06, OD13, OD20, OD25, OD30) in front of the CMOS camera because the distance to the screen is varied a little to compensate for their optical thickness. The left part of Fig. 6.6 also demonstrates that the variation of the distance does not influence the optical resolution by more than 0.6%, which can be seen by comparing the slopes of the linear fits indicated in the legend. On the right side of Fig. 6.6, the corresponding inverse of the slopes ($\mu\text{m}/\text{pixel}$) is plotted for all attenuators. Thus, the resolution is $5 \mu\text{m}/\text{pixel}$ for all attenuators.

The analysis of each picture is done with a commercial mathematical program^b by fitting a 2D Gaussian equation to the pixel matrix and fitting two 1D Gaussian equations to the projections of the beam profile to the horizontal and vertical plane, respectively. In general, the resulting beam dimensions of the analyzed projections are about 1% to 2% larger than the corresponding values of the 2D Gaussian fit. Thus, the results presented here are based on the values of the projected distributions.

The emittance measurement is done for different electron currents and different laser beam spot sizes on the photocathode. Experiments on the pulsing behavior of the laser diodes have shown that these depend on the laser diode current. Because of this, the laser power on the photocathode is varied by changing attenuators in the laser beam line rather than through a variation in the laser diode current to ensure that the pulse profile is the same for each electron current produced. The laser spot size on the photocathode is adjusted by the telescope in the optical beam line, which is introduced in Sec. 5.2. Fig. 6.7 shows the dimensions of the used laser spot sizes for the blue and the green laser diodes. These spot sizes will be called “small”, “medium” and “big” in the further text.

^bWolfram Mathematica

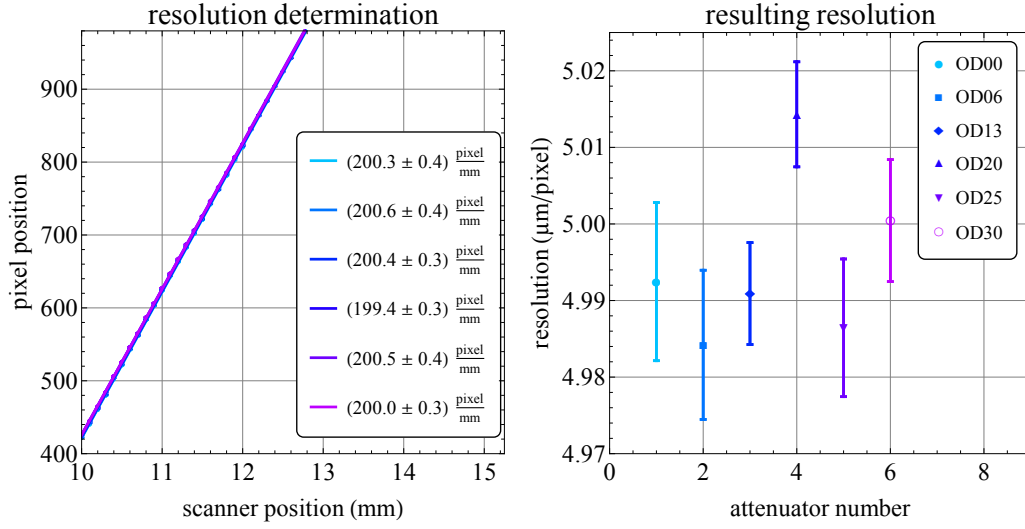


Figure 6.6.: The left plot shows an example of the resolution determination on the screen for all attenuators (none, OD06, OD13, OD20, OD25, OD30). During such a measurement, the sled is moved in steps of $100 \mu\text{m}$, and with each step, the pixel value increases by about 20 pixels, resulting in a slope of approximately $200 \text{ pixel}/\text{mm}$. In the right plot, the resolutions for all attenuators are compared with each other, and the central values scatter by about $5 \mu\text{m}/\text{pixel}$.

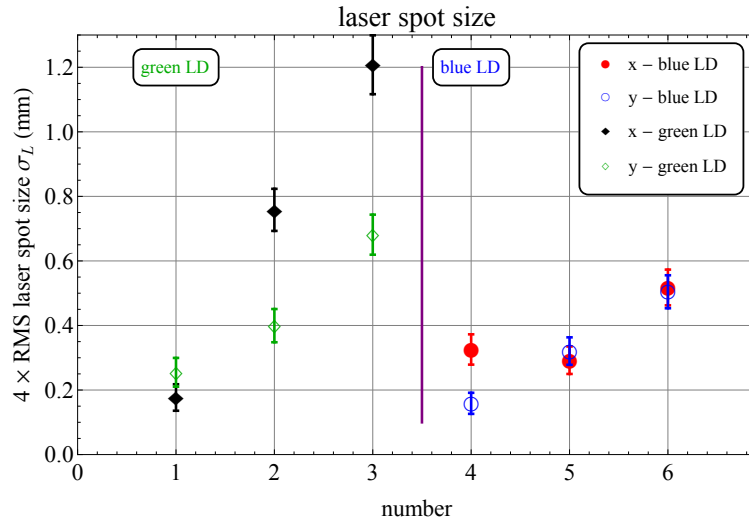


Figure 6.7.: Dimensions of the laser spot size with the blue and green laser diodes used.

6. Experiments and results

Table 6.1.: Resulting slopes of the emittance measurement.

	SLS	MLS	BLS
blue laser (x)	$(0.793 \pm 0.040) \frac{\mu\text{m}}{\text{mA}}$	$(0.342 \pm 0.007) \frac{\mu\text{m}}{\text{mA}}$	$(0.254 \pm 0.010) \frac{\mu\text{m}}{\text{mA}}$
blue laser (y)	$(0.377 \pm 0.021) \frac{\mu\text{m}}{\text{mA}}$	$(0.190 \pm 0.005) \frac{\mu\text{m}}{\text{mA}}$	$(0.125 \pm 0.006) \frac{\mu\text{m}}{\text{mA}}$
green laser (x)	$(0.832 \pm 0.013) \frac{\mu\text{m}}{\text{mA}}$	$(0.451 \pm 0.009) \frac{\mu\text{m}}{\text{mA}}$	$(0.303 \pm 0.009) \frac{\mu\text{m}}{\text{mA}}$
green laser (y)	$(0.386 \pm 0.029) \frac{\mu\text{m}}{\text{mA}}$	$(0.220 \pm 0.006) \frac{\mu\text{m}}{\text{mA}}$	$(0.134 \pm 0.026) \frac{\mu\text{m}}{\text{mA}}$

Furthermore, two different wavelengths were used to check their influence on the emittance. The two laser diodes show different pulsing behavior as illustrated in Fig. 5.9, and thus, these measurements allow to measure the influence of the pulse shape on the emittance growth for higher bunch charges.

On the top of Fig. 6.8, the resulting normalized emittances for the blue laser diode are presented for three different laser spot sizes and plotted over an equivalent c.w. electron current. The plots on the left side correspond to the x dimension and the right ones to the y dimension of the electron beam.

The visualized results show that the increase in emittance for higher electron currents depends on the laser spot size used. In the case of the smallest laser spot size, the growth in emittance starts below 0.1 mA. The slope is around $0.79 \mu\text{m}/\text{mA}$ for the x dimension and $0.38 \mu\text{m}/\text{mA}$ for the y dimension. The emittance values for the two highest currents seem to have an additional systematic error because they give the impression that something like a saturation effect occurs, and this cannot be explained physically. It could be that the electron beam was not well aligned on the screen. This could have an influence on the extraction of the beam dimension. Thus, these values are not taken into account for the determination of the slope. For the medium sized laser spot, the emittance also stays stable up to 0.1 mA, and after that, it starts to rise with a slope of $0.34 \mu\text{m}/\text{mA}$ for x and $0.19 \mu\text{m}/\text{mA}$ for y. The big laser spot also shows equal emittance values up to 0.1 mA and increases at higher currents with a slope of $0.25 \mu\text{m}/\text{mA}$ for x and $0.13 \mu\text{m}/\text{mA}$ for the y dimension. The slopes of the blue and the green laser diode have an error below 8% and are summed up in Tab. 6.1.

Fig. 6.8 also shows an increase in the extracted current with increasing spot size using the same laser power, which hints at the current limit in the gun being affected by space charge. This is caused by the resulting electric field from the electrons on the surface of the photocathode that shrinks the accelerating field on the surface. If the electron density on the surface is decreased by increasing the laser spot size, this phenomenon shifts to higher currents. For example, the maximum extracted current for the small laser spot is 1.6 mA and for the big spot 2.8 mA. Not only the spot size has an influence on the maximum extractable current, but also the electric field in the gun, the field strength on the surface, and for sure, the QE. This conclusion is independent of the wavelength and is also valid for the green laser diode. Eq. 3.2 supports this statement.

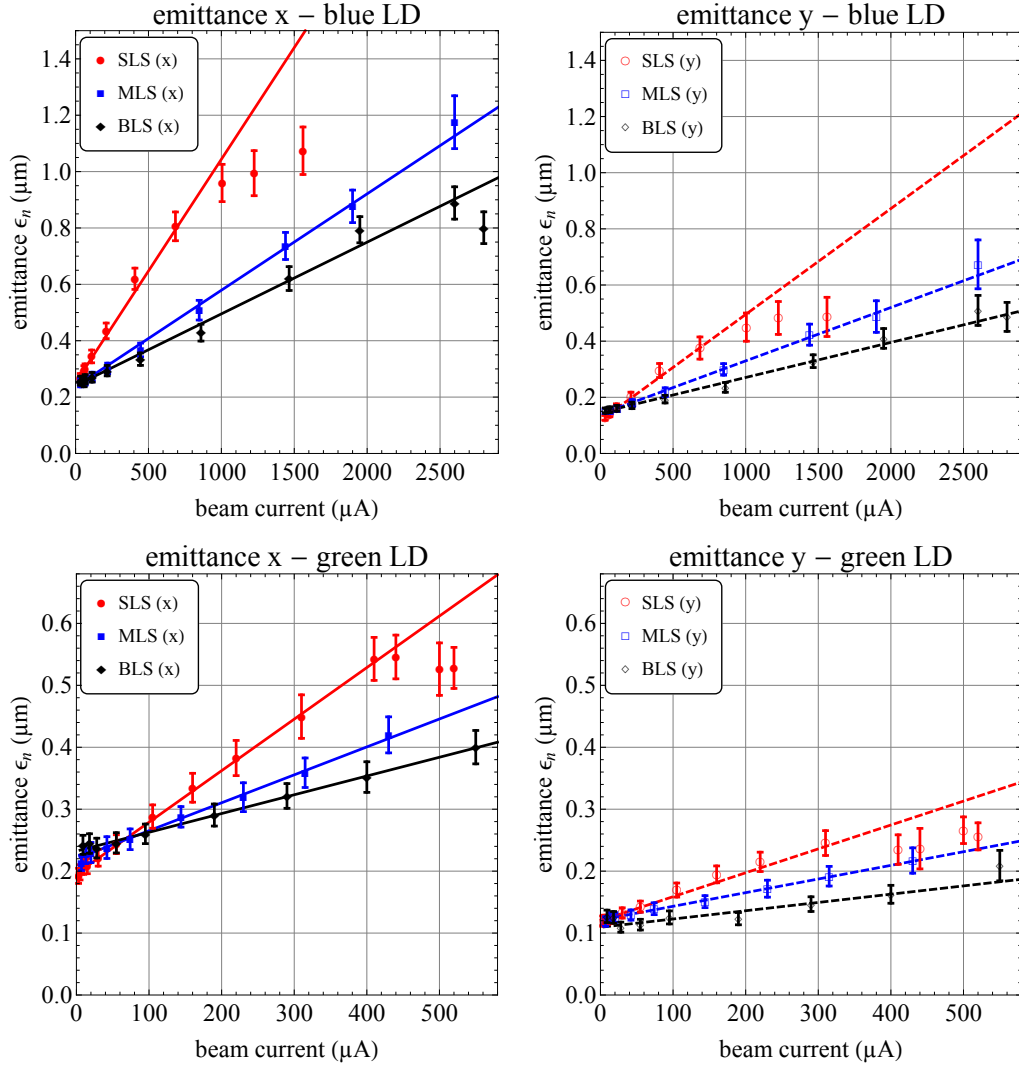


Figure 6.8.: The top visualizes the current-dependent emittance of the blue laser diode for three different laser beam spot sizes (SLS - small laser spot; MLS - medium laser spot; BLS - big laser spot). On the bottom, the same is shown for the green laser diode. The results of the x and y dimension of the electron beam are shown with the solid and the dashed lines, respectively.

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On the bottom of Fig. 6.8, the results of the normalized emittance for the green laser diode are presented. In comparison with the top of Fig. 6.8, it is conspicuous that the maximum current is below 0.6 mA. This is caused by the fact that the QE is wavelength dependent, i.e. it decreases with decreasing photon energy (see Fig. 3.6). Moreover, the maximum laser power is lower than for the blue laser diode (see Fig. 5.6). The latter can be compensated for by using a different laser diode driver which provides a higher maximum laser diode current. The analysis of the quad scan results leads to the same conclusion as with the blue laser diode. Also the smallest laser spot size causes the highest slope of $0.83 \mu\text{m}/\text{mA}$ and $0.39 \mu\text{m}/\text{mA}$ as it is shown in Tab. 6.1. The slopes of the medium laser spot size are around $0.45 \mu\text{m}/\text{mA}$ and $0.22 \mu\text{m}/\text{mA}$ for the x and the y dimension, respectively. In the case of the big laser spot size, the values are halved with respect to the small laser spot size: for the x dimension, the slope is $0.30 \mu\text{m}/\text{mA}$, and for the y dimension it is $0.13 \mu\text{m}/\text{mA}$.

The difference in the slopes for the x and the y dimensions is caused by the laser spot size on the photocathode having an elliptical shape as illustrated in Fig. 5.10 and Fig. 6.7. One reason for the plateau in the emittance below 0.1 mA is that the electrodes of the electron gun are designed in such a way that peak currents up to 1 mA have no influence on the emittance. Moreover, in this electron current region, space charge forces are negligible (see left plot in Fig. 6.16).

Unfortunately, the sleds can rotate around the moving direction inside the scanner chamber owing to its mechanical construction, but this will be improved in the new versions of the analyzing stages planned at MESA. This rotation can cause restrictions on the optical resolution, which can influence the minimum observable spot size on the screen.

The emittance design value for MESA is $< 1 \mu\text{m}$, and the investigations at the PKA2 have shown that this can be reached with all spot sizes used up to a current of 1 mA using the blue laser diode. An extrapolation of the values for the green laser diode would also lead to the conclusion that also all laser spot sizes can satisfy the requirements of MESA stage-1. However, the medium laser spot size is more recommendable. Larger spot sizes can interfere with the handling of the beam line, and it could be possible that the losses of electrons in sections with small apertures become non-negligible.

6.2.1.2. Wire measurements

In Sec. 4.1.1, the occupancy of the analyzing stages was introduced. In addition to the screens, the sleds are equipped with tungsten wires with a diameter of $40 \mu\text{m}$. Scanner 1 and scanner 2 each contain three wires in total, two of which are oriented perpendicularly to each other, and the third one is mounted at 45° with respect to the previous one. The orientation of the wires to each other and an example of the resulting and analyzed signals are illustrated in Fig. 6.9 on the right and left side, respectively. The purpose of these three wires is to determine the beam profile on the x and y axis and the correlation between both. The overall orientation of the

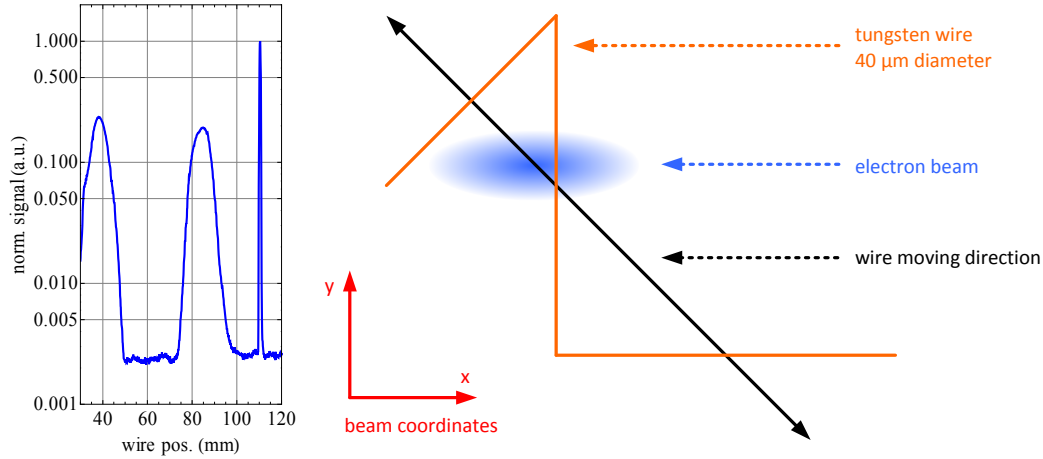


Figure 6.9.: Determination of the electron beam size with wires. On the right, the orientation of the wires with respect to the electron beam is visualized. The moving direction of the electrons is into the paper plane. Electrons that are stopped by the wire create Bremsstrahlung photons which are detected outside the vacuum chamber with a scintillator PMT configuration. On the left, a typical signal of such a measurement is plotted over the wire position.

wires with focus on the main axes of the electron beam is implemented in such a way that the scanner device has to move at an angle of 45° relative to the axes. This fact can also be extracted from Fig. 4.2 where the occupancy of the sleds is illustrated. Unfortunately, the scanner devices could not be mounted at 45° with respect to the beam axes due to the lack of space and the fact that—especially for scanner 1—the support structure for the PKA2 prevents this intention. The orientation of the scanner devices is taken into account in the design of the support structure for STEAM and MELBA.

To check the results from the screen quad scan measurements, an additional quad scan—with the same method as described in Sec. 2.3—has been performed, in which the beam size was obtained with a scintillator PMT configuration. In Sec. 4.3, the optimum position for the X-ray detector was determined. The discussed experiment was conducted with an electron current of $I_{\text{beam}} = 1 \mu\text{A}$. For this quad scan measurement, the scanner device was moved in steps of 0.1 mm, and the signal from the PMT was recorded along with the corresponding position for each quadrupole setting. This procedure was carried out with multiple values of k . In general, the scanner moved 90 mm in total, and at each position, five measurements were taken. The current from the PMT is fed into the control system by an IUFC.

Due to the misalignment of the scanner device mentioned above, it was only possible to analyze one axis of the beam. In Fig. 6.10, the normalized intensity signals from the beam distribution obtained with the scintillator PMT configuration are plotted over the sled position (x axis) for the adjusted k values (z axis) of the quadrupole. The illustrated data show how the beam dimension changes over the

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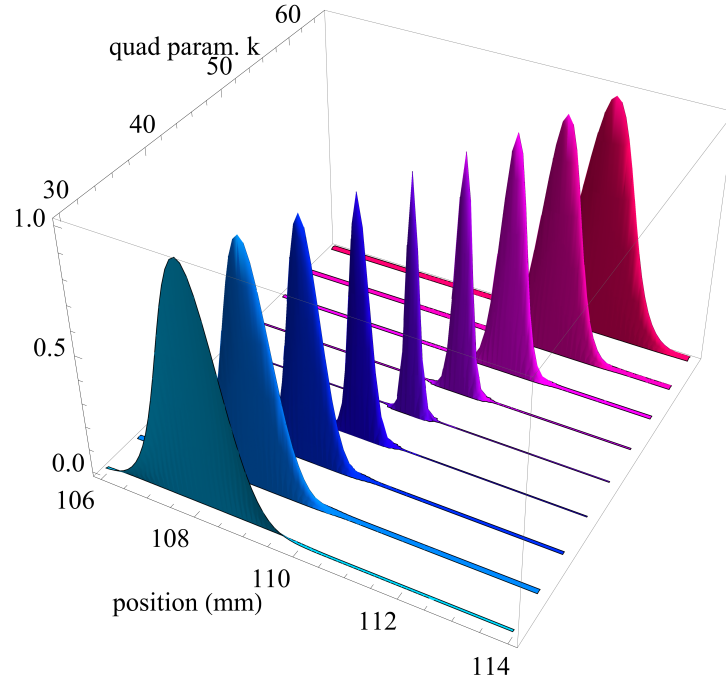


Figure 6.10.: Normalized intensities of the beam profile plotted over the sled position (x axis) for different k values (z axis) obtained with the scintillator PMT configuration. The data show how the profile in the x axis changes during a quad scan. The profiles are shifted along the x axis for a clearer perspective.

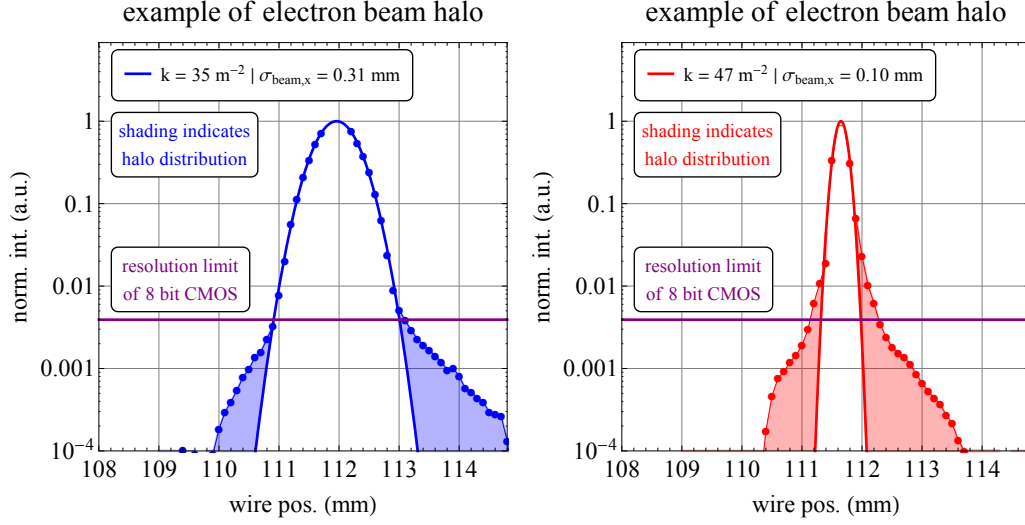


Figure 6.11.: The plots visualize the dynamic range of a beam size determination via the wires for two different quad settings. Dependent on the focus strength k , the intensity distribution starts to differ from a Gaussian distribution below 1% in the left plot and 10% in the right plot. The beam halo—which lies outside the Gaussian distribution—is indicated with the colored shading. Especially the case illustrated in the left plot is difficult to determine with an 8 bit CMOS camera.

performed quad scan. One of the benefits of a PMT measurement, namely the higher dynamic range in comparison to a screen measurement, is not obvious in this picture. But in a logarithmic representation, this fact comes across much more clearly. Apart from a very high amplification of up to 10^6 , PMTs also have a very broad dynamic range in combination with a well chosen DAQ^c in the order of $10^4 - 10^5$, whereas CCD or CMOS cameras in general only have 8 bits = 256. The plots in Fig. 6.11 visualize the dynamic range of a beam size determination via the wires for two different quad settings. Dependent on the focus strength k , the intensity distribution starts to differ from a Gaussian distribution below 0.8% in the left plot and 7% in the right plot. The intensity distribution which lies outside the Gaussian distribution is known as beam halo. Especially in cases like the one illustrated in the left plot, it is difficult to determine a beam halo with an 8 bit CCD or CMOS camera.

Regardless of the size of the beam dimensions measured using the wire-based technique, for the subsequent calculations the wire diameter ($\sigma_{\text{wire}} = 40 \mu\text{m}$) is subtracted from the measured values by performing a deconvolution. Since the wire cannot be considered Gaussian, a detailed deconvolution has to be performed.

The electron beam dimensions were extracted from the data shown in Fig. 6.10, squared afterwards and plotted over the k parameter of the quadrupole to deter-

^cDAQ - data acquisition

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mine the normalized emittance ϵ_n . For a direct comparison between the wire and the screen measurement, the same experiment was repeated. This time, the beam distribution was taken with a screen and a CMOS camera. The data points on the left side in Fig. 6.12 illustrate the values for both measurement methods. Now Eq. 2.17 can be fitted to the data to get values for the m_{ij} parameters. Subsequently, the emittance can be determined using the m_{ij} by inserting them into Eq. 2.3. For the wire measurement, the normalized emittance is $\epsilon_n = 0.05 \mu\text{m}$ and for the screen measurement $\epsilon_n = 0.19 \mu\text{m}$. Thus, the screen measurement yields an almost four times higher emittance than the wire measurement. This discrepancy is mainly caused by the difference in the beam dimensions at the focus. Comparing the two fit functions, it is apparent that while the screen values are generally higher, the shapes of the curves are about the same. This statement should not mean that the camera-based data acquisition is more uncertain in general because in former experiments smaller beam dimensions ($\sigma_{\text{beam}} \simeq 150 \mu\text{m}$) have been measured. Instead, the conclusion of this comparison should be that the camera-based measurement method is influenced by the alignment of the camera to the screen, whereas the wire-based technique is not because the position of the X-ray detector affects only the height of the signal and not the shape. In addition, on the right side of Fig. 6.12 is illustrated a comparison of the resulting emittance ellipse for the screen and wire measurements at the entrance of the quadrupole. Both ellipses have a similar orientation, but the one of the screen measurement is larger. This is caused mainly by the beam dimension at the focus.

The emittance depends on the laser spot size, which is a fundamental property. Unfortunately, this does not become clear in the screen emittance measurements presented in Fig. 6.8. To ensure that the fit function used (Eq. 2.17) delivers proper results, additional quad scans were performed and the electron beam dimension was obtained with the wire-based method. These emittances show an approximately linear dependence on the spot size used, which is illustrated in Fig. 6.13. This confirms that the diagnostic tools and the analyzing method are able to reproduce the expected physical behavior. A comparison with the results presented in [Baza08] shows that the wire-based measurements are about 17% to 22% smaller than the results from Eq. 3.5. One reason for this discrepancy is that the thermal emittance depends on the QE of the photocathode. The measurements presented in Fig. 6.13 had a two times higher QE than the photocathodes used in [Baza08].

6.2.1.3. Conclusions concerning the emittance measurements via quadrupole scan

Comparing the screen-based and the wire-based emittance measurements presented in Fig. 6.12, there is a discrepancy between both methods. Furthermore, the emittance results given in Fig. 6.8 do not show the behavior predicted by Eq. 3.5, namely a proportional increase in emittance with increasing laser spot size used. This effect should be mainly visible when small electron currents are used.

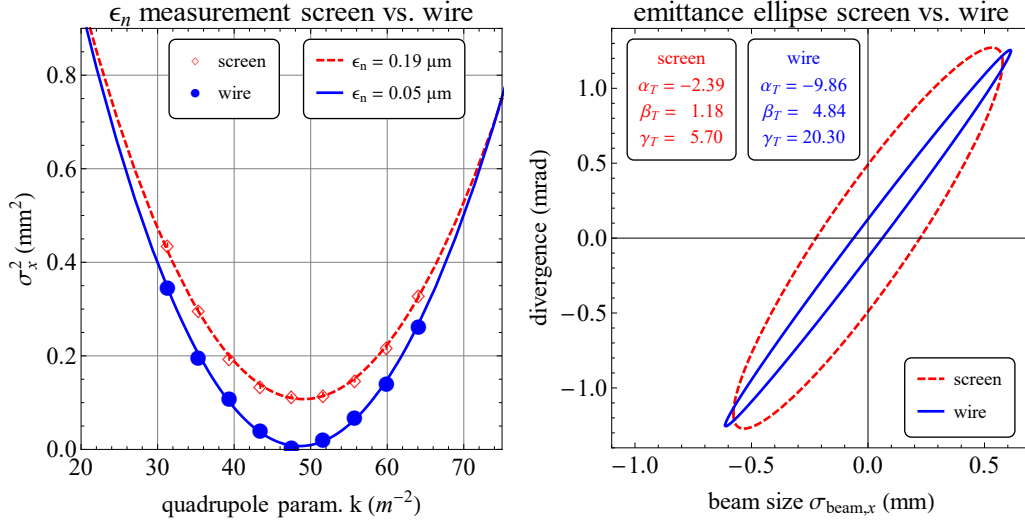


Figure 6.12.: The plot on the left shows the extracted and squared beam dimensions for the wire and the screen measurements plotted over the k parameter of the quadrupole. Additionally, Eq. 2.11 is fitted to both pairs of data sets and the resulting ϵ_n is presented in the legend. On the right, the shape and orientation of the corresponding emittance ellipses are illustrated in the (x, x') phase space.

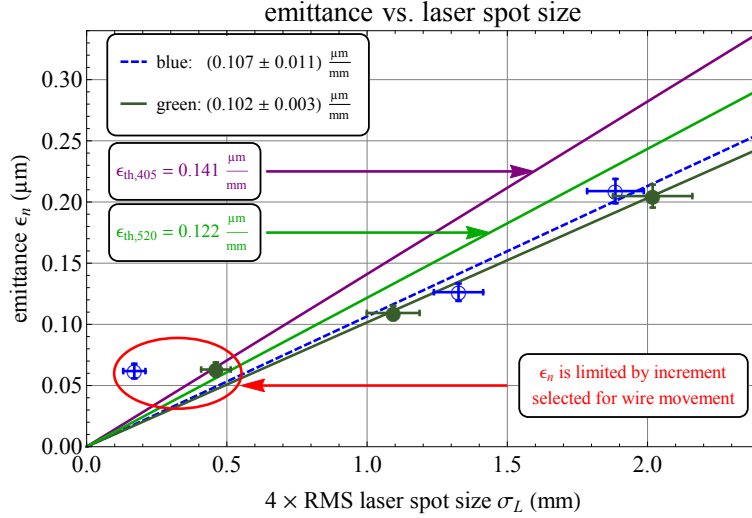


Figure 6.13.: The plot illustrates the emittance for all three laser spot sizes and for the blue and green laser diode, respectively. A linear fit is also included, and the slope is presented in the legend. These results confirm that the diagnostic tools and the analyzing method are able to reproduce the expected physical behavior. In addition, the results from [Baza08] are included in the plot which are calculated via Eq. 3.5.

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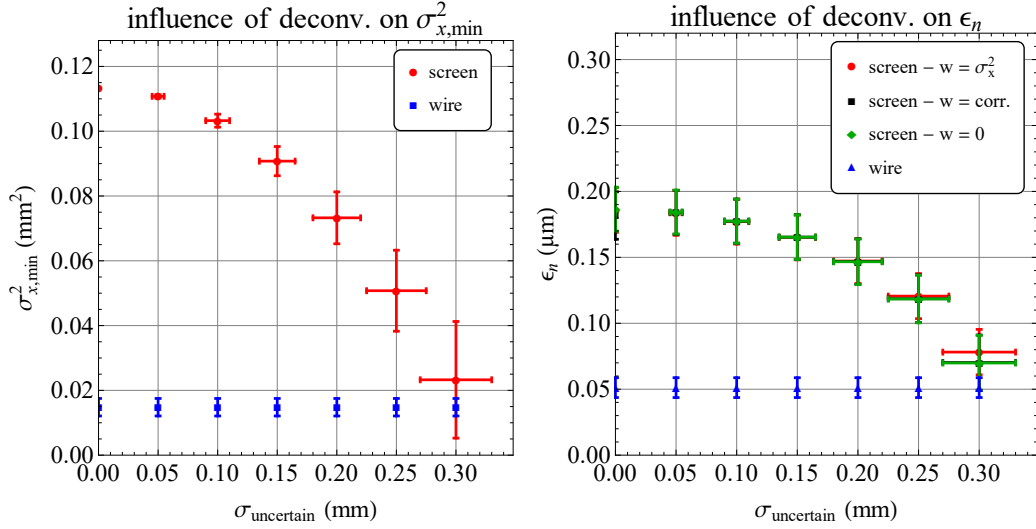


Figure 6.14.: Both plots illustrate the influence of an piecewise increase of the amount that is used in the deconvolution. On the left, this is presented for the squared beam size, and on the right, for the resulting emittance. As the fraction taken into account in the deconvolution increases, so does its dominance with respect to the error of the data points.

One reason for such a discrepancy could be that the screen was outside the focal plane of the CMOS camera. From the left plot in Fig. 4.11, it can be extracted that the Rayleigh length for the $f/\#$ of the imaging lens used yields small values ($z_R \simeq 1.5\text{ mm}$). Since the sled of the scanner device can also move in a direction other than the desired one, a shift in the range of a few millimeters can easily occur. To determine the increase in beam size obtained by the CMOS camera when the screen has moved out of the focal plane, Eq. 4.4 is used. An offset of 1 mm, 3 mm or 4.5 mm results in a 20%, 124% or 216% larger beam size, respectively. Due to the results illustrated on the right side in Fig. 4.11, it seems possible to observe similar small beam sizes compared to the wire-based measurements using the CMOS camera.

The manner in which the misalignment affects the beam size can be treated as additional uncertainty, such as electron scattering within the Ce:YAG screens, and this allows the effect to be deconvolved by applying:

$$\sigma_{\text{real}} = \sqrt{\sigma_{\text{meas}}^2 - \sigma_{\text{uncertain}}^2}$$

This simplification of a deconvolution is done because both distributions are Gaussian like. The effects of deconvolution on the emittance are illustrated by the comparison between the screen-based and the wire-based measurement that is depicted in Fig. 6.12. The left plot in Fig. 6.14 shows the influence of an increasing amount deconvolved from the beam size obtained by the CMOS camera at the k value corresponding to the focus. For the sake of comparison, the plot on the left in

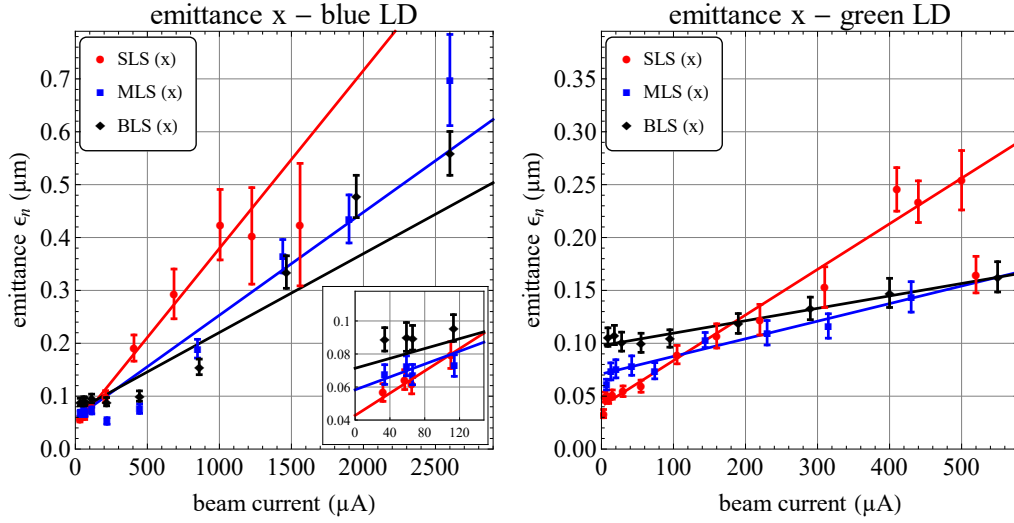


Figure 6.15.: Both plots show the emittance results after deconvolution of an additional effect for the blue (left) and the green laser diode (right), respectively. Since the wire-based emittance measurement only works in one dimension, only the emittances corresponding to this axis are depicted here.

Fig. 6.14 also contains the smallest beam size determined by the wire-based technique. In order to get the beam sizes of the wire measurements, the deconvolution must be performed with similar numbers as the actual beam size. This leads to an increase in the error of the data points.

The right plot in Fig. 6.14 illustrates the effect of the deconvolution on the emittance. In addition to the emittance value of the wire measurement, which serves as comparison value, the plot contains three more emittance values. For each emittance value the weighting of the data points is changed. The different weighting methods are defined as follows:

- weighting factor is equal to σ_x^2 . This corresponds to the largest possible uncertainty.
- weighting factor is determined using the Gaussian error propagation. This represents the mathematically correct approach.
- without weighting of the data points

Examinations related to stable outcomes of the fitting algorithm have indicated that some emittances become negative due to the weighting method used. Especially for the small beam dimensions close to the focal plane, the error of a data point can be up to twice its value. In the case visualized on the right in Fig. 6.14, the weighting methods do not have much impact on the emittance result. Rather, it looks like the emittance will remain largely unaffected by the weighting method chosen.

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In Fig. 6.14, the amount that should be considered in the deconvolution to get similar results compared to the wire-based emittance measurement was determined. Next, this approach can be applied to the emittance results presented in Fig. 6.8. The emittance determination based on the wire measurements only works in one dimension, and because of this, the influence of the deconvolution will be calculated only for this axis. The results are illustrated in Fig. 6.15 for the blue and the green laser diode, respectively. By applying this correction method, all emittances have become smaller. In addition, the emittance values related to small beam currents now also show the behavior predicted by Eq. 3.5.

6.2.2. Slit mask measurements

In the previous section, the emittance was determined by a quad scan. Since space charge forces can disturb these measurements, the experiments were repeated with a slit mask, and the results will be introduced in this section. The slit mask measurement technique is based on cutting out one or more small beamlets out of a beam distribution. This measurement technique has the advantage that if the initial electron bunch is space charge-dominated, the beamlets behind the slit mask will be emittance-dominated if the mask is well optimized.

For the optimization process, there are several formulas available, and a selection of them are presented in [AnRo02]. With the equation

$$R_{\text{beam}} = \frac{I_{\text{beam,max}} \sigma_{\text{beam}}^2}{2 I_{\text{Alfven}} \gamma_L \epsilon_n^2}, \quad (6.1)$$

the degree of space charge dominance of the incident beam can be calculated. The parameter I_{Alfven} is the characteristic or Alfven current and is defined as $I_{\text{Alfven}} = \frac{4\pi\epsilon_0 m_e c^3}{q_e} = 17\beta_L \gamma_L \text{ kA}$ [Reis08], γ_L indicates the Lorentz factor, and $I_{\text{beam,max}}$ is the peak current within the electron bunch. Values for R_{beam} greater than 1 indicate the presence of space charge, and values less than 1 mean emittance is dominating. In the left plot of Fig. 6.16, the space charge/emittance ratio is calculated over a peak current range of $(0.1 \leq I_{\text{beam,max}} \leq 50) \text{ mA}$ and an estimated normalized emittance of $(0.15 \leq \epsilon_n \leq 1.5) \mu\text{m}$. Here it can be seen that the incident beam becomes space charge-dominated in the lower half of the parameter space. Values less than one where emittance is dominant are indicated in white. This also confirms the calculations presented in the lower row of Fig. 2.15. In addition, the beam parameters investigated by the experiments carried out in this thesis are marked via an ellipse. Furthermore, it is possible to calculate the same space charge emittance ratio for the beamlets behind the slit mask via

$$R_{\text{mask}} = \sqrt{\frac{2}{3\pi}} \frac{I_{\text{beam,max}}}{\gamma_L I_{\text{Alfven}}} \left(\frac{\sigma_{\text{slit}}}{\epsilon_n} \right)^2. \quad (6.2)$$

This ratio is plotted over the same range of current and emittance as for the incident beam and is shown in Fig. 6.16 on the right side. The investigated beamlets are emittance-dominated because all values are below one.

In [AnRo02] several parameters are given to optimize the slit mask, namely:

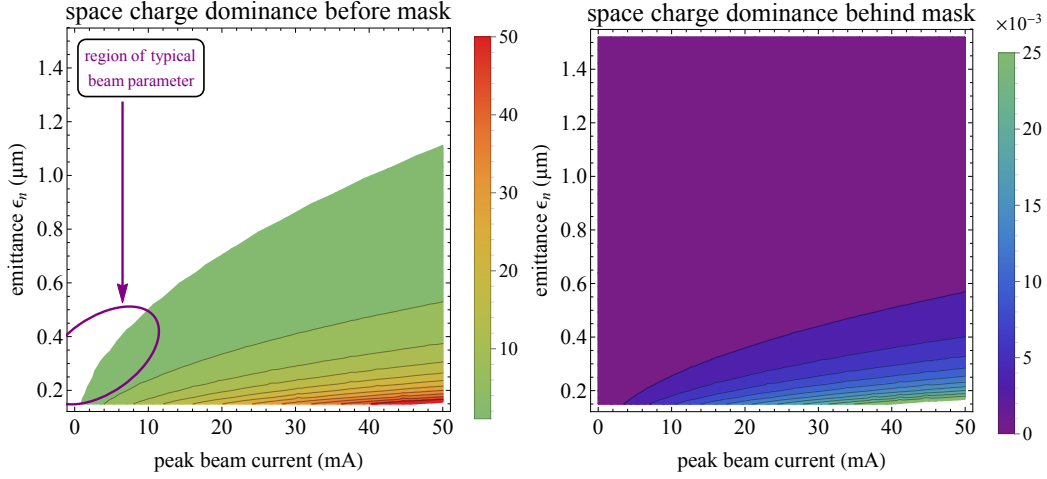


Figure 6.16.: Plots of the ratio between space charge and emittance for the incident beam (left) and for the analyzed beamlets behind the mask (right). The white area in the left plot visualizes values below one and indicates the dominance of emittance. For an emittance of about $0.6 \mu\text{m}$, the influence of space charge becomes dominant above a peak current of approximately 14 mA. The beam parameters investigated by the experiments is marked via the purple ellipse. The beamlets behind the mask are dominated by emittance in the whole plotted parameter space.

- angular acceptance: $R_{\text{angular}} = \frac{2d_{\text{mask}}}{\sigma_{\text{slit}}} \frac{\epsilon_n}{\sigma_{\text{beam}}}$
- beamlet separation: $R_{\text{separate}} = 2 \frac{d_{\text{drift}}}{d_{\text{slit}}} \frac{\epsilon_n}{\gamma_L \sigma_{\text{beam}}}$
- space charge dominance: $R_{\text{sc}} = \frac{2I_{\text{beam,max}}}{I_{\text{Alfvén}} \gamma_L^2 \epsilon_n} \frac{\sigma_{\text{slit}} d_{\text{drift}}}{d_{\text{slit}}}$

With the following parameters of the slit masks used:

- beam size: $\sigma_{\text{beam}} = 1 \text{ mm}$
- slit width: $\sigma_{\text{slit}} = 0.025 \text{ mm}$
- slit spacing: $d_{\text{slit}} = 0.25 \text{ mm}$
- thickness of the mask: $d_{\text{mask}} = 0.05 \text{ mm}$
- drift length: $d_{\text{drift}} = 19.6 \text{ mm}$

The results of these three optimization parameters are summed up in Tab. 6.2 for three different emittances and the maximum assumed peak current of $I_{\text{beam,max}} = 0.05 \text{ A}$, which corresponds to MESA stage-2. The results demonstrate that all requirements can be met.

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Table 6.2.: Results of the optimization parameter of the slit mask geometry.

	$\epsilon_n = 0.1 \mu\text{m}$	$\epsilon_n = 0.3 \mu\text{m}$	$\epsilon_n = 0.7 \mu\text{m}$
$R_{\text{angular}} (\ll 1)$	0.4×10^{-3}	1.2×10^{-3}	2.8×10^{-3}
$R_{\text{separate}} (\ll 1)$	13.2×10^{-3}	39.7×10^{-3}	92.7×10^{-3}
$R_{\text{sc}} (\ll 1)$	81.5×10^{-3}	27.2×10^{-3}	11.6×10^{-3}

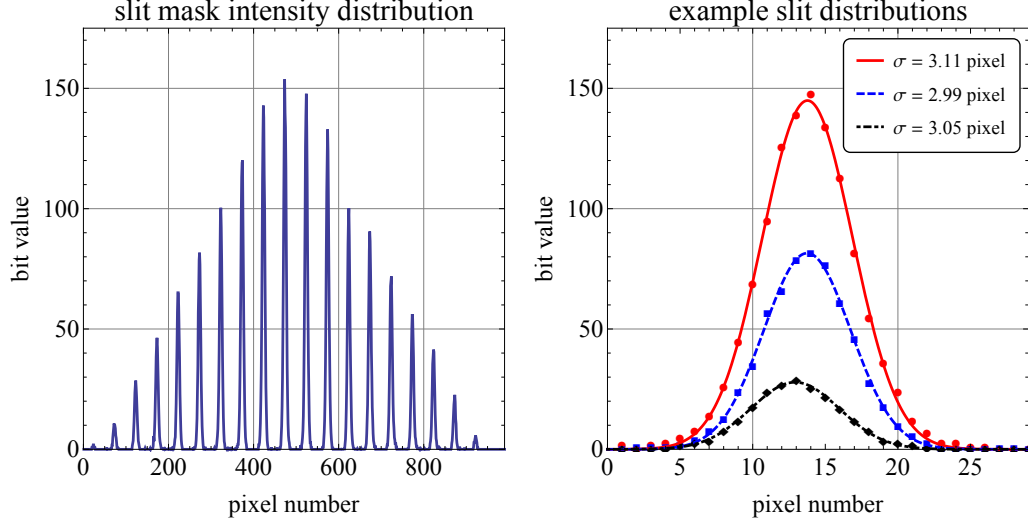


Figure 6.17.: On the left side, a line scan through the intensity distribution behind the slit mask on the screen is shown. The graph on the right side zooms in on three different peaks from the distribution shown on the left side with their Gaussian fit functions. Note that the pixel values are shifted to display the different slit distributions in the same graph.

For the slit mask measurements, pictures with 1200×1200 pixels are taken with a 5MP CMOS camera^d, and a line scan through such a picture is shown on the left side of Fig. 6.17 as an example. The number of pixels used is caused by the fact that the camera distance to the screen is also used for the quadrupole scan where the dimensions of the observed intensity distribution are much larger than the $(5 \times 5) \text{ mm}^2$ of the slit mask. For the analysis, the picture is trimmed to the region of interest. It can be seen that the peaks are clearly divided and that no overlapping occurs. Generally, the peaks are $6 - 8\sigma$ apart. On the right side of Fig. 6.17, three example beamlet distributions with different intensities are illustrated with their corresponding Gaussian fit functions. This plot shows that the model of a Gaussian function is applicable to describe the data. Thus, this technique will be applied.

^dVision Components GmbH - VC 4012, sensor size: 2592×1944 pixel

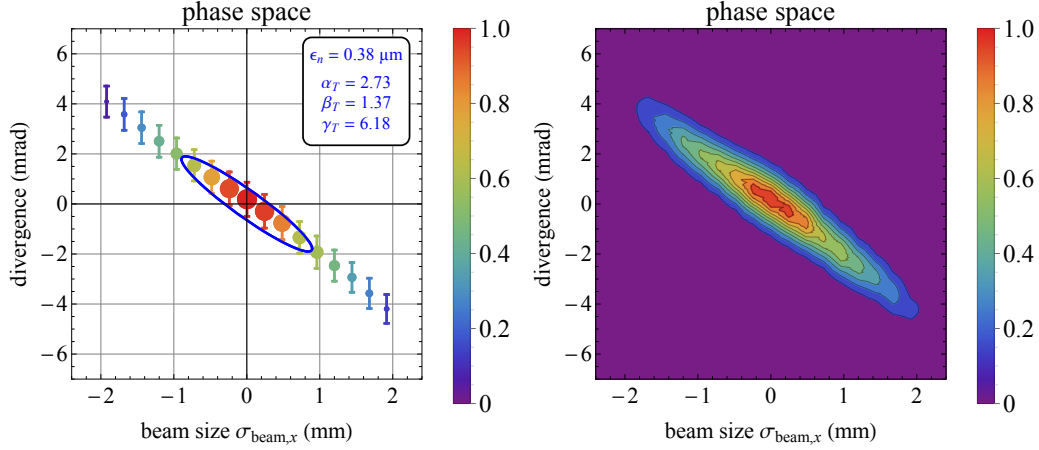


Figure 6.18.: Presentation of a reconstructed phase space. The left side shows the data from the picture analysis and the right side a contour plot of the same calculation. The point size and the color coding in the left graph are a measure of the intensity of the corresponding slit. The error bars indicate the divergence spread of the beamlets. The emittance of the presented phase space is calculated via Eq. 2.26 and amounts to $\epsilon_n = 0.38 \mu\text{m}$. In contrast to the quad scan, this measurement represents the beam properties at the position of the slit mask.

The conversion factor from pixel number to length unit is determined in the same way as for the quadrupole scan described in Sec. 6.2.1 and reproduced in Fig. 6.6. For the slit mask measurement, the resulting resolution is $4.8 \mu\text{m}/\text{pixel}$ and $4.7 \mu\text{m}/\text{pixel}$ for the vertical and horizontal slits, respectively. The influence of the attenuators used in front of the CMOS camera on the conversion factor is 0.38% and 0.61% for the vertical and horizontal direction, respectively. After the conversion factor is calculated, the width and placement of the slits can be transformed into a phase space reconstruction. An example of this is given in Fig. 6.18 on the left side with the slit positions and on the right side as a contour plot. The point size and the color coding in the left graph are a measure of the intensities of the corresponding slit, and the “error bars” indicate the divergence spread of the beamlets. The emittance of the presented data in Fig. 6.18 is calculated via Eq. 2.26 and amounts to $\epsilon_n = 0.38 \mu\text{m}$.

Prior to the current-dependent emittance measurements, some additional investigations were performed to check if the measurement method is reliable. Therefore, the emittance was measured for different solenoid and electron currents. As shown in Fig. 5.1, close to the scanner 1 there is a solenoid pair, and by changing the current of these solenoids, the phase space will rotate, but the emittance should not change. Some resulting emittances for a solenoid current of $650 \text{ mA} < I_{\text{sole}} < 750 \text{ mA}$ varied in steps of 25 mA are presented in Fig. 6.19 on the left side. In the case of a lower solenoid current, the electron beam would be larger than the slit mask. At higher solenoid currents, the focusing of the electron beam is so strong that it occupies

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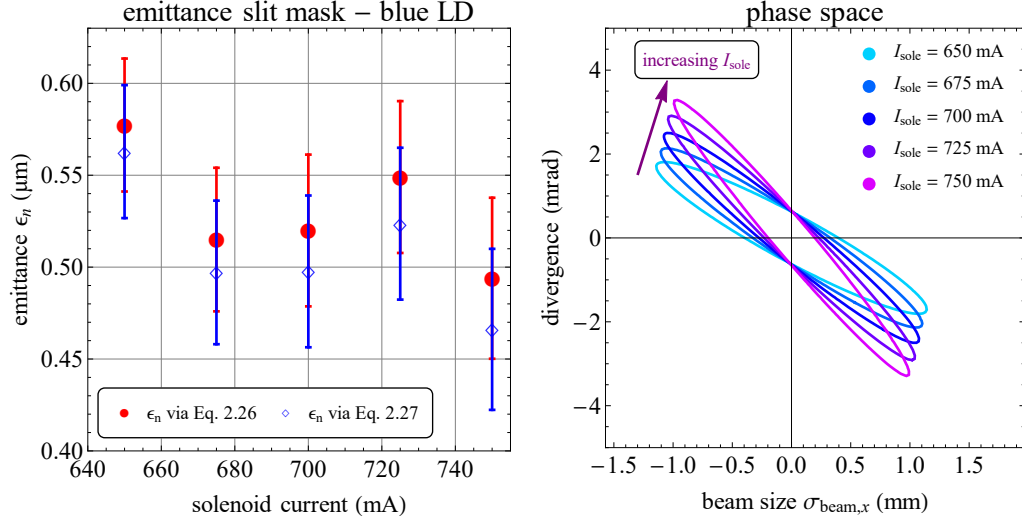


Figure 6.19.: The left side visualizes the emittance plotted over the solenoid current. The measurements were carried out with the blue laser diode. The right side shows the orientation and shape of the phase space ellipses for the solenoid currents indicated in the legend. The rotation of the phase space through the stronger focusing of the solenoid can be easily extracted from this plot.

only a few slits. Both cases influence the emittance result. This experiment was carried out with the blue laser diode. The error of the calculated mean is about 6%. Thus, it can be assumed that the measuring method is reliable. The Twiss parameters have been extracted to calculate the phase space ellipses and they are visualized on the right side of Fig. 6.19. This representation clarifies the rotation of the phase space caused by the different solenoid currents and shows that the phase space rotation can be reconstructed.

As a next step, the influence of the maximum intensity in the picture taken on the calculation procedure is investigated for each attenuator. Therefore, the exposure time of the CMOS camera is kept fixed at 200 ms, and the macro pulse duration of the laser is varied from 0.3 ms to < 10 ms to increase the maximum intensity. Values for the brightest beamlet below 40 are not investigated because the number of analyzable slits becomes too low. The results of this check are illustrated in Fig. 6.20 where the emittance is plotted over the maximum intensity of the brightest beamlet. This plot reveals that the calculation method is not completely independent of the maximum intensity. The differences between the individual attenuators can be due to the increase in c.w. current with increasing attenuation. Furthermore, the optical properties of the attenuators can have an influence on it because they are not of the same type (reflective or absorbent). The different slopes confirm this assumption. But for the different intensities within one attenuator, only the macro pulse duration was extended, which should not lead to an emittance increase. A closer look at the Twiss parameters and their

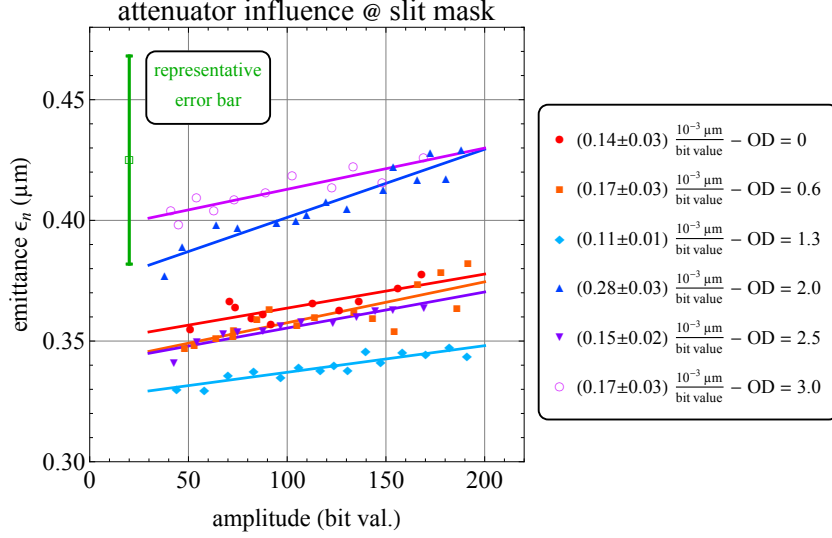


Figure 6.20.: Investigations on how the maximum intensity in the picture taken influences the calculation procedure. The plots reproduce the resulting emittances over the maximum intensity of the brightest beamlet for the different attenuators. The presented emittances are calculated with Eq. 2.26. Since the results calculated via Eq. 2.27 do not differ, they are not shown here.

visualization shows that neither the shape nor the orientation of the phase space ellipse is affected. The only thing that changes is the size of the ellipse, which can be caused by a larger number of beamlets being taken into account for the emittance calculation with increasing macro pulse length. To avoid this kind of uncertainty, the maximum intensity in the captured pictures is set to a bit value of 140 – 150 in the following emittance measurements.

The introduced procedure is now applied to the measurements which have been performed with the same laser spot sizes as used in the quadrupole scan emittance measurements (see Fig. 6.7) and for different average electron currents which correspond to c.w. operation. Fig. 6.21 compares the resulting emittances for the different laser spot sizes. The emittances are calculated with Eq. 2.26 and the results of Eq. 2.27 are not shown since they do not differ. In the case of the blue laser diode, the emittances increase up to an electron current of 0.5 mA from initially 0.26 μm and become stable up to the maximum current of 2.2 mA. In the electron current region above 0.5 mA, the emittance results to be around 0.40 μm . This statement is valid for all three laser spot sizes. In the case of the green laser diode, the emittance starts around 0.30 μm and becomes stable at an electron current of 0.2 mA. The mean value for the emittance above 0.2 mA amounts to 0.48 μm . The higher emittance values for the green laser diode can be caused by the intensity pattern of the laser spot (see Fig. 5.10).

An additional measurement series was performed to extend the beam current produced by the green laser diode to values around $I_{\text{beam}} \simeq 1 \text{ mA}$. The calculated

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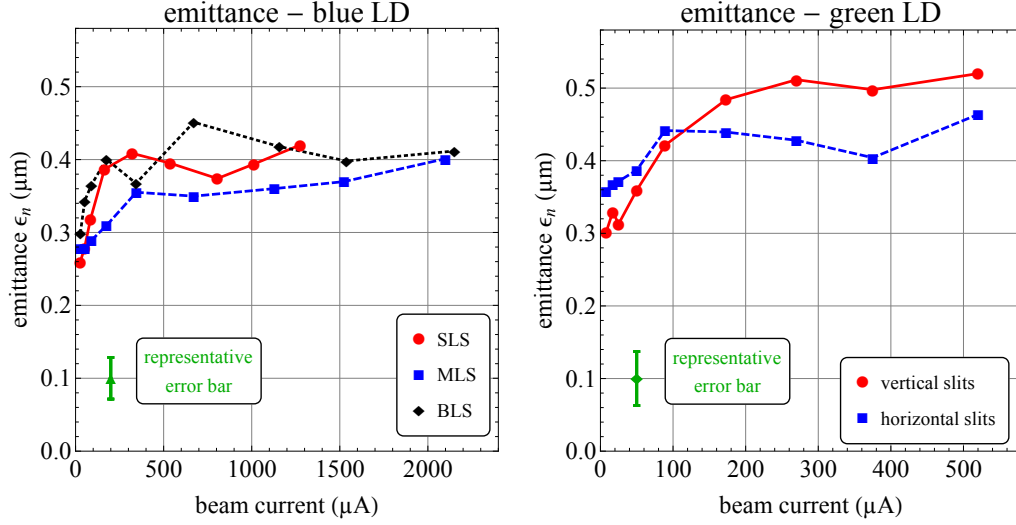


Figure 6.21.: Results of the emittance measurement with the slit mask for the blue LD and for three different laser spot sizes are illustrated on the left side. The graph on the right shows the results for the green LD. The emittance is plotted over the equivalent c.w. electron current. The emittances are calculated with Eq. 2.26.

emittances are depicted on the right side of Fig. 6.22 with an example of the phase space distribution on the left side. The phase space distribution represented by the slit position on the screen, their width (error bar) and intensity (point color and size) includes, in addition, an ellipse (Eq. 2.1) which is calculated via the Twiss parameters of Eq. 2.26. The ellipse corresponds to the $\pm 1\sigma$ emittance. The resulting emittances presented in Fig. 6.22 are smaller compared with those of Fig. 6.21. The difference is caused by an optimization of the camera orientation with respect to the surface normal of the screen.

The left plot in Fig. 6.21 only shows the emittance values for the vertical slit mask. This is due to the fact that the construction of the scanner system unfortunately allows the sled to rotate around the moving axis. Because of this rotation, it is not possible to arrange the CMOS camera in such a way that the direction of view is parallel to the surface normal of the screen, which is very important because of the tiny dimensions of the resolved beamlet distributions and the fact that the vacuum viewport poses a limiting aperture. As mentioned in Sec. 4.4.1, the investigations were made with an opened aperture of the imaging lens ($f/\# \simeq 3$) to keep the influence of diffraction effects as low as possible. But this adjustment of the optical system results in short “depth of field” of about ≤ 0.5 mm (see left plot in Fig. 4.11). This is taken into account in the improved version planned for application at the MESA facility.

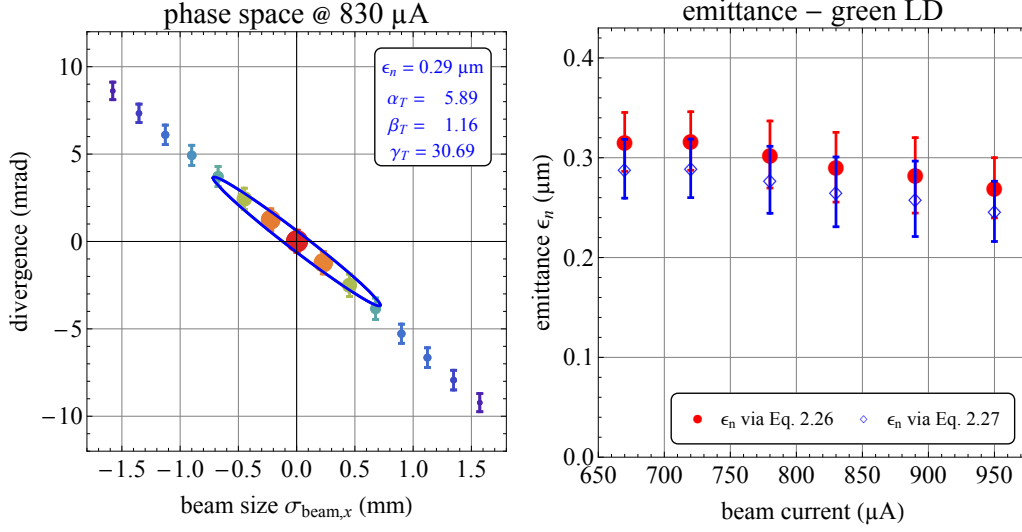


Figure 6.22.: The left side shows an example of the phase space distribution measured by the slit mask. The phase space distribution represented by the slit position on the screen, their width (error bar) and intensity (point color and size) includes, in addition, an ellipse (Eq. 2.1) which is calculated via the Twiss parameters of Eq. 2.26. The ellipse corresponds to the $\pm 1\sigma$ emittance. The calculated emittances are depicted on the right side for both calculation methods.

6.2.3. Conclusions concerning both emittance measuring methods

Both emittance measuring methods deliver different outcomes in the resulting emittances. This is caused by the different Twiss parameters of the measurement methods (compare left plot in Fig. 6.22 and right plot in Fig. 6.12) and the fact that the emittance determination takes place at two different positions along the beam line (see Fig. 2.4). During a quad scan procedure, only one quadrupole within the quadrupole doublet is active, and the second one is switched off. But in the case of an emittance determination via the slit mask, both quadrupoles are active in order to obtain a round beam profile. This is necessary because the overall dimensions of the masks ($(5 \times 5) \text{ mm}^2$) and the slit spacing ($d_{\text{slit}} = 0.25 \text{ mm}$) cause some limitations on the maximum and minimum beam size. If the electron beam is larger than the size of the mask, important information may be lost. On the other hand, if the electron beam is too focused, it covers only a few slits, making analysis difficult. In addition to the second quadrupole, a double solenoid in front of scanner 1 is active whose focusing properties are unknown. These unknown properties make it difficult to transform the Twiss parameters of the results presented in Sec. 6.2.2 along the beam line for a direct comparison.

As discussed in Sec. 2.3, two models are available to describe a quadrupole, the conventional hard edge model (CHE) via Eq. 2.8 and Eq. 2.9, and the sliced one (SHE) using the Eq. 2.17 and Eq. 2.18. The data sets of Fig. 6.13 were analyzed

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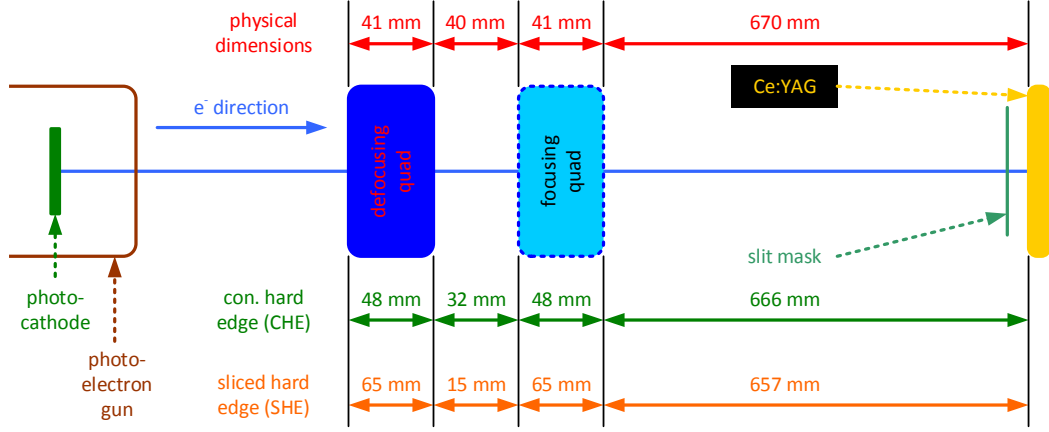


Figure 6.23.: Sketch of the beam line configuration during the phase space comparison. In the upper part the physical dimensions of the setup are presented. The different effective length of the quadrupole models shrink both drift spaces, especially for the sliced hard edge model whose parameters are shown on the bottom. For the quad scan only the first quadrupole is used.

using both models to determine the emittance as well as the phase space in front of the quadrupole used. To compare the phase spaces of both measuring methods, the Twiss parameters of the quad scan are transformed through the beam line used for the slit mask measurements. A sketch of the beam line which includes the physical dimensions as well as the effective lengths of the quadrupoles is depicted in Fig. 6.23. The transformation of the Twiss parameters is performed via a matrix multiplication as presented by Eq. 2.5. Since more fringe field is taken into account in the sliced hard edge model, both models are represented by different matrices, which are calculated as follows:

$$R_{\text{CHE}} = R_{\text{drift},4} R_{\text{CQF}} R_{\text{drift},2} R_{\text{CQD}} \quad (6.3)$$

$$\begin{aligned} R_{\text{SHE}} &= R_{\text{drift},4} \underbrace{R_{\text{drift},3,2} R_{\text{QF}} R_{\text{drift},3,1}}_{R_{\text{SQF}}} R_{\text{drift},2} \underbrace{R_{\text{drift},1,2} R_{\text{QD}} R_{\text{drift},1,1}}_{R_{\text{SQD}}} \\ R_{\text{SHE}} &= R_{\text{drift},4} \quad R_{\text{SQF}} \quad R_{\text{drift},2} \quad R_{\text{SQD}} \end{aligned} \quad (6.4)$$

Fig. 6.24 depicts two examples of the phase space comparison. The shape and the orientation of the phase space ellipses do not match exactly. In addition to the ellipses, the positions of the individual slits in the phase space, including the width of the divergence, are also illustrated in the plots. As a note, it should be mentioned that the illustrated width of divergence (represented by the “error bar”) at the slit position is related to the intensity of the respective slit. The inclusion of the slits allows further verification of the data. Both quadrupole models and the slit mask enclose the same amount of slits within the phase space. But the phase space ellipse of the slit mask has a broader distribution of divergence. This can be considered one reason for the larger emittance values (compare the lowest ϵ_n in Fig. 6.21 with the results presented in Fig. 6.13). However, this is consistent with the width of

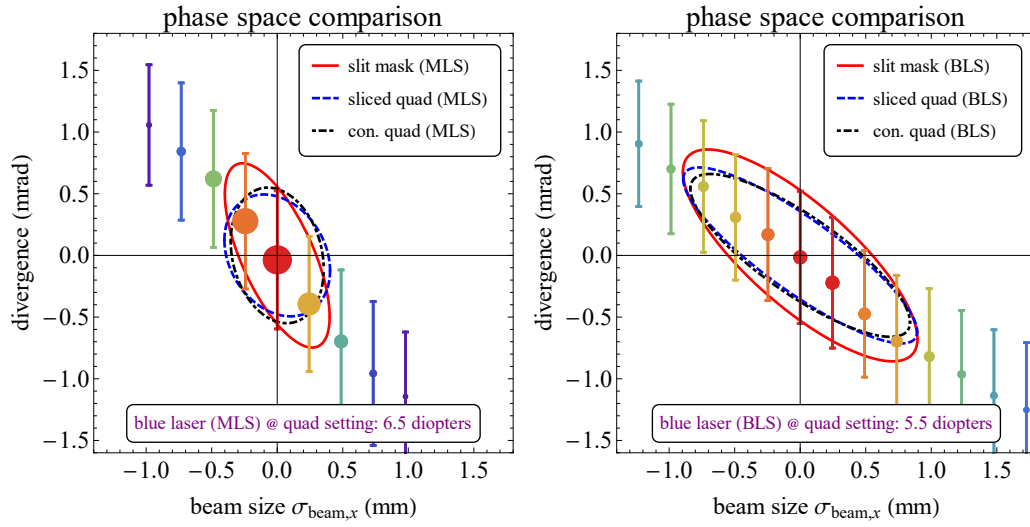


Figure 6.24.: Both plots each show one example of the phase space comparison for different parameters of operation. The plots contain the phase space of the slit mask, the phase space of the sliced hard edge model, and the phase space of the conventional hard edge model at the position of the slit mask. Furthermore, the results of the slits—with their position within the phase space and the width of the divergence—are included in the plots. This allows further verification of the data. Especially in the right plot, it is conspicuous that the information of the slits indicate a curved phase space.

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the divergence distribution represented by the individual slits. A closer look at the slit positions depicted in the right plot of Fig. 6.24 suggests, among other things, the conclusion that the phase space is curved. This type of information cannot be obtained by means of quadrupole scans and is accordingly not considered. As already mentioned in Sec. 2.3, the description of a curved or distorted phase space leads to increased emittance values on the basis of an ellipse. In the case of the slit mask, however, this information is used to determine the Twiss parameters used to reconstruct the phase space ellipse. Not only in comparison with the results of the slit mask, but also among each other, the quadrupole models differ. These deviations are within the measurement uncertainties. In addition, the quadrupole doublet will affect these deviations, since the fringe field used (presented in Fig. 2.6) to calculate the effective length of the SHE model would extend into the respective other quadrupole.

Apart from the orientation and the shape of the phase spaces, a look can be taken at the beam dimension $\sigma_{\text{beam},x}$ at the position of the slit mask that can be determined by the Twiss parameters via $\sigma_{\text{beam},x} = \sqrt{\beta_T \epsilon_x}$. In Fig. 6.25, this comparison is shown for the three different laser spot sizes introduced in Fig. 6.7 in the case of the blue laser diode, and for the small laser spot in the case of the green one. The beam sizes calculated by the results based on the conventional hard edge model are in general about 10% smaller than the ones of the slit mask. If the transformed Twiss parameters of the sliced hard edge model are used to calculate the $\sigma_{\text{beam},x}$ at the position of the slit mask, the resulting deviation is less than 2%. An exception are the results of the blue laser diode using the big laser spot. The discrepancy in the beam sizes between both measurement methods is not as big as the deviation in the emittance would suggest. The sliced hard edge model of the quadrupole used herein has been evolved for a singlet and not for a doublet, and yet, a more accurate reproduction of the beam sizes occurs.

According to the calculations presented in Sec. 2.4, the electron bunches investigated are dominated by emittance, which is why the introduced quad scan technique works.

6.3. Pulse length investigations

After the determination of the transverse emittance, the temporal shape of the electron bunches is considered in more detail. In this chapter, the results of the pulse length measurements are given. The deflecting cavity described in Sec. 5.3 is a powerful tool to do this kind of experiments.

At the beginning of each measurement, the focus of the distribution (CM_{def}), the dimension and the orientation of the deflected beam is determined using a dc beam. A graphical illustration of this procedure is depicted in Fig. 6.26. The horizontal ($0.5y$) and vertical center ($0.5d_x$) of the deflected beam is identified. This is done by analyzing the central row of the picture by fitting two separate Gaussian functions to the data. The mean value of the peak positions ($0.5d_x$) determines the column

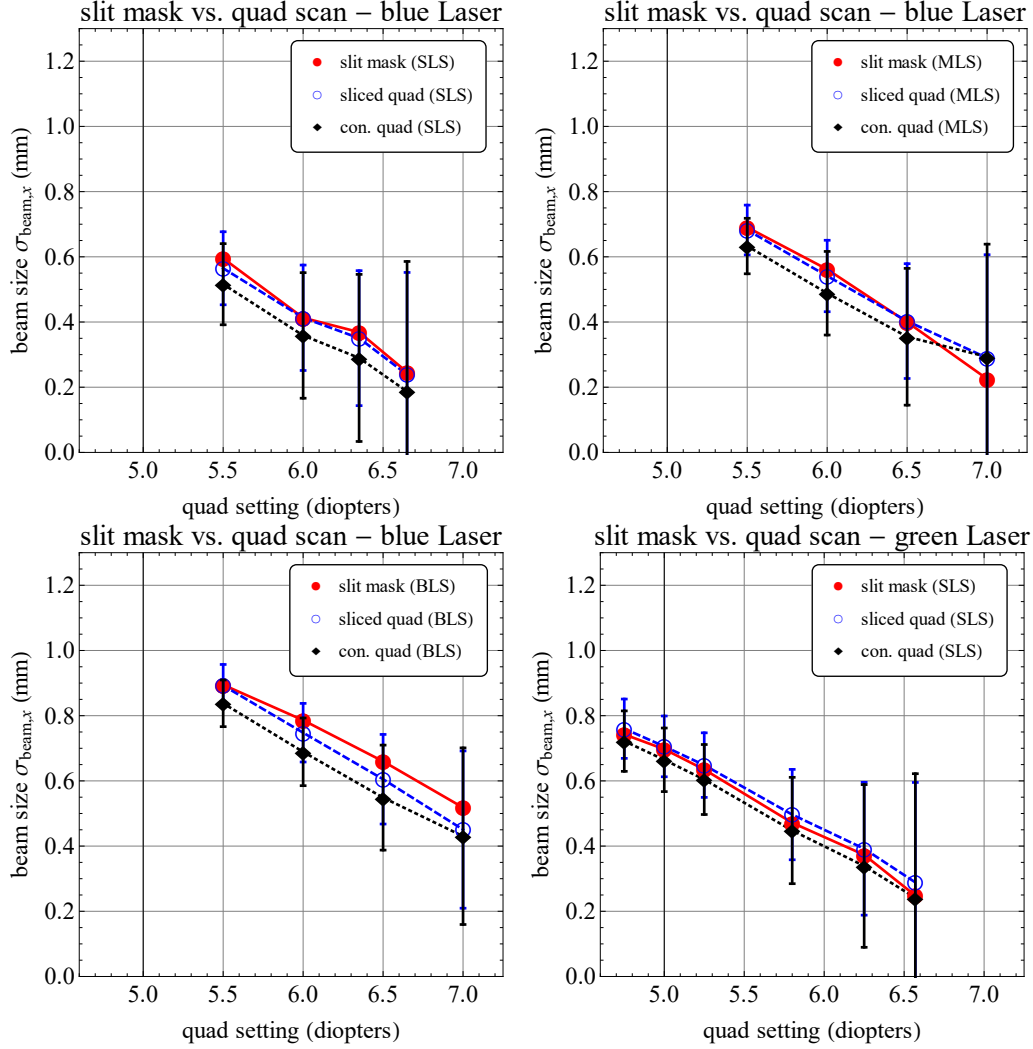


Figure 6.25.: The plots compare the calculated beam sizes at the position of the slit mask for different quadrupole strengths and laser spot sizes. Despite the different phase spaces, the beam sizes of the quad scan can be mapped to the beam sizes of the slit mask measurements. The results of the green laser diode are an exception.

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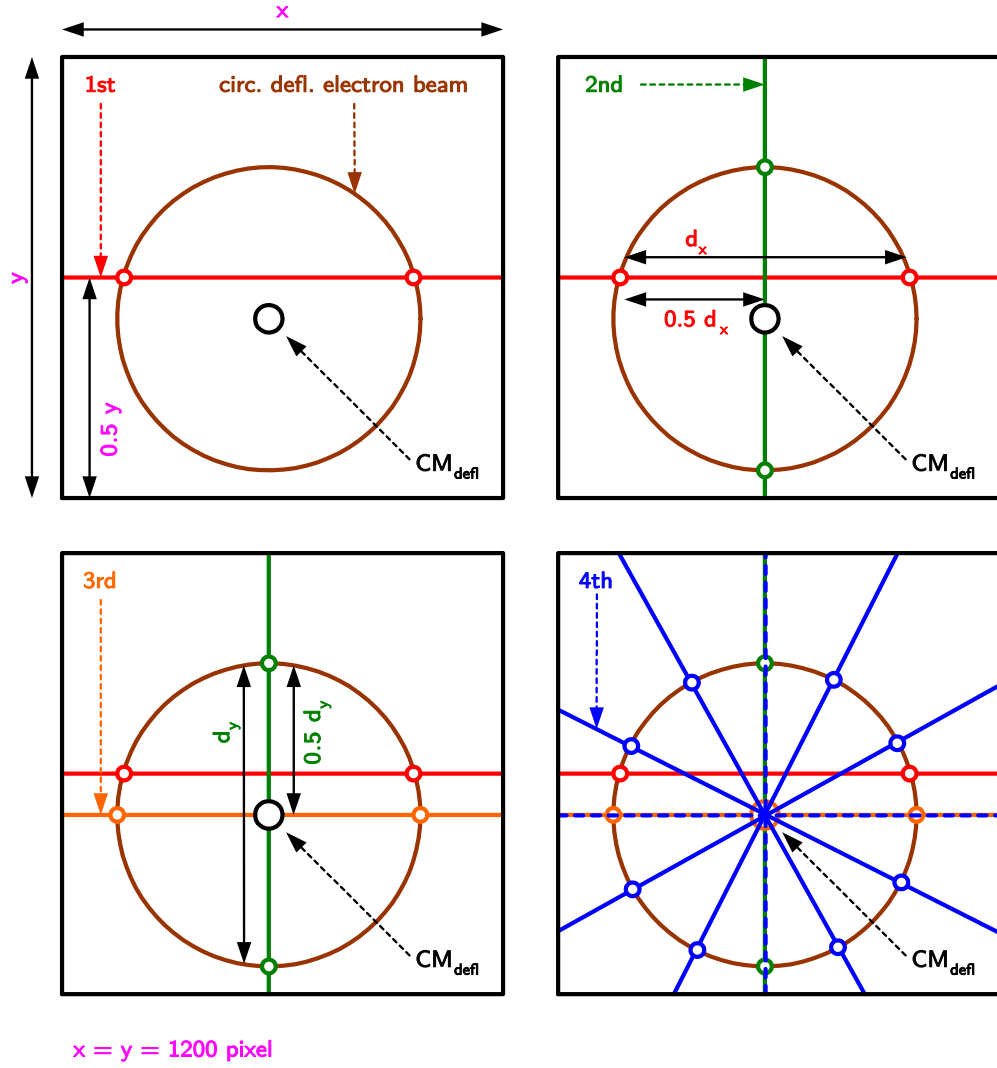


Figure 6.26.: Illustration of the procedure to determine the focus of the distribution (CM_{defl}) and the shape of the deflected electron beam. The first step is to perform a line cut at $0.5y$ and to determine the peak positions of the deflected electron beam. The center of these two peaks ($0.5d_x$) is taken for the second line cut. Repeating this procedure leads to the third step in which the CM_{defl} is determined with sufficient accuracy. In the fourth and last step, several line cuts at different angles are performed to get enough data points for the elliptical fit function (Eq. 6.5).

at which this procedure is repeated. An additional repetition delivers the center of the ellipse. These three steps are necessary due to the fact that the deflected beam is not always centered on the picture taken. In general, more points are needed to describe the ellipse reliably. Thus, additional data points are collected by rotating the line cut used to analyze the intensity profile around the polar angle (fourth step in Fig. 6.26). 10 to 16 steps are sufficient. Examples of different deflected beams are given in Fig. 6.27, namely a dc beam (top), a pulsed beam using the blue laser diode (lower left), and another one using the green laser diode (lower right). For the visualization of the beam profiles, the number of pixels in the x and y direction was divided by four. During all measurements, no RF phase-shifter was used due to the fact that the screen shows the complete bunch distribution at once.

The procedure with the dc beam is done because in some cases—especially with the green laser diode—the pulse length is too short and does not deliver enough points to fit an ellipse equation reliably. The chosen fit function has the form

$$g_{\text{def}}(a, b, \theta, \vartheta) = \frac{a \times b}{\sqrt{\frac{b^2 \cos(\theta) \sin(2\vartheta) - a^2 \sin(2\vartheta) \sin^2(\theta)}{+ (a \times b)^2 \sin^2(\vartheta) \sin^2(\theta) + \cos^2(\vartheta) (b^2 \cot^2(\theta) + a^2 \sin^2(\theta))}}}. \quad (6.5)$$

The parameters a and b are the axes of the ellipse, θ is the tilt angle of the ellipse, and ϑ describes the polar angle. With the analysis of the dc beam, θ is calculated and fixed for the subsequent measurements.

The plot on the left side of Fig. 6.28 shows a set of temporal distributions for the small laser spot of the blue laser diode. Comparing these results with the pulse structure of the laser diode presented on left side of Fig. 5.9, it is obvious that even the low electron currents have a longer tail. Furthermore, the ratio of the first to the second maximum changes and becomes lower until the second pulse vanishes completely.

With the medium and the big spot size, it is possible to push forward into a higher bunch charge region, but there have been observed some extraordinary longitudinal bunch profiles. An example at two different currents is given in Fig. 6.29. These temporal distributions could not be fitted with an ellipse function as presented in Eq. 6.5.

A reason for this could be a combination of the effects of beam profile distortion caused by space charge, higher energy spread, and the bunch charge taking too much energy out of the RF field of the deflecting cavity. The last two effects can influence the intensity distribution displayed on the screen in such a way that it cannot be described by an ellipse equation anymore. The deflecting cavity is designed for a specific energy, namely the central beam energy of 100 keV. If the energy spread of the beam becomes too large, it is possible that the imaging properties of the cavity no longer meet the intended properties, which could lead to the extraordinary distributions illustrated in Fig. 6.29. To confirm this assumption, it would be necessary to investigate the energy width of the electron bunches. An attempt

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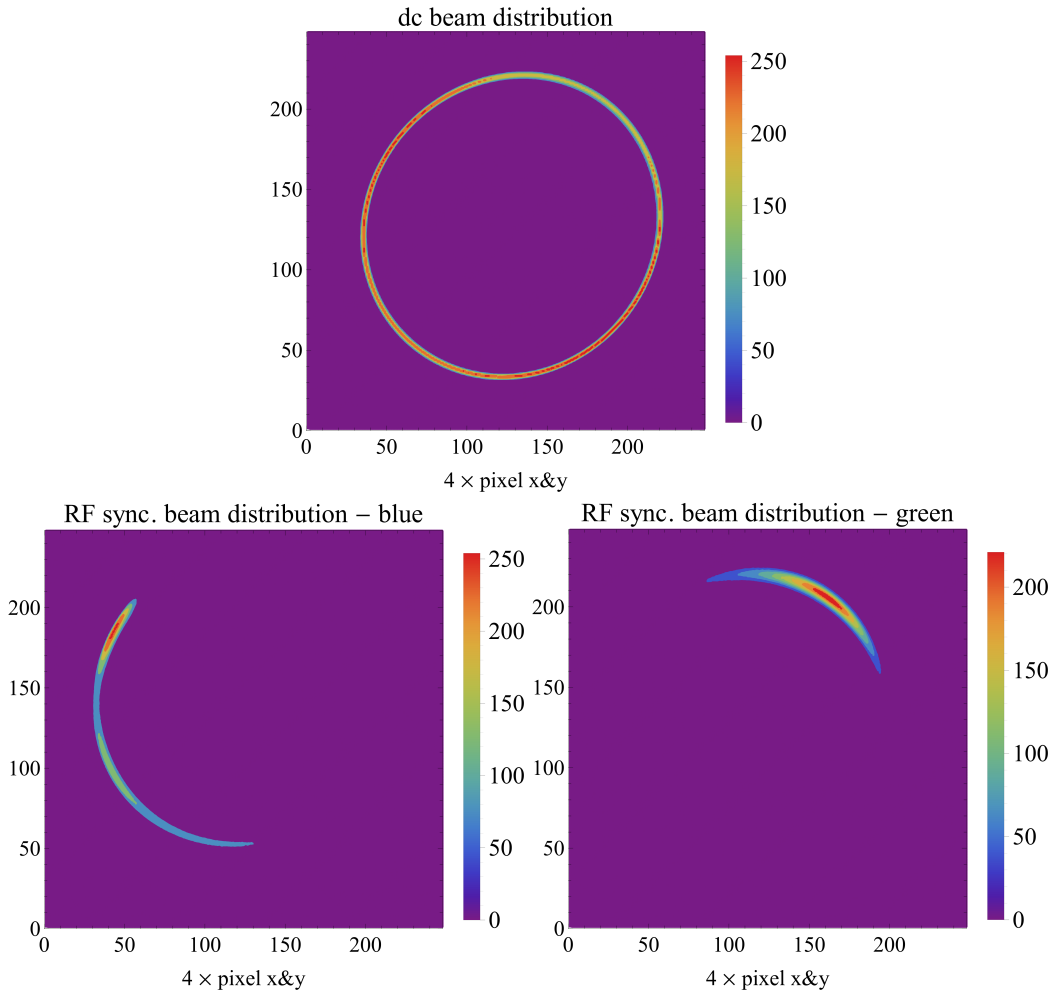


Figure 6.27.: The plots each illustrate an example of a dc beam (top), an example of the pulse shape of the blue laser diode (lower left), and one for the green laser diode (lower right). The color code is linked to the intensity in the picture taken.

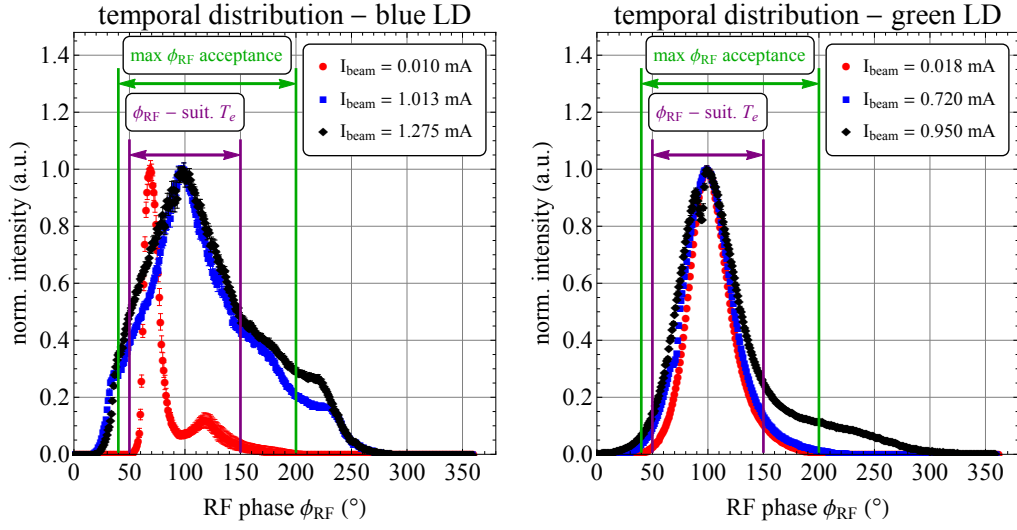


Figure 6.28.: Results of the temporal distribution of the electron bunches produced by the blue laser diode with a small laser spot are shown in the left plot. The results show that the pulse length increases with increasing electron current and the structure of the second pulse vanishes. The plot on the right side illustrates the temporal distribution produced by the green laser diode. Moreover, an RF phase width for a suitable electron transmission and one for the max. acceptance of the buncher system is included in both plots. To achieve a high electron transmission, it could become necessary to shift the phase of the bunches.

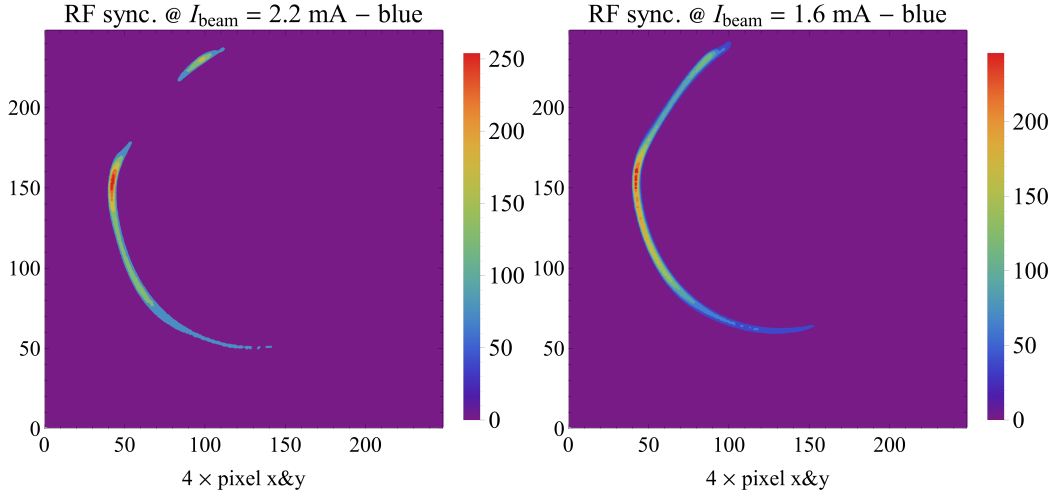


Figure 6.29.: Two examples of a distorted temporal distribution which could not be fitted with an ellipse equation. The left plot shows a bunch profile that was observed at a current of 2.2 mA, and on the right side, a profile corresponding to a current of 1.6 mA is visualized. Both examples were produced with the blue laser diode.

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was performed with the Wien filter mounted in the beam line on the way to the double scattering polarimeter. But the results have shown that some improvements are necessary to get clear results for the energy distribution. A more detailed description follows in the outlook.

The results for the blue laser diode presented on the left side of Fig. 6.28 are longer than 150° , and for higher currents, the pulse length can increase to more than 200° . The developed buncher section can handle pulse lengths of up to 160° with respect to the RF phase [Heil15] (see Fig. 3.22). Thus, in high-current operation, too many electrons would be wasted and dumped in the chopper section installed upstream. This would cause radiation and thermal stress to the mechanical components, which should be avoided.

The evolution of the temporal distribution of the electron bunches with increasing current produced by the green laser diode are illustrated on the right side of Fig. 6.28. A comparison with the pulse structure of the green laser diode illustrated on the right side of Fig. 5.9 shows that this pulse shape is not affected by space charge as much as the blue one is. This could be explained by the fact that the pulse profile of the green laser diode is more Gaussian-like and occupies a larger amount of the RF phase from the beginning as shown in Fig. 5.9. The temporal distribution for almost all investigated currents fits into an RF phase range of 100° , which is suitable for the buncher section [Heil15] in front of the planned MESA injector. Although the maximum produced current of around 1 mA has a tail, the results look promising that these pulses can serve MESA.

Furthermore, two phase intervals are also marked in both plots of Fig. 6.28. One represents a suitable electron transmission (100°) and is based on the experience gained during the operation of MAMI, and the second one denotes the maximum accepted phase interval by the buncher system. To achieve the maximum possible transmission, it could become necessary to shift the electron bunches along their phase. This aspect should be taken into account when deciding on the technique to be adopted for ramping up MESA.

Now that the temporal distributions of the electron bunches are determined for different beam currents, this can be included in the calculations of the operating point of the laser diodes. As the occupied RF phase also increases with increasing electron current, the phase acceptance of the buncher system can lead to a reduction of the electron transmission. Taking into account this additional influence, it is possible to estimate whether the laser system presented in Sec. 3.3 is capable of operating MESA. In comparison with Fig. 3.12, where a constant electron transmission of 100% was assumed, Fig. 6.30 considers the effect of a current-dependent transmission. Despite reduced T_e , both laser diodes are able to serve MESA with the desired electron current for stage-1. However, the pulse profile was neglected in this consideration.

The results of the green laser diode are very encouraging that the first beam tests on the low-energy beam transport system could be performed with this kind of laser

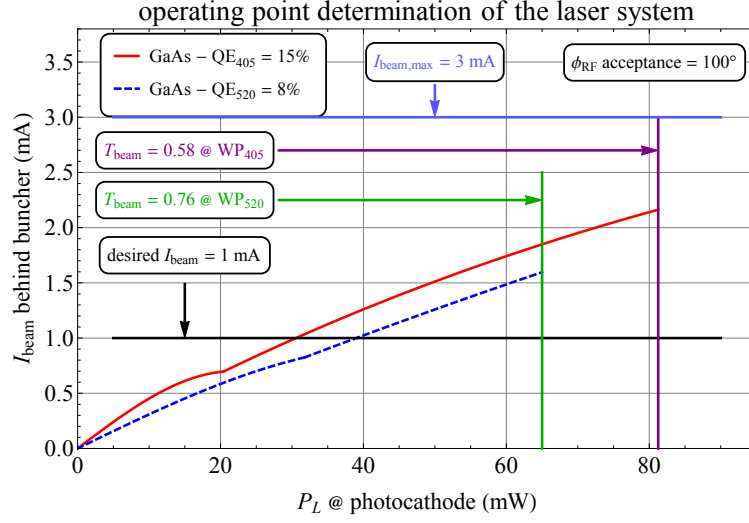


Figure 6.30.: The plot shows the operating point determination of the laser system used. The initial laser pulse is set in such a way that it promises a high electron transmission (T_e). Otherwise, the electron current would drop much faster at higher laser powers than the ones shown. With increasing electron current, also the occupied RF phase increases, and thus, the phase acceptance of the buncher system can cause a decrease in T_e . Despite reduced T_e , both laser diodes are able to serve MESA with the desired electron current for stage-1.

system. Nevertheless, a dedicated fiber-based MOPA^e laser system—comparable to [OBD+07]—should be installed to ensure very clean operation conditions for the accelerator.

^eMOPA: Master Oscillator Power Amplifier

7. Conclusions

The main purpose of this thesis was to investigate the beam dynamics of the MESA photoinjector and to build up a diagnostic test beam line. For the diagnostic elements, a scanner device was optimized, for which the existing system at MAMI was used as a template. The new design now fulfills the requirements on the vacuum conditions and is bakeable. The constructed devices can operate very close to the source at pressures below 3×10^{-10} mbar, which is the lower limit of the measuring range of the Bayard Alpert gauge^a used. An influence on the cathode lifetime during the operation of the scanner devices was not recognized, and this is a good hint to use them for MESA. The targets mounted inside the scanner devices (see Fig. 4.2) enable to perform several measuring techniques like quadrupole scans with a screen or a wire (results presented in Sec. 6.2.1) and to perform crosschecks on the emittance results with slit masks (introduced in Sec. 6.2.2). Apart from the transverse diagnostic elements, there is also a deflecting cavity mounted in the beam line, which enables to take a closer look at the temporal shape of the beam distribution with a screen (depicted in Sec. 6.3).

To push forward into the desired bunch charge regime for MESA, an RF-synchronized laser system was built up, which contains two different laser diodes (an overview is given in Sec. 5.2). The laser system poses an easy means to perform the necessary investigation to characterize the reliability of the analyzing stages. Nevertheless, a dedicated fiber-based MOPA laser system [OBD+07] should be purchased in order to produce very clean operating conditions for MESA.

MESA has some requirements that should be fulfilled by the photoelectron source. To check if these could be achieved by an existing source (PKA2), several experiments have been performed. An important aspect is the cathode lifetime, and the PKA2 is able to deliver a vacuum lifetime—in the IR region of light—of more than 26 d in an “armed” and ready to use mode (see Sec. 6.1). This means that the HV is switched on and the valve to the beam line is opened. The vacuum lifetime for photocathodes in the closed source chamber and for the visible range of light can easily reach several months. Moreover, high-current investigations have shown that a charge of ~ 700 C could be extracted within one charge lifetime of the photocathode by exceeding > 1 mA average current (illustrated in Fig. 6.2). Thus, the PKA2 is able to create good experimental conditions for the investigations presented in this thesis.

With reference to these initial conditions, further tests of the transverse emittance could be carried out to determine if the measuring methods presented in chapter 6.2

^aVacum GmbH - ATMION, wide range gauge, $(1000 - 3 \times 10^{-10})$ mbar

7. Conclusions

are implementable at MESA. The quad scan emittance measurement technique is a well known technique at the KPH and easy to realize because every accelerator has quadrupoles and screens. Thus, this technique has been studied (results are shown in Fig. 6.8). Furthermore, a technique never used before at the KPH, namely the emittance determination via slit masks, was tested with focus on their performance (resulting emittances are shown in Fig. 6.21).

Apart from the option to obtain the beam profile with a screen and a CMOS camera, there are also mounted wires in the sled of the scanner device. With these wires, quad scans can also be done (introduced in Sec. 6.2.1.2). The comparison between the wire and the screen method (illustrated in Fig. 6.12) shows that the wire has the advantage that the resolution during the beam distribution determination is always the same, namely the wire diameter. There are no other uncertainties, like sensor alignment, additional attenuators and so on, that have to be taken into account. Thus, this method would be the treatment of choice for a precise emittance measurement.

A beam has not only transverse dimensions but also a longitudinal one. To investigate the longitudinal beam distribution, a deflecting cavity was mounted in the beam line. Through this diagnostic element, it was possible to take a closer look at the pulsing behavior of the laser diodes used within the temporal domain of the RF of MESA. Furthermore, investigation of the electron current-dependent evolution of the longitudinal bunch distribution could be performed (shown in Fig. 6.28). The low-energy beam transport system of MESA will contain two of these deflecting cavities in the chopper section to ensure very clean operation conditions for the accelerator. Within the chopper system, it is also possible to determine the longitudinal bunch distribution, but the screen will be replaced by electrically insulated plates which can be read out via amperemeters.

8. Outlook

The diagnostic test beam line behind the second α -magnet in the direction to the double scattering polarimeter (see Fig. 5.1) includes a Wien filter to manipulate the spin orientation of the electrons. Because of the way the spin manipulation is realized, a Wien filter also has some energy-resolving properties, so it could be used as a spectrometer to investigate the sixth dimension of the phase space (dE , $d\varphi$). Some experiments have been performed to figure out if it is possible to perform this kind of investigations with the existing beam line. It is evident that for low dc and c.w. currents this is realizable, but with increasing currents the defocusing space charge forces become more and more dominant. In the case of low electron currents, the energy spread is not very large, and there is no difference between the spot sizes of the dc and c.w. beam. It is assumed that the difference in the energy width will become more dominant for higher bunch charges. To compensate for the defocusing forces during high bunch charge operation, the focusing elements in the beam line must be adjusted to the new resulting beam envelope, and thus, the orientation of the phase space ellipse at the entrance of the Wien filter is changed. Furthermore, the Wien filter has some additional focusing properties [TiAu06] that have to be taken into account, and this makes a comparison of the beam spot sizes for a dc and c.w. beam on the screen located downstream very difficult if not impossible. Therefore, some additional elements such as a slit must be installed in front of the Wien filter to decrease the influence of the aforementioned effects. The slit will always create the same initial beam size at the entrance to the Wien filter, enabling a comparable measurement. A matrix-based simulation of the beam line to determine the orientation of the phase space ellipse could also be very helpful to estimate the influence of the base beam size on the observed energy-resolved spot size behind the Wien filter.

Another aspect that would still need to be investigated is the extension of the sliced hard edge model of the quadrupole for doublets and triplets. This is due to the short and compact design of the quadrupoles. The comparison presented in Sec. 2.4.2 as well as the conclusion of the emittance measurements in Sec. 6.2.3 have shown that the use of the sliced hard edge model leads to more accurate results for the quadrupoles used in the low-energy transport system. The fringe field taken into account in the SHE model is in general longer than the drift space between two adjacent quadrupoles. This can have an influence on the final effective length. A reliable quadrupole model is desirable for a meaningful simulation of the beam line.

A. List of variables

variable	description	value / unit
α	anti-guiding factor of an active laser medium	3.5
$\alpha_{0,\text{GaAs}}$	photon absorption coefficient of GaAs	m^{-1}
α_{int}	internal losses of a laser cavity	m^{-1}
α_m	mass attenuation coefficient for electrons	cm^2/g
α_{sat}^{-1}	saturation charge density of Ce:YAG	$48 \text{ fC}/\mu\text{m}^2$
α_T, β_T and γ_T	Twiss or Courant-Snyder parameters	rad, m and m^{-1}
$a_{\tilde{g}}$	slope of the gain of an active laser medium	$9.8 \times 10^{-13} \text{ m}^3/\text{s}$
$a_{\text{BSC},i}$	parameter for the empirical formula to calculate η_{BSC}	dimensionless
a_m	coefficients of the Enge function	dimensionless
A_{ϵ}	phase space area of an ellipse	$\text{mm mrad} = \mu\text{m}$
A_{beam}	area of the beam	m^2
A_{emit}	emitting area of a photocathode	m^2
$A_{\tilde{g},p}$	linear gain coefficient for laser mode p	
A_{pv}	count rate asymmetry in parity-violation experiment	%
$\hat{A}_{\text{RF}}$	amplitude of a rotating RF field	
A_{RF}	amount of RF power in I_{LD}	dimensionless
A_{Y}	atomic mass of yttrium	89
β_L	relativistic velocity ($E_{\text{kin}} = 100 \text{ keV}$)	0.55
$\beta_{\text{sp},p}$	spontaneous emission factor for laser mode p	dimensionless
b	dispersion of gain spectra	$1.25 \times 10^{42} \text{ m}^4/\text{s}$
B_0	field strength at the pole tip of the quadrupole	T
$B\rho$	magnetic rigidity	Tm

A. List of variables

variable	description	value / unit
B_{sat}	factor for self-saturation effects in laser diodes	
B_i	rotating force field (deflection cavity)	
c_{vac}	speed of light in vacuum	$2.99792 \times 10^8 \text{ m/s}$
CoC	circle of confusion	0.013 mm
C	contrast	dimensionless
CM	focus of an intensity distribution	(x, y)
CM _{defl}	focus of the distribution	(x, y)
$\delta\lambda_{\text{sp}}$	HWHM of the spontaneous emission spectra	3.5 nm
$\Delta\sigma_{\text{beam}}$	dev. between measured data and the solutions of the envelope Eq.	dimensionless
$\Delta\lambda$	mode spacing wavelength of a laser diode	38 pm
ΔE_{BBR}	energy shift caused by the BBR	0.5 eV – 0.7 eV
d_{abs}	photon absorption length in a photocathode	m
d_{Airy}	diameter of an Airy disk (first zero)	m
d_{BBR}	depth of band bending region (BBR) within a photocathode	6 nm – 12 nm
d_{drift}	drift space behind the slit mask	19.6 mm
d_{esc}	electron escape depth in a photocathode	m
d_{far}	far distance	m
d_{mask}	thickness of the mask	0.05 mm
d_{near}	near distance	m
d_{object}	working distance	130 mm
d_{PKA2}	cathode-anode distance of PKA2	150 mm
d_{slit}	distance of the slits on the slit mask	0.25 mm
d_{STEAM}	cathode-anode distance of STEAM	37 mm
d_x	spacing between adjacent holes on the hole mask (x axis)	(51.46 ± 0.03) pixels
d_y	spacing between adjacent holes on the hole mask (y axis)	(51.22 ± 0.03) pixels
dE	energy spread of particle beam	eV
$D = \tau_{\text{pulse}}/\tau_{\text{rep}}$	duty cycle	$1.5 \times 10^{-3} - 6 \times 10^{-3}$
D_{pq} and H_{pq}	factors for cross-saturation effects	
ε_0	permittivity	$8.85419 \times 10^{-12} \text{ As/Vm}$
$\varepsilon_{\text{r,GaAs}}$	permittivity of GaAs	13

variable	description	value / unit
ϵ	RMS emittance	mm mrad = μm
ϵ_n	normalized RMS emittance	mm mrad = μm
$\epsilon_{n,\text{max}}$	desired norm. emittance of MESA	1 μm
ϵ_{th}	thermal emittance	eV
e	Euler constant	$\simeq 2.7183$
E_0	rest mass energy of an electron	0.511 MeV
E_C	conduction band energy	eV
E_{Fermi}	Fermi level	eV
E_g	band gap energy of GaAs	1.4 eV
E_{kin}	kinetic energy of electrons	0.100 MeV
E_V	valence band energy	eV
E_{vac}	vacuum energy	eV
E_{ph}	photon energy	eV
$f/\#$	size of internal variable aperture in the imaging lens	2.8 – 16
f_{hyper}	hyperfocal length	m
f_{optic}	optical focal length	50 mm
f_{sole}	solenoid focal length	m
$g_{\text{Airy}}(x)$	formula for an Airy disk	a.u.
$g_{\text{defl}}(a, b, \theta, \vartheta)$	elliptical fit function	
$g_{\text{Enge}}(s)$	Enge function	Gauss/cm
$g_i(x)$	formula for emittance shape example	rad
$\tilde{g}_p$	gain for the laser mode p	m^{-1}
$\tilde{g}_{\text{th}}$	threshold gain of a laser diode	m^{-1}
γ_L	Lorentz factor ($E_{\text{kin}} = 100 \text{ keV}$)	1.20
Γ	confinement factor	0.017
$h = 2\pi\hbar$	Planck constant	$6.62607 \times 10^{-34} \text{ Js}$
I_{Alfven}	Alfven current	$\frac{4\pi\epsilon_0 mc^3}{q_e}$
I_{beam}	average beam current	A
$I_{\text{beam,max}}$	peak current within an electron bunch	A
I_{dark}	dark current of an electron gun	$< 1 \times 10^{-9} \text{ A}$
I_{dc}	dc current from a laser diode driver	A
I_{LD}	laser diode current	A
I_{loss}	current of transmission loss through beam line	$< 1 \times 10^{-9} \text{ A}$
$I_{\text{sc,lim}}$	current limit of the PKA2 due to space charge	$\simeq 3 \text{ mA}$
I_{sole}	solenoid current	A
I_{th}	laser diode threshold current	A

A. List of variables

variable	description	value / unit
$\text{Int}(t)$	temporal variable intensity	a.u.
$\text{Int}_i(o)$	intensity distribution	a.u.
$\text{Int}_{\max}$ and $\text{Int}_{\min}$	maximum and minimum intensity	a.u.
$\text{Int}_{\text{opened}}$ and $\text{Int}_{\text{closed}}$	intensity measured by CMOS sensor for an opened and closed el. shutter	a.u.
Int_{peak}	peak intensity	a.u.
$\text{Int}_{\text{slit},i}$	maximum intensity of an imaged slit	a.u.
J_1	Bessel function of the first kind	dimensionless
κ_i	a measure of the external forces	m^{-2}
k	quadrupole strength	m^{-2}
k_0	maximum quadrupole strength	m^{-2}
k_B	Boltzmann constant	$\simeq 1.38065 \times 10^{-23} \text{ J/K}$
$\vec{k}_e$	wave vector of an electron	m^{-1}
K_{en}	spontaneous emission enhancement factor	1
K_{sc}	space charge parameter or generalized perveance	dimensionless
k_{sliced}	field strength of sliced quadrupole	m^{-2}
$\lambda_{0,\text{th}}$	laser diode wavelength at threshold current	405 nm
λ_D	Debye length	m
λ_e	distance an electron travels during one RF period	m
$\lambda_{\tilde{g}}$	central gain wavelength of a laser diode	m
λ_p	wavelength of laser mode p	m
λ_{peak}	peak emittance wavelength of scintillator	m
λ_{ph}	photon wavelength emitted by the laser diodes used	405 nm or 520 nm
λ_{sp}	central wavelength of the spontaneous emission within a laser diode	416 nm
l_{cav}	cavity length of a laser diode	600 μm
l_{drift}	drift length	m
l_{eff}	effective length of a conventional HE quadrupole model	48.1 mm

variable	description	value / unit
$l_{\text{eff,sliced}}$	effective length of a sliced HE quadrupole model	65.6 mm
l_{field}	length of quadrupole field profile	150 mm
l_{fringe}	fringe field length	m
l_{quad}	physical length of quadrupole	41 mm
l_{slices}	length of slices	m
L	distance between deflection cavity and screen	380 mm
m_{ij}	elements of the beta matrix	
M_{beta}	beta matrix	2×2
MTF	modulation transfer function	%
η_{LD}	laser diode efficiency	W/A
η_{BSC}	electron back-scattering coefficient	%
n	charge density	m^{-3}
n_{Zn}	doping concentration of Zn atoms	m^{-3}
n_{gr}	group refractive index	3.59
n_{ref}	refractive index of the waveguide	2.53
n_{bunch}	number of bunches	dimensionless
N	finite number	dimensionless
N_{A}	Avogadro number	$6.02214 \times 10^{23} \text{ mol}^{-1}$
N_{cc}	charge carrier number (electron number)	dimensionless
N_{Ce}	number of Ce atoms in YAG	$\approx 2.5 \times 10^{19} \text{ cm}^{-3}$
N_{D}	number of electrons within the volume of a Debye sphere	dimensionless
N_{eh}	number of electron hole pairs generated per MeV of deposited energy in Ce:YAG	$6 \times 10^4 \text{ MeV}^{-1}$
$N_{\tilde{g}}$	transparency electron number	dimensionless
N_{sat}	electron characterizing self-saturation	$0.8 \times N_{\tilde{g}}$
$\mathcal{O}$	represents orders of magnitude	a.u.
p	laser mode number	dimensionless
p_0	perveance	$2.33 \times 10^{-6} \text{ A/V}^{3/2}$
p_e	electron momentum ($E_{\text{kin}} = 100 \text{ keV}$)	0.34 MeV
P_e	electron polarization	$\simeq 80\%$ (SLSL)
P_L	laser power	W
$P_{L,\text{avr}}$	average laser power	W
$P_{L,\text{cw}}$	c.w. laser power	W
$P_{L,\text{peak}}$	peak laser power	W

A. List of variables

variable	description	value / unit
P_{RF}	RF power	W
ϕ_{RF}	phase of accelerator RF	°
$\phi_{\text{RF,bunch}}$	bunch length with respect to RF phase	°
q_{bunch}	bunch charge	C
q_e	charge of an electron	1.60218×10^{-19} C
Q	momentum transfer in scattering experiment	eV
ρ_{mat}	material density	kg/m ³
r_{ext}	extinction ratio of electronic shutter	200 – 400
r_{ij}	elements of the transfer matrix	
r_p	random number for mode p given by the standard normal distribution	dimensionless
R and R^T	transport matrix and transposed transport matrix	2×2
R_1 and R_2	reflectivity of the laser cavity end faces	17% and 98%
R_{angular}	angular acceptance of a slit mask	dimensionless
R_{beam}	space charge dominance of the incident beam	dimensionless
R_{CV}	dipole moment of the quantum wells	2.8×10^{-57} C ² m ²
R_{mask}	space charge dominance of the beamlets behind the slit mask	dimensionless
R_{sc}	space charge dominance	dimensionless
R_{separate}	beamlet separation behind the slit mask	dimensionless
σ_i	RMS value of an intensity distribution	pixel or m
σ_{beam}	RMS dimension of the transverse projection of the beam	m
σ_{calc}	calculated beam dimension	m
σ_{hole}	width of the holes in the mask	0.025 mm
σ_L	RMS dimension of the laser spot	m
σ_{meas}	measured beam dimension	m
σ_{quad}	quadrupole aperture	40 mm
σ_{scat}	scattering width	(32.74 ± 0.88) μm
σ_{slit}	slit width	0.025 mm
σ_{wire}	diameter of tungsten wire	0.040 mm

variable	description	value / unit
$\delta\sigma_i$	standard deviation of the RMS value of an intensity distribution	pixel or m
S_{GaAs}	wavelength dependent responsivity of GaAs	A/W
$S_{\text{ph},p}$	photon number in laser mode p	dimensionless
$\tau = E_{\text{kin}}/m_e c^2$	kinetic energy of an electron in units of the electron rest mass	0.20
τ_{bunch}	temporal bunch length	s
τ_{closed}	vacuum lifetime in the closed PKA2	> 1 a
τ_d	delay time between macro pulse and CMOS	s
τ_{hc}	time constant of high-current experiment	5.5 d
τ_{in}	intraband relaxation time	25 fs
τ_{mains}	time period of the mains frequency	20 ms
τ_{MESA}	length of the accelerator RF period	$\simeq 769$ ps
τ_{nr}	non-radiative recombination time constant	9 ns
τ_{pc}	photocathode response time	s
$\tau_{\text{pc},90}$	photocathode response time which includes 90% of the extracted charge	s
τ_{PKA2}	time an electron needs to pass through the PKA2	1.46 ns
τ_{pulse}	macro pulse duration	≥ 300 μ s
τ_{rad}	radiative recombination time constant	$\tau_{\text{rad}}^{-1} = \tau_{\text{sp}}^{-1} - \tau_{\text{nr}}^{-1}$
$\tau_{\text{rep}} = 1/\nu_{\text{rep}}$	length of the repetition period	0.2 s
τ_{sp}	spontaneous carrier lifetime	4.5 ns
τ_{vac}	vacuum lifetime	26 days
τ_{YAG}	decay constant of Ce:YAG	$\simeq 80$ ns
θ_W	weak mixing angle	rad
T	electron temperature	K or eV
T_e	electron transmission through the beam line	%
T_{ph}	photon transmission through the optical elements	%
U_{acc}	accelerating voltage	-100 kV
ν_{MESA}	accelerator radio frequency of MESA	1.3 GHz

A. List of variables

variable	description	value / unit
ν_{optic}	optical frequency	160 lp/mm
ν_{rep}	repetition frequency of macro pulses	5 Hz
v_e	electron velocity	m/s
$\omega_{\text{MESA}} = \frac{2\pi}{\tau_{\text{MESA}}}$	angular velocity corresponding to the accelerator RF of MESA	2.6π GHz
$\omega_{\text{ph}} = 2\pi\nu_{\text{ph}}$	angular velocity of a photon	Hz
w_0	dimension of the waist/focus in a Kaustik determination	m
w_{Ce}	doping fraction of Ce atoms in YAG	0.18%
w_i	weighting factor	dimensionless
$w_{\text{Int},i}$	weighting of beamlet intensity	dimensionless
w_o	mass fraction weightning factor	dimensionless
w_Y	Y fraction in YAG	0.449
χ_{EA}	electron affinity	eV
ξ_p	gain fluctuation parameter for mode p	set to equal 1
Ξ	integrated charge density of Ce:YAG	(0.048 ± 0.010) fC/ μm^2
x, y and s	coordinates of coordinate system in a three-dimensional space	m
x' and y'	to the coordinates corresponding angles	rad
$\overline{x'}$	mean divergence of all slits	rad
x'_i	mean divergence of i -th slit	rad
$\overline{x_0}$	mean position of all beamlets	m
$x_{0,i}$	position of the i -th beamlet on the screen	m
x_i	position of the i -th slit on the mask	m
z_R	Rayleigh length	m

B. List of publications

- 2016 **Diagnostic Test-Beam-Line for the Injector of MESA**
I. Alexander, K. Aulenbacher
Proceedings of IBIC2016: MOPG72
DOI: <https://doi.org/10.18429/JACoW-IBIC2016-MOPG72>
- 2015 **Diagnostic Test-Beam-Line for the MESA Injector**
I. Alexander, K. Aulenbacher, V. Bechthold, B. Ledroit, C. Matejcek
Proceedings of ERL2015: THIALH2069
DOI: <https://doi.org/10.18429/JACoW-ERL2015-THIALH2069>
- 2014 **Current Status of the Mainz Energy-Recovering Superconducting Accelerator Project**
M. Dehn, I. Alexander, K. Aulenbacher, J. Diefenbach, et al.
Proceedings of LINAC2014: MOPP096
- 2012 **The Polarimetry Chain for the P2 Experiment**
K. Aulenbacher, I. Alexander, V. Tioukine
Published in Nuovo Cim. C035N04 (2012) 186-191
DOI: <https://doi.org/10.1393/ncc/i2012-11301-y>
- 2011 **High Average Photocurrent Research at MAMI**
K. Aulenbacher, I. Alexander, E. Riehn, V. Tioukine
Published in J.Phys.Conf.Ser. 298 (2011) 012019
DOI: <https://doi.org/10.1088/1742-6596/298/1/012019>

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