



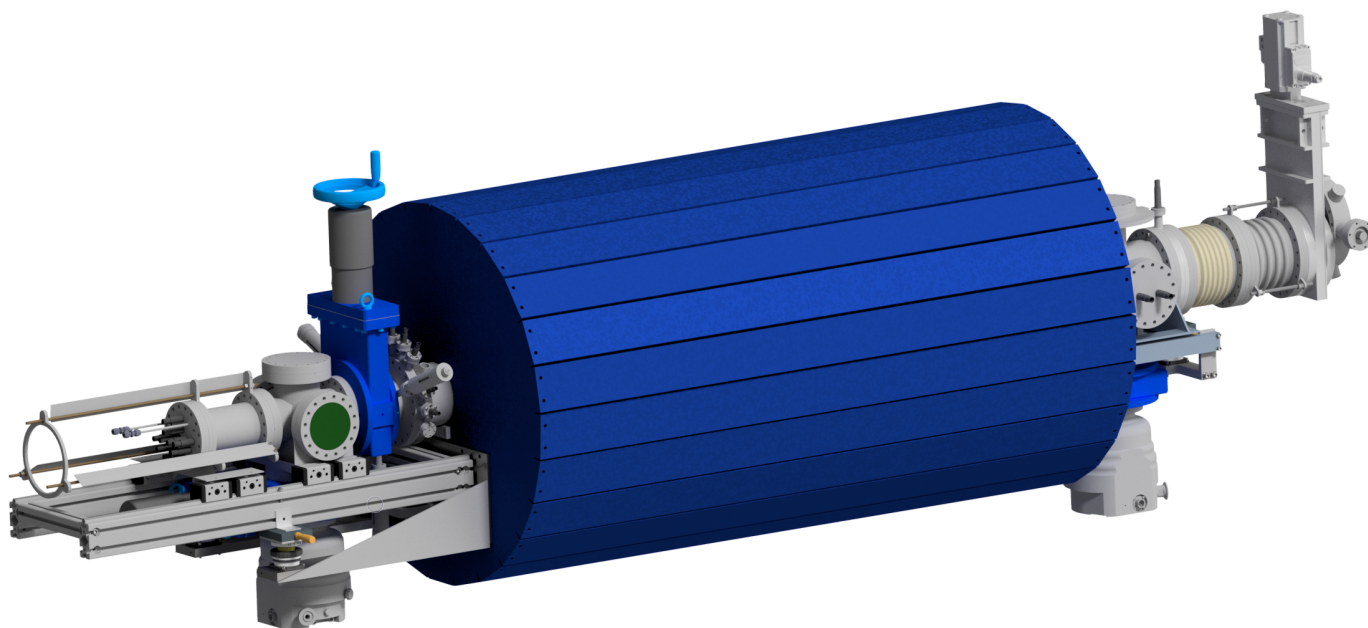
LUND UNIVERSITY

THESIS FOR THE DEGREE OF MASTER OF SCIENCE

Investigation of ion extraction anomalies at TwinEBIS

Niek van Woudenberg

Department of Physics
Division Of Nuclear Physics



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Supervisors

F. Wenander (CERN)
J. Cederkäll (LU)



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Abstract

The electron beam ion source REXEBIS at CERN-ISOLDE delivers highly-charged radioactive ions for post-acceleration in the HIE-ISOLDE LINAC. Research and development of components for electron beam ion sources is carried out at the TwinEBIS test stand, currently equipped with a Brillouin electron gun called MEDeGUN. Excessive ion extraction losses have been reported at TwinEBIS during commissioning tests of the gun, substantially reducing the efficiency of the device. As the beam time required for an experiment is directly related to the delivered intensity, maintaining a high extraction efficiency is therefore paramount.

With this in mind, a detailed study was launched to investigate if these losses could be attributed to a misalignment of the EBIS components in the collector region. Simulations of a misaligned geometry were performed in CST Particle Studio with two test beams. Furthermore, a study on the formation of a virtual cathode in the suppressor region was carried out, aiming to evaluate if losses could be produced by over-focusing of the ion beam. Also, a measurement series of the effective electron current density was undertaken at REXEBIS to determine if an electron-ion two-stream instability is present, that could lead to significant ion heating.

Simulations aimed to validate the MEDeGUN electron beam resulted in a perveance of $1.083 \text{ uA/V}^{3/2}$, which is in good agreement with previously performed measurements (accuracy of $<2\%$). Ion beam simulations in the collector region did not result in losses on the extractor for both test beams with an asymmetry of 0 mm and 1.75 mm. Only with a larger asymmetry of 3.5 mm, losses comparable to the measured values were found for the high neutralisation and extracted current test beam, where 43% of the injected current was lost on the extractor. Visual inspection of 'dust' in the ion extractor confirmed ion bombardment, however, the deposition was found to be radially uniform. The losses observed in the extractor can also not be explained by the formation of a virtual cathode, since the operational regime of the suppressor is distant from the critical condition.

An electron-ion two-stream instability was not confirmed by measurements carried out at REXEBIS, as the current density instead increased with the distance from the electron gun. This is contrary to the measurements at TwinEBIS, where the effective electron current density is reduced, consistent with an instability.

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List of Acronyms

CERN	Conseil Européen pour la Recherche Nucléaire
ISOLDE	Isotope Separator On Line DEvice
PSB	Proton Synchrotron Booster
LINAC	LInear ACcelerator
RIB	Radioactive Ion Beam
ISOL	Isotope Seperation On-Line
RILIS	Resonance Ionization Laser Ion Source
GPS	General Purpose Separator
HRS	High Resolution Separator
HEI-ISOLDE	High Energy and Intensity ISOLDE
EBIS	Electron Beam Ion Source
FC	Faraday Cup
RFQ	RadioFrequency Quadrupole
BTS	Beam Transfer Section
TOF	Time Of Flight
ECRIS	Electron Cyclotron Resonance Ion Source
EI	Electron Ionisation
RR	Radiative Recombination
DR	Dielectric Recombination
CE	Charge Exchange
ESC	ESCAPE
SRC	SouRCe
LDT	Last Drift Tube
OFHC	Oxygen-Free High thermal Conductivity
PIC	Particle In Cell
MS	Magneto-static
PEC	Perfect Electrical Conductor
SSD	Sum Squared Difference
TB	TestBeam
MLI	MultiLayer Insulation
VAC	VACuum

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Chapter 1

Introduction

1.1 Motivation

The objective of this thesis is to study beam losses in Electron Beam Ion Sources (EBIS) through simulations and complementary measurements. Specifically, the results presented here concern the TwinEBIS test bench situated at CERN's ISOLDE facility (See Section 1.3). This is an almost identical copy of REXEBIS [1], which is used to deliver highly-charged radioactive ion beams (RIB) for the HIE-ISOLDE experiment at CERN [2].

Measurements performed at TwinEBIS have reported excessive ion losses for numerous operational settings, resulting in a reduced efficiency. Since the incoming RIBs are already of low intensity ($100 - 10^7$ ions), obtaining a high efficiency is vital for the experiments utilizing the RIB. The beam time required for an experiment directly relates to the costs, and the number of experiments that can be carried out during a year. Similarly, higher beam intensities also influence which physics cases can be addressed. Consequently, the losses must be minimized in order to acquire and sustain a high efficiency.

A possible explanation of the observed losses could be a misalignment of the components of the EBIS inner structure, leading e.g. to field asymmetry. It was therefore decided to initiate an in-depth investigation of the ion extraction, using simulations, visual inspection and complementary measurements. Practically, the goals have been to:

- Determine ion losses for different ion starting conditions and for asymmetric electric field configurations with respect the magnetostatic beam axis.
- Explore the extent to which electron reflection could cause over-focusing of the extracted ion beam in the beginning of the exit region where the electron beam is collected.
- Investigate if the effective electron beam current density at REXEBIS is varying with the axial position, which could indicate the presence of a electron-ion two-stream instability. Such an instability may occur at TwinEBIS and could then cause significant ion heating.

The second point is also of interest for the electron beam propagation through the system as a whole.

Thesis structure

This introduction chapter is followed by a description of the working principle of an EBIS with an explanation of electron guns and charge breeding. The ensuing method chapter, describes the tools, procedures and software employed to perform the study. The results and discussion of the simulations and measurements are presented in Chapter 4. In the closing chapter, Chapter 5, the work is concluded and an outlook is given, based on the outlined goals and results presented.

1.2 CERN

CERN is known for exploring fundamental particle physics with the goal of describing the particles and forces constituting the universe. This is achieved through engineering and design of complex accelerator systems for high energy particle collisions. The CERN accelerator complex consists of several accelerators and beam lines that transport the particle beams to the different experiments and facilities, see Figure 1.1. One of the experiments at CERN is ISOLDE (isotope separator on line device), where the proton beam from the proton synchrotron booster (PSB) is used to produce radioactive ions. ISOLDE is one of the main users of the protons accelerated by linear accelerator 4 (LINAC4) and PSB and uses approximately 50% of the produced protons in a year.

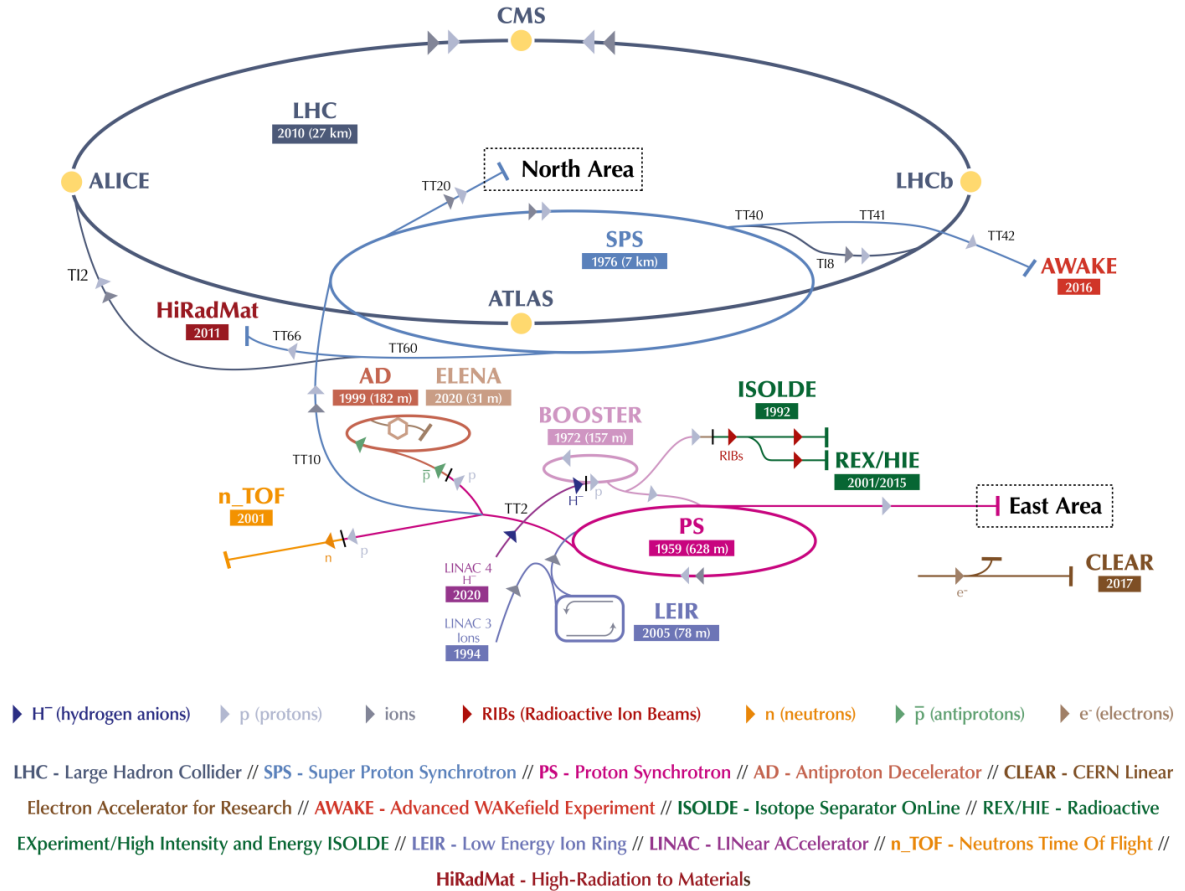


Figure 1.1: A layout of the accelerator complex at CERN, illustrating the cascade of accelerators and a selection of experiments. Reproduced from [3].

1.3 ISOLDE

At ISOLDE, experiments with RIBs are performed in a large number of areas, ranging from nuclear astrophysics to life sciences. The significance of the research carried out at ISOLDE is reflected by the publication of more than 1400 research papers since 2003 [4–11]. The RIBs at ISOLDE are produced using the isotope separation on-line (ISOL) method [12]. In this method, a thick target is bombarded with a proton beam, which at ISOLDE has an energy of 1.4 GeV and a pulse rate of 1 Hz. More than 700 different radioactive isotopes in the nuclear landscape can be produced and extracted with different intensities. This mixture of radioactive isotopes is extracted by heating the target, thereby increasing the diffusion rate and allowing extraction of shortly lived nuclei with lifetimes in the ms range. After extraction from the target, the radioactive atoms are ionized by different types of ion sources, e.g. plasma, hot surface or by resonance ionization laser ion source (RILIS), and transported to an analyzing magnet, where mass separation takes place. At ISOLDE there are two target stations connected to two separators, the general purpose separator (GPS) and the high resolution separator (HRS), both indicated in Figure 1.2. Their respective exit beam lines are merged into a single one, so that after separation, the singly-charged ions can be transported to the low-energy beam lines or to REX-ISOLDE [4, 13, 14].

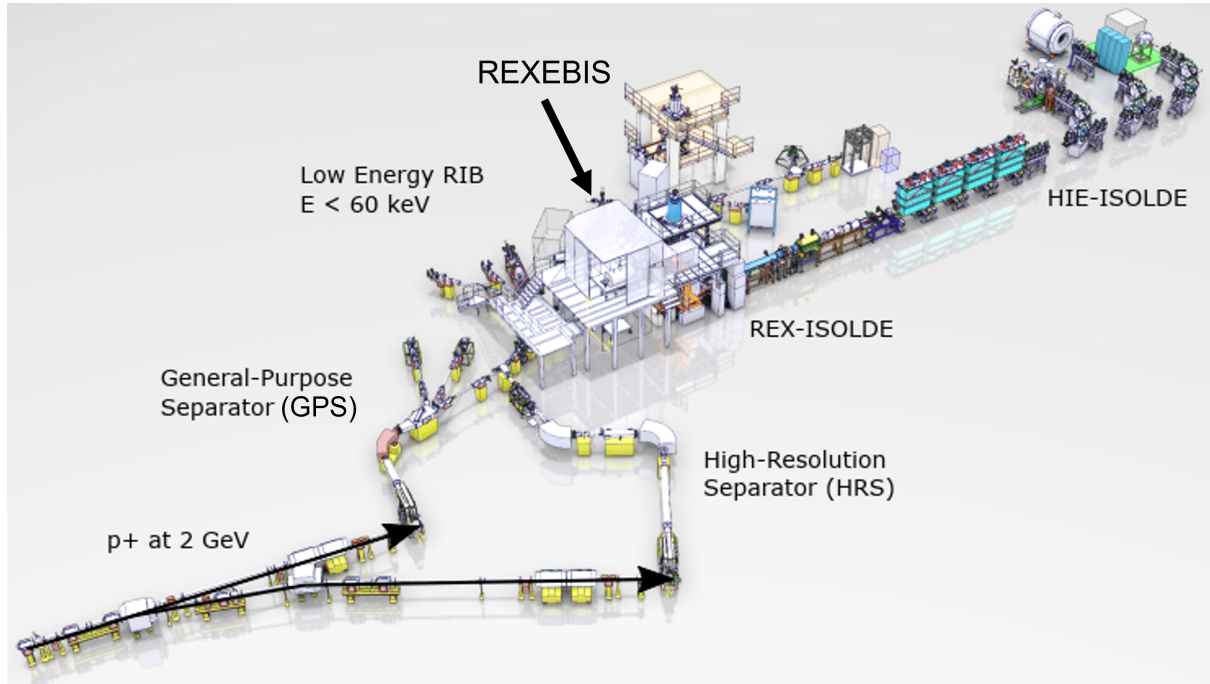


Figure 1.2: A 3D visualisation of the ISOLDE facility with the GRS & HRS target stations and separators, the low energy beam-lines, REX-ISOLDE and HIE-ISOLDE. Figure kindly provided by N. Bidault.

1.4 REX low-energy stage

The first step of REX-ISOLDE is to increase the charge state of the radioactive ions coming from the on-line separator for efficient acceleration to higher energies in the consecutive LINAC at HIE-ISOLDE (high intensity and energy ISOLDE). Increasing the charge state, i.e., charge breeding, is performed in REXEBIS, seen in Figure 1.3. This ion source is capable of producing many species of highly-charged ions, in short pulses with high intensity and efficiency. To match the beam to the injection acceptance of REXEBIS, the RIB is cooled and bunched inside REXTRAP, a Ne gas-filled Penning trap. In normal operation, REXTRAP receives singly charged ions from GPS or HRS in a continuous mode. Once the ions are conditioned in the Penning trap, they can be injected and charge bred to higher charge states. When the beam is extracted from REXEBIS, it also contains residual gas ions from both the buffer gas and the background gas. These contaminants can be removed by a mass separator that is installed after REXEBIS. The separation is based on the A/Q -ratio of the ions, where A denotes the mass number and Q the charge state. The currents before and after mass separation can be measured by two Faraday cups (FC), FC3 and FC4, respectively, which can be inserted into the beam path. A low-energy beam transfer line transports the beam to the acceleration stage, which consists of a radio frequency quadrupole (RFQ), different types of room-temperature accelerating cavities, and finally several cryostats housing superconducting cavities. This machine is capable of accelerating the beam to energies between 3-10 MeV/u, for a mass-to-charge ratio of $A/Q \leq 4.5$. The RIB can then be directed to different experiments [1, 15–19].

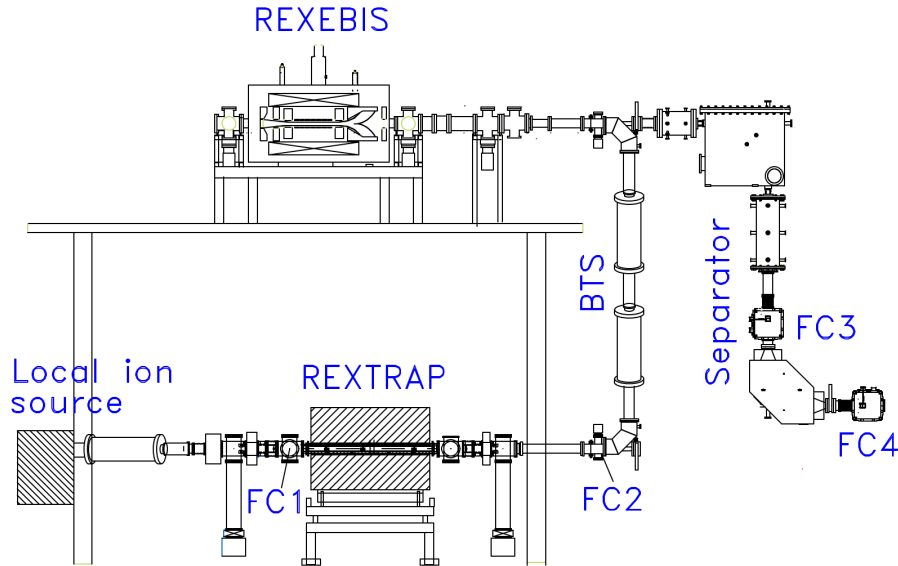


Figure 1.3: Schematic of the REX low-energy stage, showing REXTRAP, REXEBIS and the REX separator. Normally, singly charged ions are fed from ISOLDE into the system, but for setting up, K^+ ions can be produced in the local ion source in front of REXTRAP. After accumulation and cooling of the ions inside the Penning trap, the ions are transported to REXEBIS by the Beam Transfer Section (BTS). Following charge breeding (see Section 2.4), the desired ion species is selected in the separator. The total extracted current is measured with FC3, while the separated current is measured with FC4. Reproduced from [20], licensed under CC BY 4.0.

1.5 TwinEBIS test bench

Research and development of EBIS components at CERN is performed at the test bench TwinEBIS, seen in Figure 1.4. The design of the internal components of the TwinEBIS is similar to that of REXEBIS used at ISOLDE. An important component of an EBIS is the electron gun that produces the electron beam, which is used to increase the charge state of the ions by electron impact ionisation. One application of TwinEBIS is therefore, to test and characterize different types of electron guns. Presently, a Brillouin type electron gun, MEDeGUN, is used at TwinEBIS (see Section 2.2). This electron gun was designed for an EBIS aimed at C^{6+} production in future LINAC-based hadron therapy [21]. This type of gun can achieve significantly higher compression with respect to the immersed gun at REXEBIS, which results in higher electron current density. Previously, measurements with MEDeGUN have been carried out during comissioning. An electron beam with a current of up to 1.5 A has been transported through the system, with acceptable electron losses, that mainly occurred on the anode and last drift tube (LDT) [22]. Following the TwinEBIS itself, an ion extraction line is foreseen, but until now only a combined FC and Time-of-Flight (TOF) system have been used for ion extraction studies [23, 24].

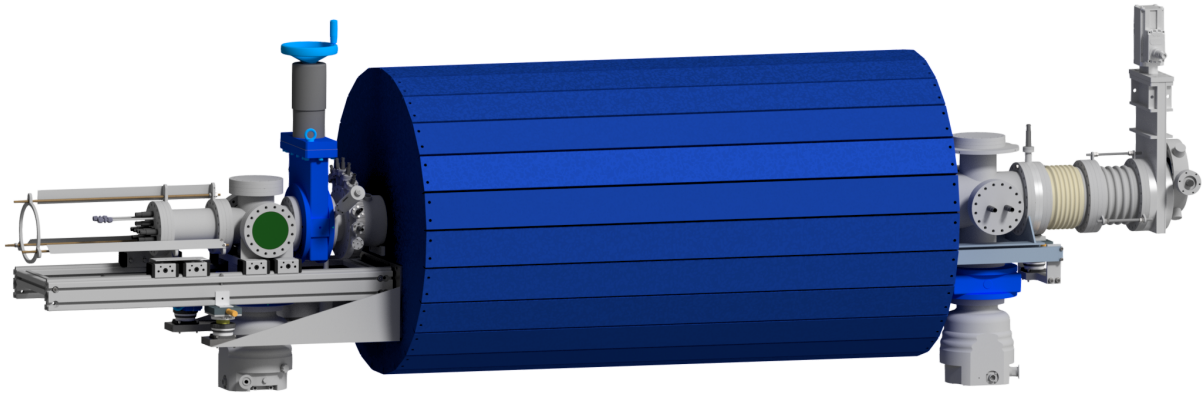


Figure 1.4: TwinEBIS test bench with housing of the electron gun and collector on the left and right respectively. The magnet iron screen can be seen in blue.

During first tests of the ion extraction at TwinEBIS, where neutral gas was injected, it was found that only a fraction of the theoretical ion capacity was extracted. Furthermore, the TOF spectra indicated low attainable charge states, even for increased breeding times. A down-stream extension of the ion extractor electrode was therefore introduced, to avoid possible strong beam retardation before the beam enters the acceleration gap. Tests were continued with injection of either Ar or isotopically enriched ^{129}Xe gas. However, impinging current on the ion extractor was reported for numerous settings as well as an effective electron current density that declined rapidly with increasing breeding time, see Figure 1.5. In one of the measurements, the collected charge on the FC and extractor was measured for different breeding times and extractor voltages, presented in Figure 1.6a. The relative losses are indicated in Figure 1.6b and for breeding times greater than 5 ms, the losses are higher than 50% for all extractor potentials, in other cases even more than 80%. There exists a clear correlation between losses and ion extractor potential. The primary motivation of the work presented here, lies in addressing these excessive ion losses leading to a substantial decrease in the efficiency of TwinEBIS.

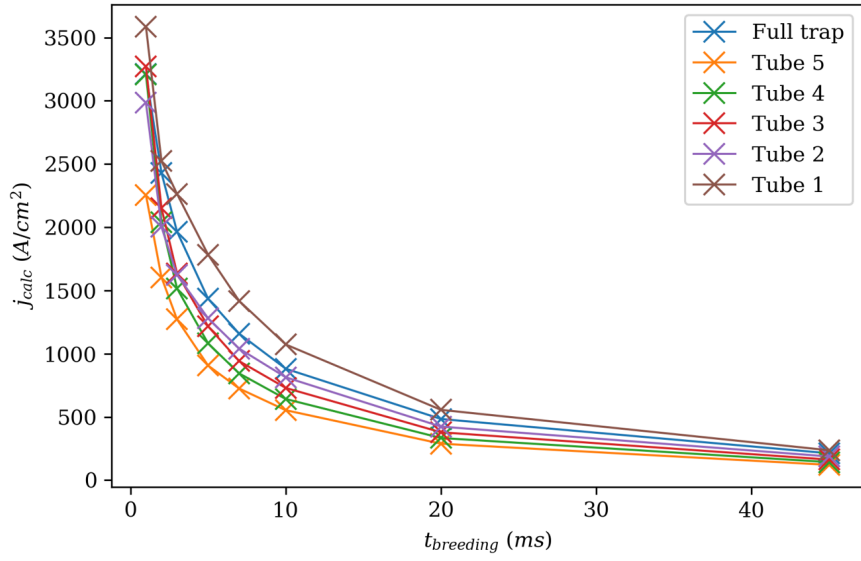


Figure 1.5: Measurements of the effective current density expressed as a function of the breeding time for different trap combinations at TwinEBIS. Tube 1 is situated close to the gun while Tube 5 is furthest from the gun.

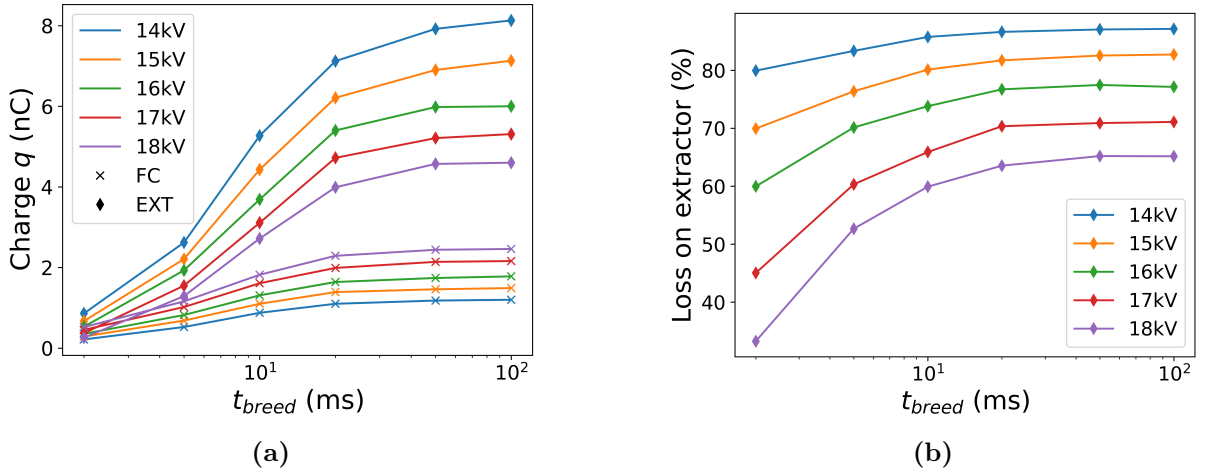


Figure 1.6: (a) Collected charge on the Faraday cup (FC) and ion extractor (EXT). (b) Relative loss on extractor for different extractor potentials. Both expressed as a function of the breeding time.

Chapter 2

Theory

An EBIS is able to deliver highly-charged ions of a large variety with unprecedented intensity, high purity and in short pulses. This chapter will explore the physical principles underlying the operation of EBIS devices, as well as their various components and sub-systems. The theory behind EBIS devices is complex, involving a multitude of physical phenomena. Therefore, the theoretical discussion presented in this chapter is limited to an overview. For a more comprehensive and detailed explanation the reader is referred to [25–29].

2.1 EBIS principle

Charge breeding in an EBIS is driven by electron ionisation (EI), facilitated by an electron beam. The electron beam is generated by an electron gun, typically installed at the far end of the EBIS, see Figure 2.1. A high current density is achieved by compression of the electron beam, initially by the focusing electrical field in the gun and thereafter by an external magnetic field. The external magnetic field is usually produced by a superconducting solenoid magnet, with a central field strength in the order of a few Tesla. Charge breeding of the ions takes places inside the drift tube structure (grey tubes in Figure 2.1) at full field, where the electron beam radius is small. The drift tube structure is also referred to as breeding region or trapping region. The space charge potential (ϕ_r), generated by the highly compressed electron beam, is responsible for the radial confinement of the ions. The axial confinement of ions is realized by applying a potential barrier to the outer and inner drift tubes of the trapping region (ϕ_a). Due to the strong reduction in the axial magnetic field at the end of the trapping region, the electron beam is diverted and deposited into the collector. The ions are released from the trap by the lowering the outer barrier potential (ϕ_{out}) in a pulsed operation mode, see the dotted line in Figure 2.1. Subsequently, the ions are accelerated and extracted [26,27,30].

2.2 Electron guns

The electron beam used in an EBIS allows for precise and accurate control of the ionization process, which enables production of ion beams with a specific range of charge states tailored to experimental needs. An emitting surface, referred to as the cathode, and a

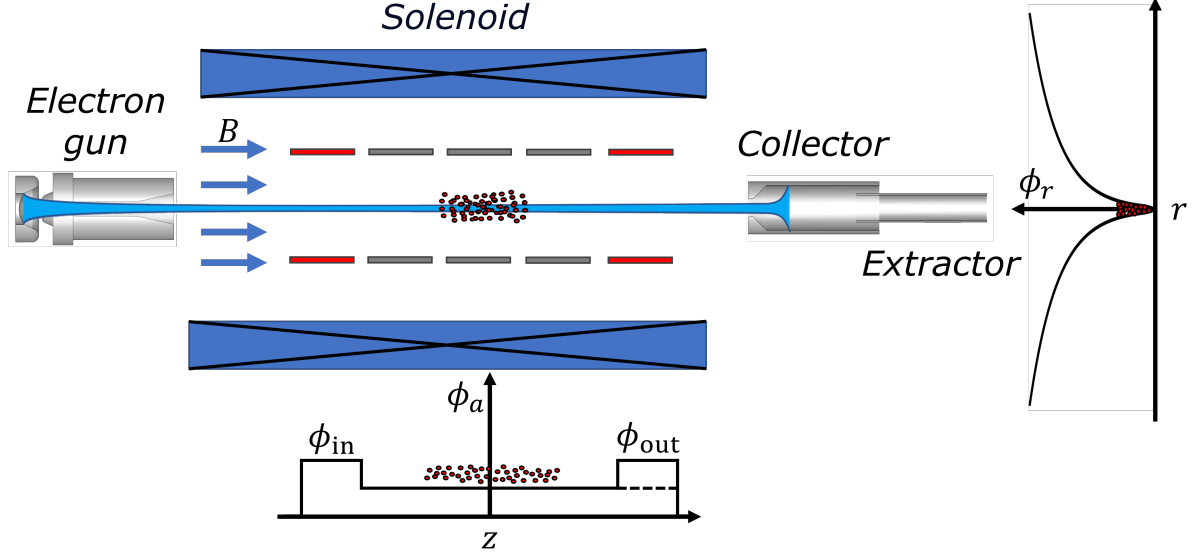


Figure 2.1: Schematic representation of the principle and components of an EBIS. The electron gun, solenoid magnet, collector and extractor are shown, including the radial and axial trapping potentials, indicated by ϕ_r and ϕ_a , respectively. B denotes the axial magnetic field and ϕ_{in} and ϕ_{out} the inner and outer barrier potentials (colored in red).

reference potential, known as the anode, comprise the electron gun. Generally, a heated filament cathode is used, where the electrons are released by thermionic emission and are extracted by the anode potential. Emitted electrons from the surface will produce a field that counteracts the applied accelerating field. The maximum attainable current is reached when the applied electric field and the space charge field are in equilibrium. The space charge limited emission of electrons from the cathode surface is described by the Child-Langmuir (CL) law [31–34],

$$j_{CL} = \frac{4}{9} \epsilon_0 \left(\frac{2e}{m_e} \right)^{1/2} \frac{V^{3/2}}{d^2}, \quad (2.1)$$

where j_{CL} is the extracted current density, ϵ_0 the vacuum permeability, e the elementary charge, m_e the electron mass, V the accelerating potential and d the distance between anode and cathode. The Child-Langmuir law only holds for non-relativistic velocities.

The performance of an electron gun can be described by its perveance, P . To enable the emission of a high current at a low applied voltage, a high perveance is required. It expresses the maximum obtainable electron current I_e for a specific gun geometry, given an accelerating potential V as,

$$I_e = P \cdot V^{3/2}. \quad (2.2)$$

2.2.1 Brillouin guns and immersed guns

In an EBIS, the electron gun can be installed in two different magnetic configurations: the immersed gun, positioned within the fringe field of the main solenoid, or the Brillouin gun, situated in a field-free region. In an immersed electron gun the electrons are created

in, and guided by the axial magnetic field. The compression of such an electron beam scales with B_z/B_c , where B_z is the full axial field and B_c the field on the cathode. This means that for higher field on the cathode, the compression is reduced and, as a result, the resulting current density is lower. A higher current density can be achieved by employing a Brillouin gun. In this type of gun the cathode is shielded from magnetic field by either an iron mantle or by a compensating solenoid. Inside the electron gun, the electrons are focused by the electric field and subsequently, guided and compressed adiabatically by the magnetic field ($j \propto B_z^2$) once they leave the shielded region. In Brillouin flow the space charge forces are exactly balanced by the magnetic forces, and under this condition the electron beam is at its maximum compression. In the case of a non-zero transverse velocity, the electrons will perform a gyro-motion, following the magnetic field lines on the cyclotron radius. For a non-adiabatic gun, the magnetic field is locally disturbed by an iron shield or a small coil, which results in a reduction of the magnetic field. Generally, it is used to control the cyclotron motion of the electrons, improving the flow conditions and increasing the current density [35, 36].

2.2.2 Herrmann radius

One of the properties crucial for predicting the current density is the transverse size of the electron beam. In the space charge limited regime, with no magnetic field and temperature on the cathode, the flow is considered Brillouin and electrons propagate alongside each other without crossing. The beam radius can under these conditions be approximated by the Brillouin radius r_B [37], expressed as,

$$r_B[\text{cm}] = \frac{147.6[\mu\text{m}]}{B_z[\text{T}]} \sqrt{\frac{I_e[\text{A}]}{\sqrt{E_e[\text{keV}]}}}, \quad (2.3)$$

where E_e is the energy of the electron beam.

A more realistic case, including the effects of magnetic field and temperature on the cathode, is described by Pierce and further improved by Herrmann [38, 39]. This 'corrected' Brillouin radius, or Herrmann radius, is given by,

$$r_H = r_B \left(\frac{1}{2} + \frac{1}{2} \left(1 + 4 \left(\frac{8k_b T_c r_c^2 m_e}{e^2 B_z^2 r_B^4} + \frac{B_c^2 r_c^4}{B_z^2 r_B^4} \right)^{1/2} \right)^{1/2}, \quad (2.4)$$

where k_b is the Boltzmann's constant, T_c the cathode temperature, r_c the cathode radius, B_z the axial magnetic field and r_H the Herrmann radius. The latter is generally conceived as containing 80% of the current.

2.3 Space charge potential

The highly compressed electron beam causes a strong potential field due to the enclosed charge, which is referred to as the space charge potential. In a drift region, the total experienced effective potential by the ions is a combination of the space charge potential of the electron beam and the external magnetic field. The trapping potential can therefore

be expressed by equation 2.5, containing both electric (term 1) and magnetic potentials (term 2). The effective potential is given as,

$$\phi_{r,eff}(r) = \phi_r(r) + \frac{eQB^2r^2}{8m_i}, \quad (2.5)$$

where $\phi_{r,eff}(r)$ is the experienced radial potential at a distance r from the beam axis, Q the charge state, $\phi_r(r)$ the space charge potential of the electron beam, e the elementary charge, B the magnetic field strength and m_i the ion mass, all expressed in SI units. The magnetic term is in most cases small compared to the electrostatic force, particularly for particles inside the electron beam, and therefore ignored. An expression for the space charge potential, $\phi_r(r)$, can be found by solving Poisson's equation and is expressed by [40],

$$\phi_r(r) = \frac{\sqrt{m_e/2}}{4\pi\epsilon_0} \frac{I_e}{\sqrt{E_e}} \begin{cases} \frac{r^2}{r_e^2} & \text{for } r \leq r_e, \\ (2 \ln \frac{r}{r_e} + 1) & \text{for } r \geq r_e, \end{cases} \quad (2.6)$$

where r_e is the electron beam radius. Although Equation 2.6 is expressed for an electron beam here, the relation is valid for any charged particle beam with a uniform distribution. Figure 2.2 shows the space charge potential of a typical electron beam in the TwinEBIS trapping region. Because the radius described by Herrmann depends on the energy, the electrons will redistribute themselves under the influence of their own potential and a correction has to be applied. A detailed calculation of the space charge potential inside the trap is shown in Appendix A.

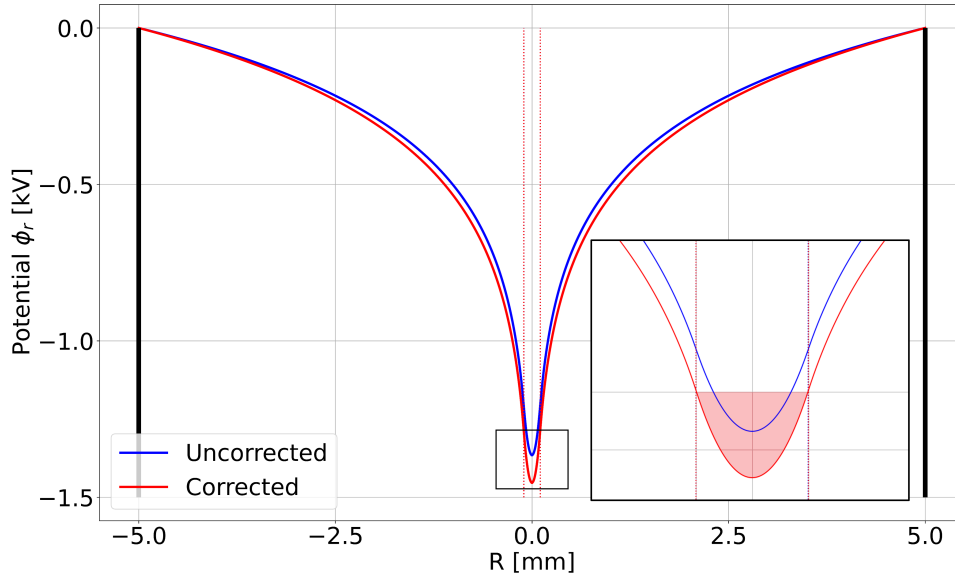


Figure 2.2: The corrected and uncorrected radial potential in a drift tube (black solid lines) with typical TwinEBIS parameters. The electron beam radius is indicated by dotted lines and by the red shaded area for the corrected case.

2.3.1 Bursian instability

Another effect of the space charge potential is the compensation of applied external accelerating fields that are present in the system. Due to the interplay between the self-electric field of the beam and the external fields, a virtual cathode can arise. It occurs when the space charge of the electron beam becomes so intense that it forms a localized potential that opposes the flow of electrons. This is usually a concern in regions of beam focusing, where the charge density is very high. The Bursian limit defines the threshold at which the virtual cathode forms and represents the maximum current that can be transported for specific beam parameters [41–44]. The maximum current is given as,

$$I_{max} = \frac{2}{3\sqrt{3}} 4\pi\epsilon_0 \sqrt{\frac{2e}{m_e}} \frac{\Phi_0^{3/2}}{2\ln(r_{dt}/r_e) + 1} \approx 25.4 \mu A / V^{3/2} \frac{\Phi_0^{3/2}}{2\ln(r_{dt}/r_e) + 1}, \quad (2.7)$$

where r_{dt} is the drift tube radius and ϕ_0 the applied potential between cathode and drift tube. The stability criterion is given by the space charge potential ϕ_{sc} as,

$$\phi_{sc} = -\frac{2}{3}\phi_0. \quad (2.8)$$

2.4 Charge breeding

Charge breeding is the process of increasing the charge state of single charged RIBs or injected neutral gas. The highly charged RIBs can then be used in either trapping experiment or efficiently be post-accelerated to higher energies. There are in principle three methods to increase the charge state: electron foil stripping, injection into an EBIS or injection into an ECRIS (Electron Cyclotron Resonance Ion Source). This work will only discuss and present results on EBIS-type charge breeding, which rest on the principle of electron impact ionisation [40, 45, 46].

2.4.1 Increasing the charge state

The charge state of the ions is increased through successive electron impact ionisation by an electron beam. High energy electrons knock out electrons from the target ion, resulting in a higher charge state, i.e. $A^{n+} + e^- \rightarrow A^{(n+1)+} + 2e^-$. The charge state evolution can be modelled by keeping track of the processes that either increase or decrease the charge state. This is done by using charge conservation and rate equations. The different production and loss mechanisms with their respective cross sections are given in Table 2.1.

Using this nomenclature, the rate of change of particles for one species in charge state Q is given by,

$$\begin{aligned} \frac{dN_Q}{dt} = & \frac{j_{eff}}{e} [\sigma_{q-1}^{EI} N_{q-1} - (\sigma_Q^{EI} + \sigma_Q^{RR} + \sigma_Q^{DR}) N_Q + (\sigma_{q+1}^{RR} + \sigma_{q+1}^{DR}) N_{q+1}] \\ & - n_0 v_{ion} [\sigma_Q^{CX} N_Q - \sigma_{q+1}^{CX} N_{q+1}] - N_Q R_Q^{ESC} + N_Q^{SRC}, \end{aligned} \quad (2.9)$$

Table 2.1: The charge breeding processes, including their respective acronyms, the corresponding cross section symbols and a short description.

Process	Acronym	Symbol	Description
Electron Impact Ionisation	EI	σ^{EI}	Ionisation can occur when the impact energy exceeds the binding energy of the bound electron.
Radiative Recombination	RR	σ^{RR}	Capture of an electron from the beam and emission of a photon.
Di-electronic Recombination	DR	σ^{DR}	A resonant process in which a capture of the electron occurs and results in a double-excited state that later decays with the emission of either a photon or an Auger electron.
Charge Exchange	CE	σ^{CE}	Ions capture an electron from collision with neutral atoms.
Charge Escape	ESC	σ^{ESC}	Escape of ions through diffusion.
Source	SRC	σ^{SRC}	Single charge or neutral gas.

where j_{eff} is the effective current density, $N_{\pm 1}$ the number of particles in the current or neighbouring charge states, R_Q^{ESC} an escape term and $\sigma_{q\pm 1}^p$ the cross sections. The ionisation and recombination cross sections are also a function of the electron beam energy. In this model, temperature effects are ignored, also, only coupling of neighbouring charge states is considered and it includes only charge exchange with neutrals because of the large Coulomb repulsion between ion species [45, 47, 48].

2.4.2 Effective current density

The probability of ionisation scales with the effective current density of the electron beam, making it an essential parameter for the charge breeding process. When ions are injected with a non-zero energy, they undergo oscillations within the radial potential well of the electron beam (depicted in Figure 2.2), and may not consistently remain within the electron beam. Consequently, the effective current density for charge breeding is reduced. This reduction is calculated by taking into account the fractional time that the ions spend in the electron beam, as the ions can only be ionized when struck by the electron beam. The effective current density is expressed by,

$$j_{e,eff} = j_e \kappa = j_e \frac{t_{inside}}{t_{total}}, \quad (2.10)$$

Here j_e is the electron beam current density, $\kappa = t_{inside}/t_{total}$ the temporal overlap factor, t_{inside} the time that the ions are within the electron beam, and t_{total} is usually defined as the breeding time and is the time that the ions are trapped within the EBIS before being extracted. The breeding time is an operational parameter and is set according to the desired charged state of the ions [45].

2.4.3 Neutralisation

The neutralisation degree is a measure of the compensation of the electron space charge potential by the ion cloud in the trap and is directly linked to the space charge potential introduced in Section 2.3. The space charge potential of the electron beam traps the ions, that partially neutralise the negative charge. As a result, the space charge potential of the beam becomes less deep, and ions with adequate kinetic energy may spend time outside the electron beam, thereby decreasing the effective electron current density. The linear charge density ρ can be used to define the neutralisation factor inside the trap, as expressed by,

$$\eta_{trap} = \frac{\rho_i}{\rho_e}. \quad (2.11)$$

This definition does not cover high local neutralisation degrees, for example, when ions are cold and situated along the axis of the electron beam, the neutralisation can be very high in this case, even though the ion linear charge is low compared to the electron linear charge. The degree of neutralisation in an EBIS is dependent on the pressure in the breeding region (but also on the breeding time), where a higher pressure corresponds to a greater level of neutralisation.

The neutralisation outside of the trap (in the LDT) can be expressed as,

$$\eta_{LDT} = \frac{I_i v_e}{I_e v_i}, \quad (2.12)$$

where v is the velocity and I the current of the ions and electrons, with subscript i and e respectively.

2.4.4 Ion heating

Ion heating refers to the process where ions gain energy through the ionisation process, collisions or by plasma instabilities. When ions gain energy, they might at some point have enough energy to overcome the confinement potential of the electron beam and be lost. This can be mitigated by introducing cooling gasses into the trap. In the case of electron impact ion heating (collisions), the heating rate is inversely proportional to the charged state and the mass of the ions. Additionally, plasma instabilities might occur, for instance, it is suggested that the electron-ion two-stream instability acts on the ions until they are driven out to very large radii (corresponding to a large ion temperature). In Figure 2.3, the crossing between the two curves indicates the ion temperature and electron-ion overlap factor (κ) when the two-stream ion heating halts for typical TwinEBIS parameters. As can be seen, the overlap factor is very small and the normalized temperature so high ($\sim 11.5 \text{ T}/\Delta\phi_{sc}/Q$) that ions may be lost radially to the drift tube. For more information regarding ion heating, the reader is referred to [49–52].

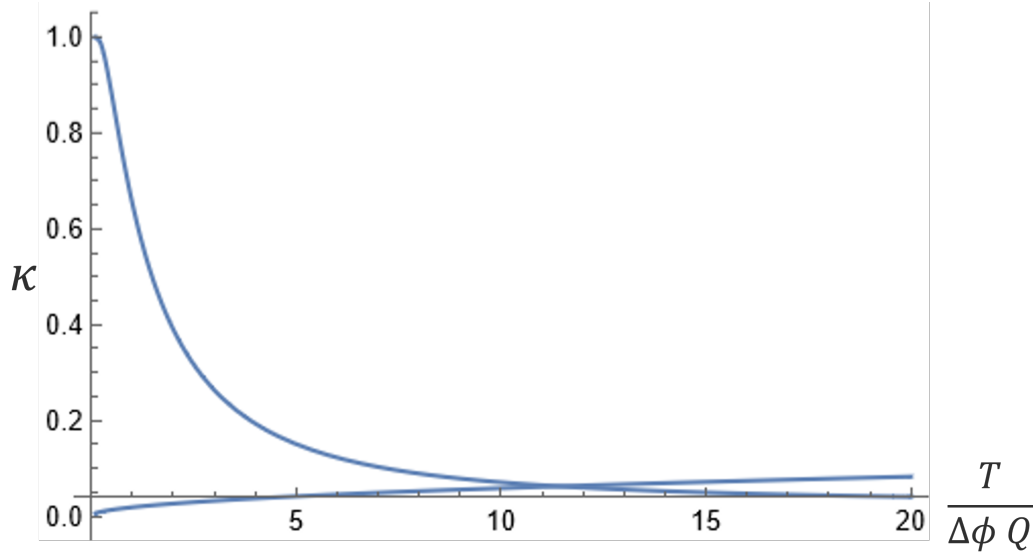


Figure 2.3: Predicted electron-ion overlap (κ) and ion temperature (normalized by charge Q and depth of electron beam potential $\Delta\phi_{sc}$) for typical TwinEBIS commissioning parameters, i.e. $I_e=1 \text{ A}$, $E_e=8000 \text{ eV}$, $129\text{Xe}20+$ at 0.3 neutralization degree.

Chapter 3

Setup and Method

3.1 Setup

3.1.1 REXEBIS

REXEBIS, the charge breeder for HIE-ISOLDE, was introduced in Section 1.4. The electron gun installed at REXEBIS is of a non-adiabatic type, immersed in an fringe field of 0.07 T. It is designed to have a perveance of $0.87 \mu\text{A}/\text{V}^{3/2}$ and to generate >500 mA electron beams at an energy of ~ 6 kV. A superconducting solenoid, manufactured by Oxford Instruments, provides a central magnetic field of 2.0 T at 4.2 K in a persistent operation mode. At full field the electron beam radius is approximately $187 \mu\text{m}$. A large iron screen limits field leakage into the surrounding area. The superconducting magnet is 1200 mm long and has a 150 mm diameter warm bore with a full-field region of around 800 mm. The magnetic field increases the current density from $\sim 10 \text{ A}/\text{cm}^2$ at the cathode to $\sim 300 \text{ A}/\text{cm}^2$ in the breeding region, at a typical operational current of 250 mA. Three trapping tubes, trap tube 1 with a length of 400 mm and trap tubes 2 and 3 with lengths of 200 mm, all with an inner radius of 5 mm, are constituting the breeding region and are axially surrounded by two short barrier tubes. Typical pressures in this region are $<10^{-10}$ mBar. The tube potentials are set by function generators feeding power converters. Apart from external injection of singly charged ions, neutral gas injection directly into the EBIS can also be used. In the measurements presented in this work, ^{129}Xe was injected by connecting a gas bottle to the gas inlet at the gun side [1, 16, 20, 53, 54].

3.1.2 TwinEBIS with MEDeGUN

The TwinEBIS test bench, which was previously introduced in Section 1.5 is also located at CERN and currently equipped with a Brillouin type electron gun called MEDeGUN. This electron gun is capable of delivering currents higher than 1 A for a given anode-cathode potential of 10 kV. Figure 3.1 shows the layout of the TwinEBIS setup. A magnetic shielding structure (made of ARMCO iron) reduces the magnetic field on the 6 mm radius cathode significantly (~ 0.4 mT) and a Wehnelt electrode [55] is installed around to cathode to provide additional focusing. The beam is compressed to a radius of $\sim 100 \mu\text{m}$ in full field. This would theoretically suggest current densities higher than

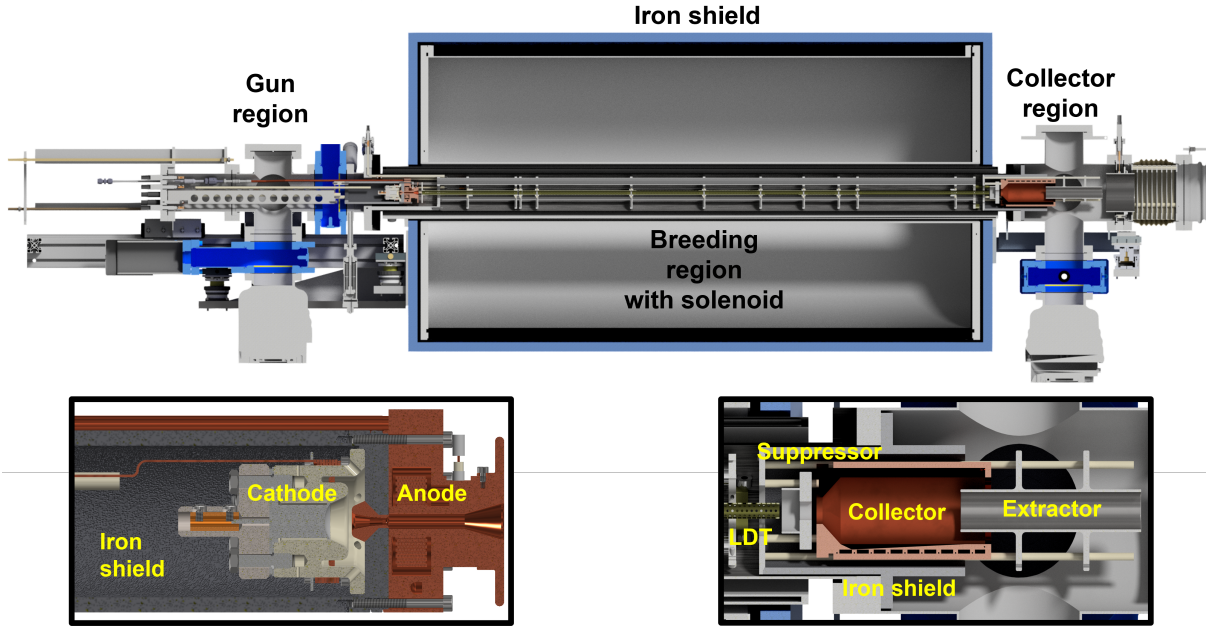


Figure 3.1: Mechanical drawing of the TwinEBIS. Cutouts show a zoom of the gun and collector regions.

3000 A/cm² at a 2 T field. The breeding region of TwinEBIS consists of five drift tubes, compared to the three at REXEBIS, with lengths ranging from approximately 90 to 250 mm, all with an inner radius of 5 mm. On each side of the trap are two short barrier tubes, the outer one being pulsed in time for ion extraction. After the outer drift tube follows the LDT, which leads the beam to the suppressor. The purpose of the suppressor is to avoid secondary electrons (produced on the collector walls) from returning back into the trapping region. The water-cooled electron collector is made of OFHC (Oxygen-Free High thermal Conductivity) copper and is shielded by an iron shield made of ARMCO, reducing the field to <0.02 T inside the collector. The ion extractor is identical to the one used at REXEBIS, although at the downstream end an extender is installed to keep the ions at the extraction potential until they reach the acceleration gap (not shown in Figure 3.1). After the acceleration, a gridded electrostatic lens is positioned to focus the beam onto a FC or into the TOF spectrometer. The FC is surrounded by a suppressor electrode to avoid overestimation of ion current readings due to escaping electrons [21, 23, 24, 56].

3.2 CST Studio Suite

All simulations in this work were carried out using the commercial package CST Studio Suite [57]. This 3D simulation software offers multiple specific simulation tools to study different problems in a dedicated graphical user interface. The main advantages of using such a commercial software package are the flexibility in defining geometries, ease of preliminary analysis and combined solver capabilities. CST Studio Suite consists of several sub-modules, each suitable for different applications. The magnetic field simulations were carried out in CST EM Studio. This module can calculate and export magneto- and electrostatic field-maps for defined geometries. For ion and electron beam tracking, the

module CST Particle Studio was employed [58]. This tool has different types of solvers that can be used depending on the tracking purpose. Apart from simple particle tracking, it can solve self-consistent fields and perform Particle In Cell (PIC) simulations [59–61]. It is important to emphasize that simulation results do not inherently reflect reality, and furthermore, variations can arise between outputs from different simulation codes and methods [62].

Because of the discrete nature of the simulation program, the geometry has to be defined on a computational grid, called a mesh. The meshing is a discrete subdivision of the defined geometry in cells and determines the precision of the represented geometry as well as the precision of the results. In CST Studio Suite it is possible to generate cells with a hexahedral or a tetrahedral shape. For the same amount of cells, a hexahedral meshing is more accurate, however, a tetrahedral meshing can produce much higher mesh density in very localized regions [63].

3.2.1 Solvers

Magnetostatic

The magnetostatic solver (MS) is able to solve magnetic problems where sources are defined by currents, coils, permanent magnets or source fields. For example, it can generate field maps for dipoles, quadruples, sextupoles and other type of magnetic components with complex geometries. The resulting magnetic field strength and flux density can be exported into other types of problems by defining a field source. Simulations of the magnetic field produced by the superconducting solenoid were performed in the MS solver and the field maps were exported.

Particle Tracker

Tracking of charged particles through electrostatic, magnetostatic or eigenmode fields is achieved by using the particle tracking solver (TRK). This solver is able to calculate the electrostatic potentials and track charged particles through pre-calculated fields. Because the fields are defined on a mesh, an interpolation scheme is used for intermediate particle positions. Forces on charged particles are described by the Lorentz equation,

$$\vec{F} = \frac{d}{dt}(m\vec{v}) = q(\vec{E} + \vec{v} \times \vec{B}), \quad (3.1)$$

where the force $\vec{F}$ is the time derivative of the momentum $m\vec{v}$ with velocity $\vec{v}$, q the particle charge, $\vec{E}$ and $\vec{B}$ the electric and magnetic fields, respectively. This equation becomes in the numerical discrete form,

$$m^{n+1}\vec{v}^{n+1} = m^n\vec{v}^n + q\Delta t(\vec{E}^{n+1/2} + \vec{v}^{n+1/2} \times \vec{B}^{n+1/2}), \quad (3.2)$$

where Δt is the time step and n the iteration number. Equation 3.2 updates the momentum every $n + 1$ steps, by using the average velocity $\vec{v}^{n+1/2}$ and an interpolation of the fields. The position is updated every $n + 3/2$ steps and is expressed by,

$$\vec{r}^{n+3/2} = \vec{r}^{n+1/2} + \Delta t \vec{v}^{n+1}. \quad (3.3)$$

Here $\vec{r}$ indicates the position vector with respect to a global coordinate system. This type of scheme is usually referred to as a leap-frog-integration scheme. In the tracking simulation only a set of particles is emitted and tracked, however, the resulting behaviour is modelling a steady state beam.

Particle generation

A particle beam or distribution can be initiated in different ways: by defining an area, point or circle source; or by importing a particle distribution from an external file using a particle import interface. The particle interface can only be moved and rotated by 90°(it is not possible to select an arbitrary angle), therefore any changes in angle must be introduced by a modification of the geometry. The particles from the source are emitted as 'macro-particles', representing a macro-charge, expressed as,

$$\Delta q = I \Delta t = j A \Delta t, \quad (3.4)$$

where I is the current, j the current density, Δt the initial time-step (as time stepping is not constant in CST) and A the area. The total current can be calculated by an integration over the assigned area. The available emission models are fixed, space charge limited (Child-Langmuir), plasma sheath, thermionic, field-induced or optically induced. For the space charge limited model, a finite distance must be defined between the real physical emitting surface and a 'virtual' emission surface.

Gun iteration

An option to include the influence of charges on the electrostatic potential is available in the program through the gun-iteration computation. By doing so, a self-consistent solution for a steady-state particle beam is obtained. An iterative scheme is required to recalculate the electrostatic potential from the path of the charges. In practise, the electrostatic field is calculated, the particles are tracked and their space charge is monitored. The resulting charge distribution is then used to recompute the electrostatic field and the trajectories. The latest obtained electrostatic field is used for the next iteration and the particles are tracked again. This is repeated until the required charge residual (δ) is reached, which is defined as the difference between the present and the last iteration. To find a stable solution, the charge residual error must decrease and converge as a function of the iteration number, approaching zero. It is defined as [58],

$$\delta = \frac{|\vec{q}_{n+1} - \vec{q}_n|}{|\vec{q}_{n+1}|}. \quad (3.5)$$

During the simulation run, the convergence can be tracked by observing the relative charge residual (in dB) as a function of the iteration number. The simulation is stopped when either the required relative charge residual or the maximum number of iteration steps is reached. Since a converging solution is not necessarily a physical one, as multiple stable solutions exists, it is important to investigate the convergence behaviour. The program allows control over the influence of the solutions of previous iterations via the space charge relaxation parameter, expressed by λ_{scr} that ranges from 0-1. A low space charge relaxation (e.g. 0.1) weights the average solution much more than the previous iteration. A higher λ_{scr} converges faster, but is more likely to oscillate between two

solutions. Figure 3.2 shows the influence of the space charge relaxation parameter in terms of charge residual. This was performed with a mock simulation of an electron beam drift exposed to a small focusing force.

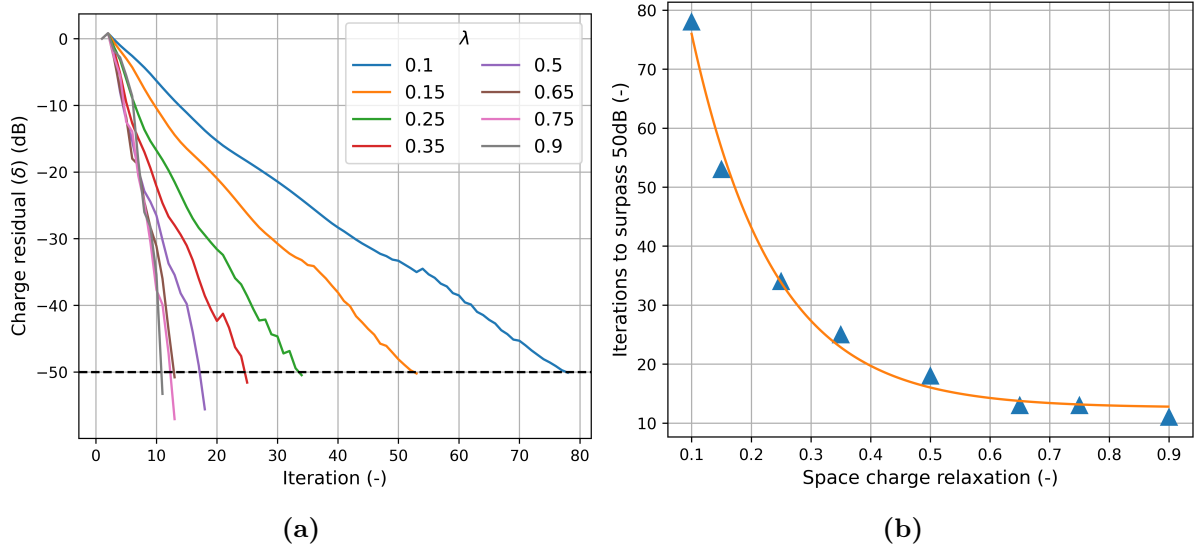


Figure 3.2: (a) Charge residual expressed as a function of the number of iterations for different space charge relaxation settings (λ_{scr}). The black line indicates the desired charge residual (-50 dB). (b) Number of iterations required as a function of the space charge relaxation setting. The orange line indicates an exponential fit, $a \cdot e^{-b \cdot x} + c$ with $[a, b, c] = [131.4, 7.3, 12.6]$.

For a lower space charge relaxation (more 'averaged' solution) the response is similar to that of a low-pass filter, as can be seen in Figure 3.2. The response is slow because only small changes are allowed for low values of λ_{scr} . At a small number of iterations, the results for a low and high λ_{scr} are similar because the last iteration solution is approximately the average solution.

3.2.2 Boundary conditions

Because the simulations are performed in a finite region ('bounding box'), conditions must be imposed on the boundaries of this region. CST Studio Suite can impose different types of boundary conditions, only the ones applicable to low frequency problems (EM & TRK) are discussed here [64]. The following boundary conditions can be used and are represented schematically in Figure 3.3:

Electric: The boundary is modelled as a perfect electric conductor, i.e. the tangential electric field and normal magnetic field components are zero. This is equivalent to Neumann condition for the electric field and Dirichlet condition for the magnetic field on the boundary.

Magnetic: The boundary is modelled as a perfect magnetic conductor, i.e. the tangential magnetic field and normal electric field components are zero. This is equivalent to Dirichlet condition for the electric field and Neumann condition for the magnetic field on the boundary.

'Open (add space if)': The condition extends the boundary virtually to infinity, i.e. the program acts as if the fields can extend to infinity. Extra space is added between the structure and the applied boundary.

It is also possible to assign symmetry planes to allow a faster computation of the fields. For the magnetic field simulations of the superconducting solenoid, the infinity ('Open (add space if)') boundary condition was used, whereas for the electron gun and collector simulations the magnetic boundary condition was applied.

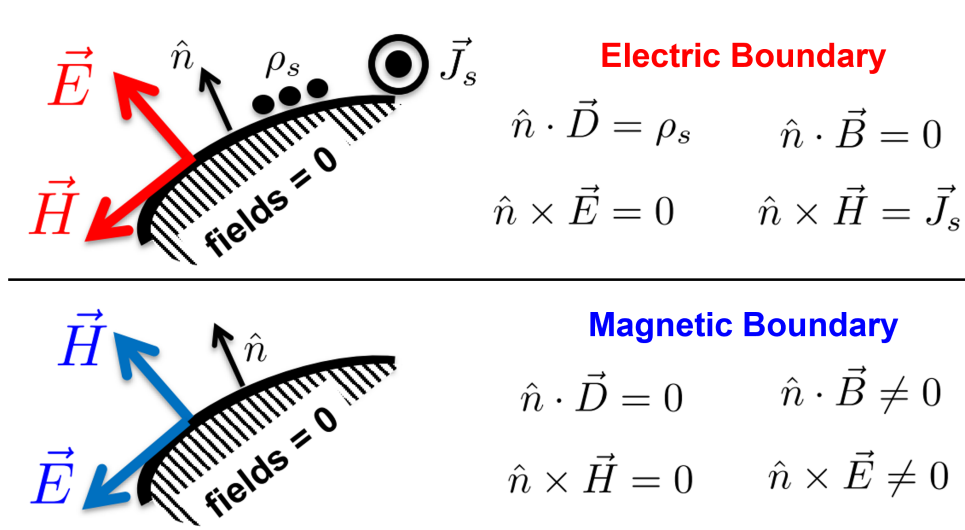


Figure 3.3: Schematic representation of the electric and magnetic boundary conditions. Reproduced with permission from [64].

3.3 Simulation approach

As mentioned in Section 1.1, the aim of this work is to investigate and explain the anomalies observed during measurements of ion extraction from TwinEBIS equipped with MEDeGUN. This was addressed by performing simulations of the various components in the TwinEBIS system, imposing different geometrical asymmetries and initial ion beam conditions. In the translation step the initial conditions from the ions inside the trap are converted to the LDT. Additionally, the conditions of the electron beam are imported in the LDT. At first, the geometries were defined and convergence studies were performed to assess the influence of different simulation parameters on the precision of the simulations. The second stage consisted of performing simulations of the geometry with perfectly aligned components, and thereafter with displaced collector components. Finally, the electron beam propagation in the collector region was simulated with different suppressor potentials. Three simulation regions were defined around the different components, which can be seen in Figure 3.4.

The procedure was as follows:

1. Simulate the magnetic field of the superconducting solenoid, incorporating the iron shielding.



Figure 3.4: Schematic representation of the simulation regions. Three distinct simulation regions were defined, namely the gun, solenoid and collector region (in blue, grey and green, respectively). The black curve represents the simulated magnetic field. Geometry in the figure is not to scale and locations are approximates.

2. Perform an electron gun simulation employing the magnetic field map calculated in the previous step.
3. Translate the electron beam from the gun side, at a certain magnetic field, to the end of the LDT.
4. Calculate the initial conditions of the ions inside the trap, followed by a translation to the end of the LDT.
5. Perform combined electron-ion beam simulations in the collector region, utilizing the previously defined electron beam, magnetic field map and initial conditions of the ions.

3.4 Assumptions and considerations

Due to the complex nature of TwinEBIS and the many physical principles that govern it, some simplifications had to be made in the simulation model. In the case of the electron beam, propagating from the electron gun to the collector, the breeding region was neglected in the simulations. This is due to the difficulty of simulating very large aspect ratio regimes. The total length is in the order of 1400 mm, while the electron beam has a diameter of 200 μm inside the full-field region, resulting in an aspect ratio of 1:12000. To accurately represent the beam inside the trap we need around 10 mesh cells per beam diameter. Under these circumstances, the requirements in terms of time, computing power and storage are very high. Instead, the electron beam was extracted at a certain magnetic field value near the electron gun and 'translated' towards the collector

at the same field value. The beam was then re-launched as if it transversed the trapping region, and this reduced simulation time and storage significantly. Particle interfaces were used in CST to translate the electron beam from the gun to the collector.

An electric current (moving charges) generates an azimuthal magnetic field. Such a magnetic field could in turn induce forces onto the particles. The induced magnetic field generated by the electron beam in our case is approximately 0.2 mT (1 mm from beam axis), and therefore any effect by this field will be dominated by the superconducting solenoid field (2 T). For the ion beam, this effect is even less significant.

It is possible to decouple the electron beam from the ion beam, using only the electrostatic potential from the surrounding electrodes and the space charge map generated by the electron beam to track the ions. However, if the ion current is significant and the energy is low, local neutralisation will be high and the coupled Coulomb interactions between ions and electrons become important. Using Equation 2.12, it can be shown that for an ion beam current of 0.1 mA and 1.0 mA at an energy of 450 eV, the linear charge neutralisation degree is 4.1% and 41%, respectively. This motivates the use of the gun-iteration scheme that includes both electrons and ions.

Another physical effect is that of beam interaction with residual gas molecules. Typically, in a EBIS the gas pressure is lower than (10^{-10} mbar) and interactions between beam and gas are rare. To simplify the simulations and avoid unnecessary complexity, the simulations were carried out in a perfect vacuum environment.

3.5 Simulations of the different components

To define the geometry of the different components, simulation models previously implemented by R. Mertzig [56] were adopted and modified according to the latest available drawings. Additionally, measurements of the geometry were taken in the beginning of 2023, when the TwinEBIS magnet was dismantled due to a thermal bridge, discussed in Appendix B.

3.5.1 Solenoid

As mentioned in Section 3.2.1, the solenoid simulations were carried out in the MS module of CST. The simulation models were adjusted to match the measurements by an optimisation routine that parameterized several combinations of the coil currents and the main coil length, using general knowledge about the positioning. An optimisation routine was used with a goal function, defined as the difference between measured and simulated axial magnetic field. The simulations were performed with a solver charge residual of $1 \cdot 10^{-9}$ and using a hexahedral meshing. The material for the shield was chosen as 'iron' with a permeability of 1000 H/m and stranded coils were used because of their compatibility with the hexahedral meshing. A refined mesh was imposed in the regions containing the collector and gun, since these field maps were later used for beam tracking. The hexahedral mesh was selected over a tetrahedral one to allow for a better control over the refined regions at the beam axis, in the collector and inside gun iron shield. The boundary condition was set to infinity (see 'add space if' boundary conditions) and simulations were ran with a total of 6 million mesh cells, the minimum cell size was set to 1/100

of the maximum cell size in the refined regions ('maximum cell size near to model'). A schematic of the geometry can be seen in Figure 3.5.

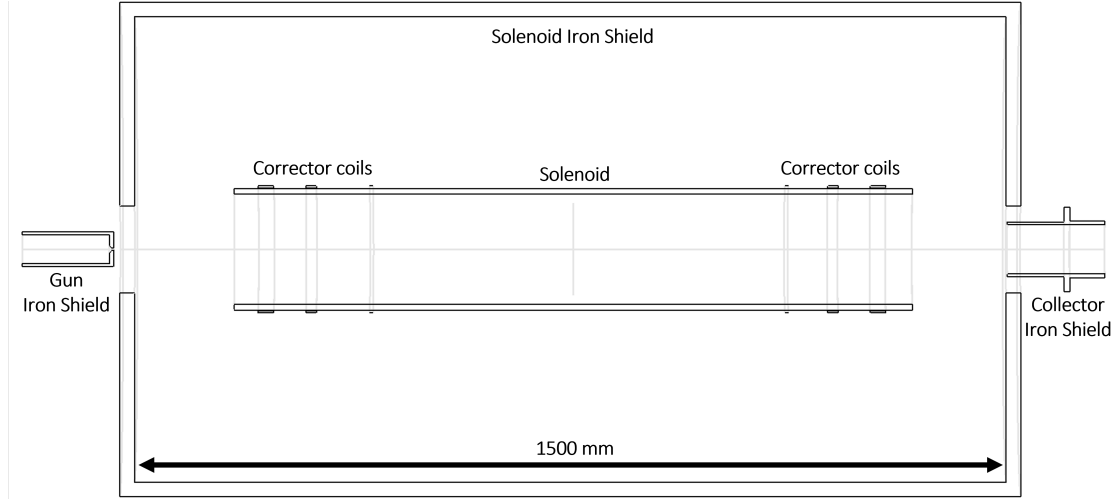


Figure 3.5: Schematic representation of the geometry used in the magneto-static simulations in CST EM studio. The beam propagates from the left to the right.

3.5.2 MEDeGUN

For simulations of MEDeGUN, the space charge limited emission model was used, described by Child-Langmuir and discussed in Section 2.2. A representation of the geometry can be seen in Figure 3.6. The magnetic field, obtained from the solenoid simulation, was imported into the region. A particle export interface was defined ~ 52 mm from the cathode center at a field of 0.169 T, capturing the trajectory conditions of the electron beam. The cathode potential was set to 0 V, the anode potential to 10 kV and the Wehnelt to a potential of -7 V, representing nominal conditions. The conducting surfaces were defined as a Perfect Electrical Conductor (PEC). The solver was set up with a total of 50 k time steps with a minimum of 5 particle pushes per cell and a time-step dynamic of 1.2. The time step dynamic is a parameter that adjusts the time stepping according to the energy of the particles neutral. To model the space charge potential of the electron beam, the gun iteration module was turned on, with a charge residual goal of -80 dB, and a space charge relaxation setting of 0.3 to obtain a good balance between simulation time and stability. To accelerate the simulations, the maximum number of cores in the local desktop were used, i.e. 8 cores with 128 threads. Simulation times with this setup were in the order of eight hours on the desktop machine.

3.5.3 Collector

As previously mentioned, the collector was modelled according to available drawings and measurements taken when the collector cross was dismantled. A schematic representation of the simulation geometry can be seen in Figure 3.7. For the majority of the simulations, the parameters for the LDT, suppressor, collector and extractor potentials were 10000 V, 2800 V, 3400 V and -7000 V, respectively, all w.r.t. the cathode potential. The material for the conducting surfaces was defined as PEC. The previously generated magnetic field

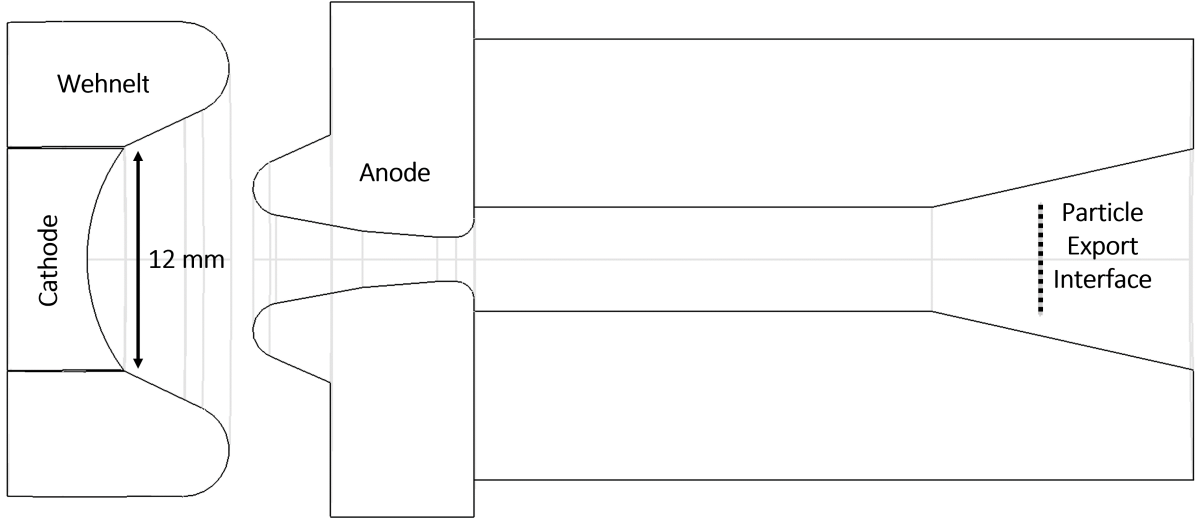


Figure 3.6: Geometry of MEDeGUN used in the simulations. The beam propagates from the cathode through the anode. The Wehnelt (-7 V) provides additional focusing. The cathode diameter is indicated.

map was imported into the simulation region. A particle import interface, defined at the start of the simulation region, was used to import the electron beam from the MEDeGUN simulation at a magnetic field of 0.169 T. For the ion beam, ^{129}Xe ions with +25 charge were emitted from the surface of a solid by a fixed emission particle source. The solid was only present for defining the surface and was otherwise not part of the simulation. The solver was set up with the same settings as for the gun simulation, however, the maximum time steps was changed to 150 k and the maximum number of iterations was set to 300 (-100 dB charge residual goal). A meshing of 5.5 million cells was used and refined areas were defined in the collector region (where the electrons are deposited) and in the LDT, to account for the small size of the beam when the magnetic field is still present. To assess if the collector was operating close to a Bursian limited regime, simulations with different suppressor potentials, ranging from 1200-3500 V were also carried out (only including electrons).

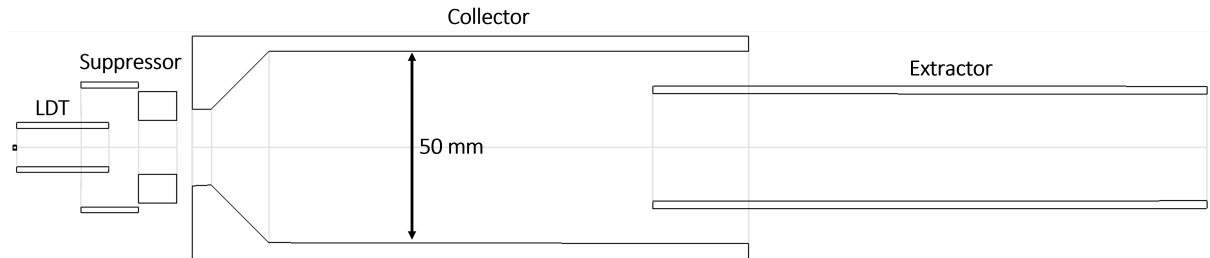


Figure 3.7: Schematic representation of the collector geometry. The ion source can be seen on the right side. The particle import interface is not shown. The beams propagate from left to right.

3.6 Convergence study

A convergence study is vital when performing simulations, predominantly to assess the precision of the results and indicate numerical errors. In the studies presented below, the convergence was mainly expressed in the axial and radial potential maps, since the resulting electric fields are crucial for the ion tracking. In most cases, only the radial potential results are presented because of the similarity to the axial results, apart from one exception where the mesh convergence of the gun is discussed. The radial potential is defined as the potential in the x-direction ($R = x$ when $y=0$). A convergence study was also carried out for the number of simulated macro-particles, N_p , in the MEDeGUN case. For the collector a similar mesh convergence study was performed, but the results were also evaluated based on the deposited power density in the collector although the results are not shown here. The mesh convergence check was performed with a slightly different collector design and using only the electron beam, by reasons of simulation time.

3.6.1 Particle parameters

Trajectory effects

To probe the effect of the number of launched particles from the cathode surface on the electrostatic potential and particle trajectories, simulations of the MEDeGUN were carried out with N_p ranging from 5k to 38k at a fixed meshing of 2.3 million cells. The results in terms of trajectories for two cases can be seen in Figure 3.8. The number of launched particles has an impact on the propagation of the electron beam, and a more laminar beam is observed for $N_p=38$ k, while for $N_p=10$ k the trajectories are crossing. The simulation time increases linearly with N_p ; on the local desktop it increased with 6.1 minutes per 1000 particles.

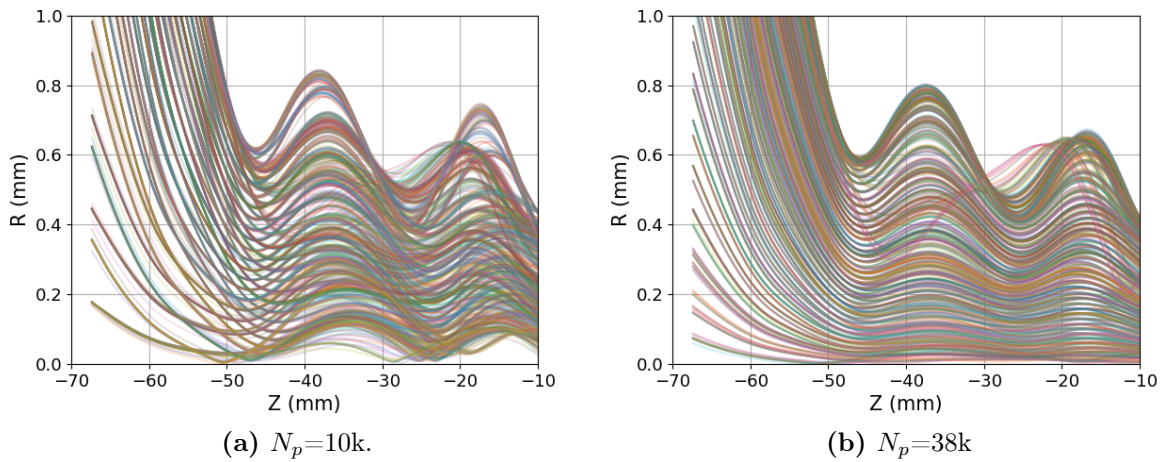


Figure 3.8: Trajectory results for different N_p . Particles start at $z \approx -67$ mm and the trajectories are expressed as $R^2 = x^2 + y^2$. Only a selection of 300 trajectories are shown here.

Electrical potential effect

The influence of N_p on the radial potential is shown in Figure 3.9. The shape of the radial space charge potential created by the electron beam, discussed in Section 2.3, can clearly be seen. Since the ions are confined to the electron beam, close to the axis, it is crucial that the potential in this region is accurately represented. The minimum potential ϕ_m (w.r.t the cathode potential), converges to a value of 9365 V for the highest N_p (38 k). A similar convergence is seen in the Sum Squared Difference (SSD), showing a sharp decrease in SSD as a function of N_p . The relative difference in ϕ_m , defined w.r.t. the $N_p=38$ k case, is less than 1% for $N_p=10$ k, while for $N_p=20$ k the difference is reduced to 0.25%. Similar results are found for the axial potential (not presented here), where the difference is less than 0.5% for $N_p=10$ k.

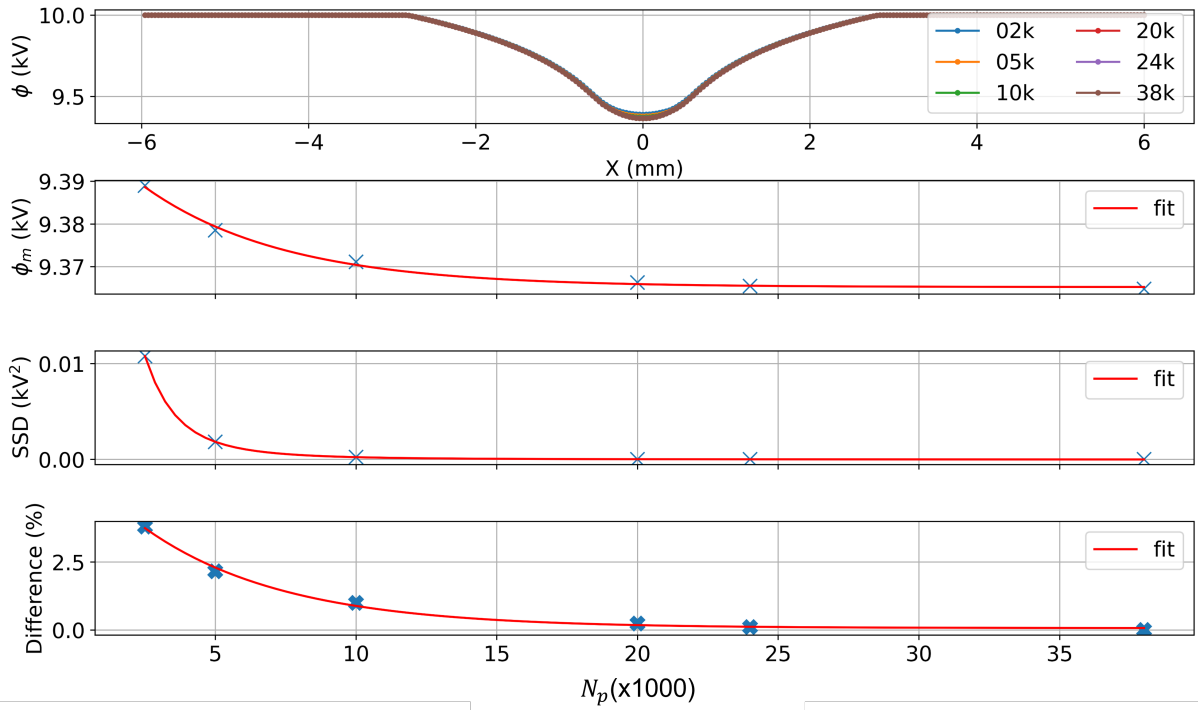


Figure 3.9: Effects of N_p on the radial potential in MEDeGUN, expressed in (from top to bottom): potential ϕ , minimum potential ϕ_m , SSD, and relative difference.

This convergence study concluded that the deviations in the radial potential are lower than 5% for all N_p and thus, the influence of N_p on the results is minimal. To represent some of the laminar flow, it is necessary to carry out simulations with more than 10 k particles. Therefore, it was decided to perform the simulations with $N_p=20$ k.

3.6.2 Mesh parameters

As is discussed in Section 3.2, the mesh type and size are important factors for the simulations. Generally, a finer mesh, i.e. a higher number of cells, denoted by N_m , will give a better solver convergence and a more accurate solution. However, the meshing has a direct effect on the simulation time for the given resources, which are limited. In the cases presented, a hexahedral mesh was chosen for a better control of refined areas.

Gun

In the mesh convergence study for the gun, five different mesh resolutions were used, ranging from $N_m = 1.8$ -10.5 million. The results for the axial potential can be seen in Figure 3.10. It is important to note that the relative differences indicated in the Figure 3.10 are with respect to the space charge potential ϕ_{sc} and not the total potential (including the field from the surrounding electrodes). From -65 mm to -55 mm, the axial potential is rising due to the difference in anode-cathode potential, whereafter the potential drops ever so slightly due to the increased space charge, as the beam is compressed and reduced in diameter. A large difference of up to almost 20% is observed for the 1.8- and 2.5 million N_m cases. For $N_m > 5.2$ million, the difference w.r.t. the $N_m = 10.5$ million is less than 4%. An exponential decrease in the SSD for a higher N_m indicates a converging result. Since the influence of N_m is significant, it was decided to use the highest N_m , ensuring a precise representation of the geometry and to obtain a relatively high potential precision.

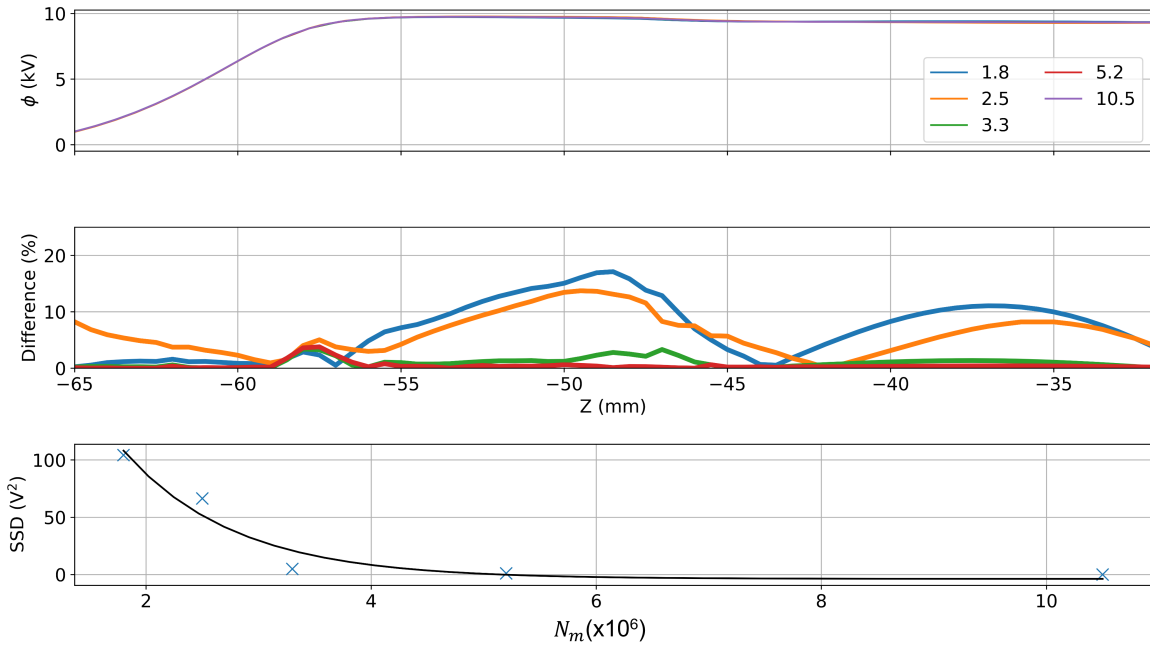


Figure 3.10: Effects of number of N_p (in million) on the axial potential in MEDeGUN; expressed in the potential ϕ , relative difference, and SSD (from top to bottom).

Collector

The mesh convergence results for the radial potential inside the collector at $Z = 1495$ mm and $Y = 0$ mm are shown in Figure 3.11. The difference between $N_m = 12$ million exceeds 2% for the case of $N_m = 1$ million in the region where x is 0. To obtain a difference less than 1% in the region close to the beam axis, $N_m = 2$ million appears to be sufficient. Also in the case of the collector, the SSD shows an exponential decrease, indicating a clear convergence of the radial potential with increasing N_m . Results for the axial potential are omitted because the differences are less significant. For example, for $N_m = 2$ million, the deviation w.r.t. $N_m = 12$ million is less than 1%.

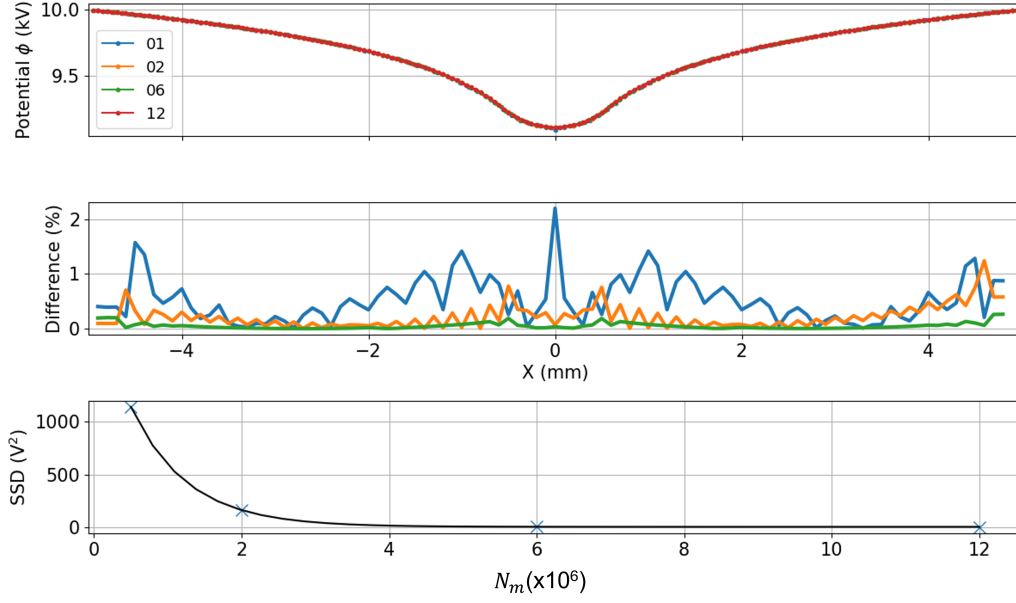


Figure 3.11: Effects of N_m (in million) on the radial potential inside the collector; expressed in potential ϕ , relative difference, and SSD. The relative difference and SSD are expressed w.r.t. the $N_m = 12$ million case.

3.7 Ion starting conditions

The starting conditions for the ions in the LDT are not easily defined, and depend on the initial conditions inside the trapping region, in combination with ion transport process to the launching surface in the LDT in front of the collector region. For the translation itself, we rely on the conservation of the normalized emittance, as has been motivated in earlier references [23, 65]. The normalized emittance ϵ is proportional to the transverse momentum and the radius R_i of the ion beam, while the former is expressed as a temperature T_i (in eV), giving us $\epsilon \propto R_i \sqrt{T_i}$. Thereby, we can relate the ion parameters inside the trap and LDT via the expression,

$$T_{trap,i} R_{trap,i}^2 = T_{LDT,i} R_{LDT,i}^2, \quad (3.6)$$

in this relation, any heating of the ions during extraction is neglected as the typical heating time is much larger than the extraction time. Note that $T_{LDT,i}$ and $R_{LDT,i}$ are not independent, but a relation is given by the space charge potential, i.e. Equation 2.6. Thus, if $T_{T,i}$ and $R_{T,i}$ are known, the one remaining free parameter $R_{LDT,i}$ in Equation 3.6 can be varied such that equality holds. The total space charge in the LDT drift tube is comprised by contributions from both the electron beam and ion beam. The electron beam space charge can be calculated by obtaining the beam radius through either electron beam tracking or by using the Herrmann formula, given by Equation 2.4. As the radial extension of the ion beam is inherently specified by Equation 3.6, the ion space charge can also be determined. The extracted ion beam current can be measured directly with a FC in the ion extraction line.

3.7.1 Ion conditions inside the breeding region

According to the argument above, it is necessary to determine the transverse ion energy and radius inside the breeding region, in order to derive corresponding values for the LDT. From ion extraction measurement at TwinEBIS, conservative values can be obtained for the former parameters. In Figure 3.12, the ion beam charge recorded on the extractor (q_e) and FC (q_{fc}) are shown as function of the outer barrier potential (ϕ_{out}) for a range of breeding times. For example, at a barrier voltage of 1200 V - that is 200 V above the trapping tube potential of 1000 V - ions with an energy higher than 200 eV/Q have the possibility to escape axially over the outer barrier (assuming a more or less isotropic momentum distribution in phase space). As the breeding time is long compared to the ion oscillation time inside the trap (both radially and axially), it is assumed that higher energy ions will escape and are not in the trap or consequently in the extracted beam pulse. Furthermore, from Equation 2.5, that relates potential energy to radial ion position, an upper limit can be derived on the ion radius as function of the outer barrier setting. Thereby, both the energy and the radius of the ions inside the trapping region are constrained. Thus, by using Equation 3.6 and Equation 2.6, assuming that the ions have a temperature T , and expressing the radius of the ion beam in terms of electron beam radius, we obtain:

$$T_{trap,i} R_{trap,i}^2 = e \phi_{sc,total,r=r_i} k^2 r_e^2, \quad (3.7)$$

where $k = R_{trap,i}/R_{trap,e}$ is the ratio of radii between the ion beam and electron beam inside of the breeding region and $\phi_{sc,total,r=r_i}$ the total space charge within the ion beam radius. A derivation for $\phi_{sc,total,r=r_i}$ in Equation 3.7 is given in Appendix A. In the case of a 1200 V outer barrier, for 50 ms breeding time, we can from Figure 3.12 see that for these initial conditions approximately 55% of the beam is intercepted by the ion extractor.

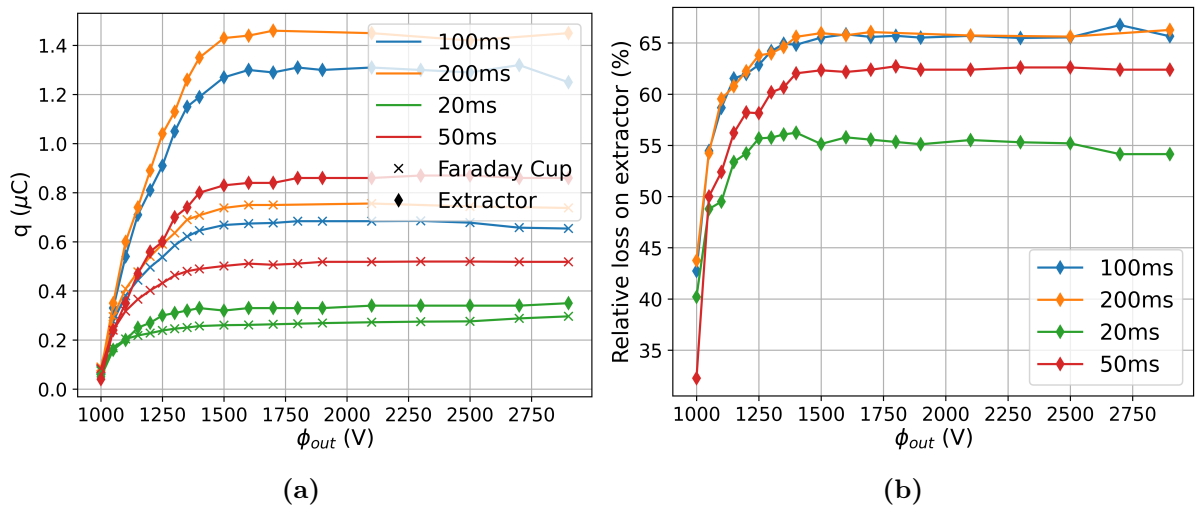


Figure 3.12: (a): Collected charge on Faraday cup and extractor for different breeding times and outer barrier voltages. (b): Associated relative losses on the extractor.

Table 3.1: Parameters inside the trap, where r_h is the Herrmann radius, k the electron ion radius factor, η the neutralisation, T the temperature, and t_{ext} the extraction time. Values without unit are unitless.

Name	Acronym	r_h (μm)	k	η	T (eV/Q)	t_{ext} (μs)
Testbeam 1	TB1	104	1	0.345	107	5
Testbeam 2	TB2	105	1	0.034	162	5

Table 3.2: Parameters in the LDT, where R_{ion} is the ion radius, I the ion current, E the energy, T the temperature and N the number of launched ions in the simulation. Values without unit are unitless.

Name	Acronym	R_{ion} (μm)	I (mA)	E (eV/Q)	T (eV/Q)	N
Testbeam 1	TB1	360	1.0	594	9	1022
Testbeam 2	TB2	250	0.1	458	27	467

3.7.2 Ion conditions inside the LDT

Two test beams with 1022 and 467 tracking particles were used for the ion beam simulations in the collector region, denoted with Testbeam 1 (TB1) and Testbeam 2 (TB2). Their respective properties inside the trapping region and the LDT are summarized in Table 3.1 and Table 3.2 respectively. The energy (E) and temperature (T) are defined with respect to the axial and radial velocity. Their main difference is the neutralization degree inside the trapping region, where TB1 is a factor 10 higher than TB2, yielding a higher energy and extracted current for the former case. In the LDT, both the radial and axial potentials are affected by the space charge potential of the electron beam, while the latter is also dependant on the potential difference between the trap and LDT regions which causes a higher ion beam energy for TB1. The neutralisation also affects the temperature, that is lower for TB1 compared to TB2 due to the partly compensated electron beam space charge. Both ion populations are assumed to be within the electron beam radius inside the trap ($k = 1$).

The difference in beam current for TB1 and TB2 required the implementation of a distinct number of simulation particles N . For both test beams, the resulting charge residual (δ) after 300 gun iterations for simulations with different displacement is shown in Figure 3.13. It is evident that the charge residual of TB2 is much lower than for TB1, reaching values of less than -90 dB for the displaced cases, indicating an excellent precision. Surprisingly, the non-displaced TB2 ends up with a charge residual of -55 dB, higher than the displaced simulations. For TB1 with 0 mm and 1.75 mm, no decrease in charge residual ($< -30\text{dB}$) is observed after 100 iteration steps.

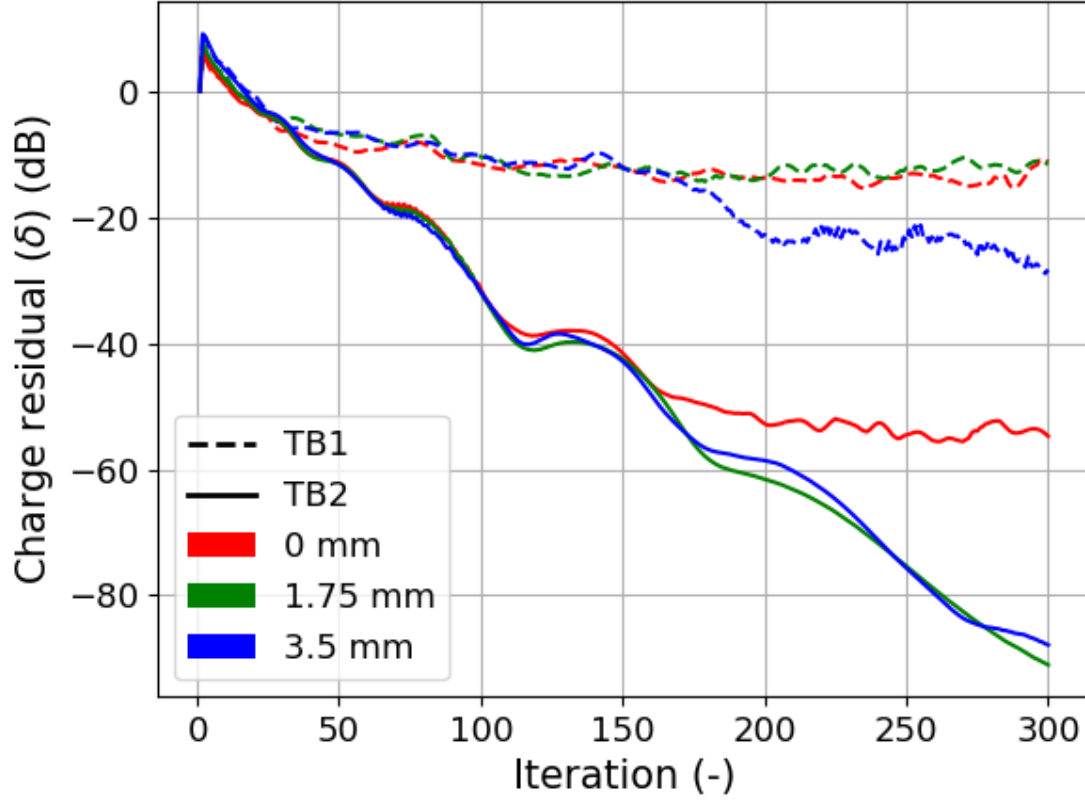


Figure 3.13: Charge residual δ for TB1 and TB2 with the displacements for a maximum of 300 iterations.

3.7.3 Field asymmetries

To address the impact of field asymmetries on the ion propagation inside the collector region, the electrostatic field axis was displaced with respect to the magnetic field axis. This was realized by applying a displacement and tilt on the electrostatic components in the collector region, emulating a misalignment error. The rotation of the electrostatic axis was defined with respect to a local reference frame, 1490 mm in front of the start of the simulation region in the LDT (67 mm from the cathode center at the gun side). Rotation angles (α) of 0.067° and 0.134° (2α) were defined, corresponding to displacements dy inside the LDT of 1.5 mm and 3.5 mm, respectively. A schematic representation of the definition of the tilt and displacement can be seen in Figure 3.14.

Because the collector shield is part of the same rigid structure as the electrostatic components in the collector region, magnetic field simulations of a titled and displaced collector shield had to be produced as well. The tilt had little influence on the axial magnetic field in the collector region, that is shown in Figure 3.15. However, more important is the displacement of the particle sources with respect to the electrostatic field axis, as the electron beam is following the magnetic axis, and the ions in turn follow the electrostatic potential of the electrons.

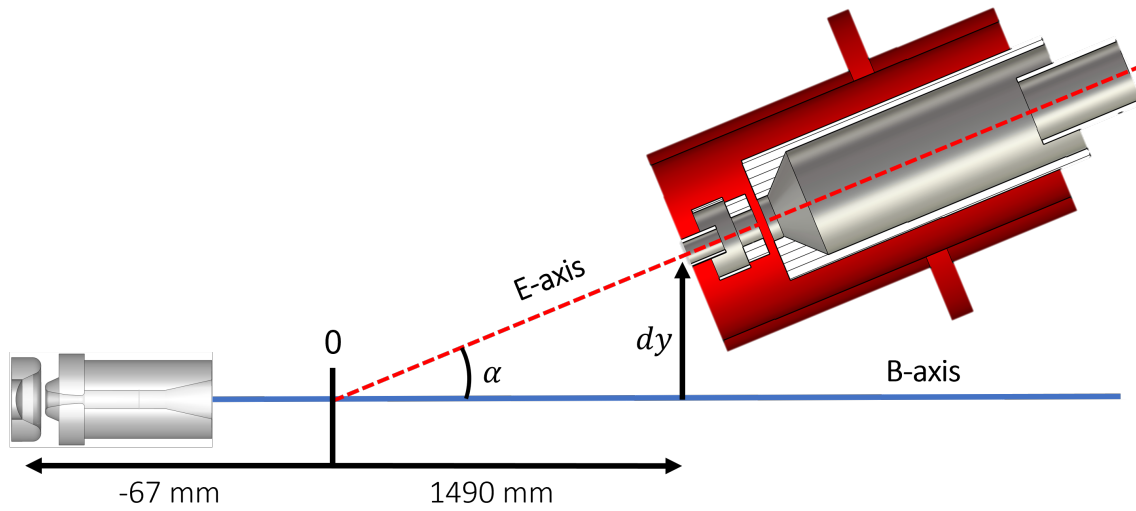


Figure 3.14: Schematic representation of the definition of a tilt (α) and displacement dy w.r.t. a local reference frame. The collector shield is shown in red. The tilt, displacement and geometry have been visually exaggerated to emphasize their effect.

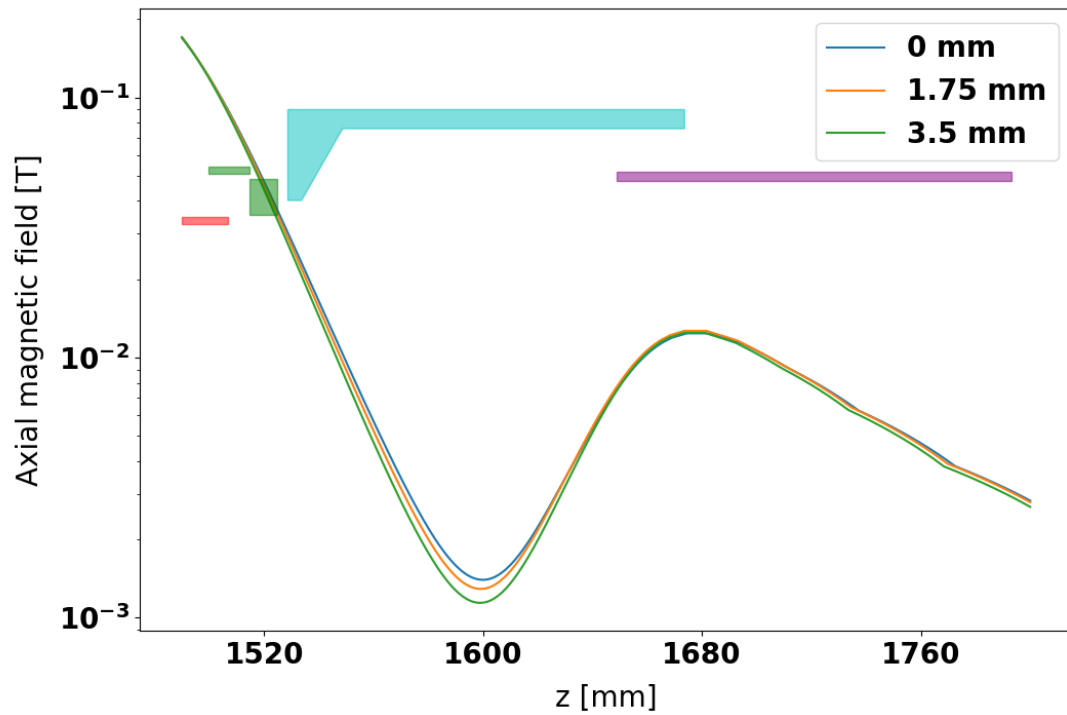


Figure 3.15: Magnetic field maps at the collector side for different tilts. The geometry (half section) of the elements in the collector region is indicated by the colored structure.

3.8 Measurements at REXEBIS

Measurements at TwinEBIS using a Brillouin electron beam suggest the presence of an instability that is axial-position dependent, as the effective current density is reduced with breeding regions farther from the gun (see Figure 1.5). An instability can result in ion heating and subsequent ion losses within the trap. One of the objectives mentioned in Section 1 was to verify the possible existence of a electron-ion two-stream instability also at REXEBIS, where we operate with an immersed electron beam. In order to establish a correlation between the axial position of the breeding region and the effective current density, measurements of charge spectra were conducted at REXEBIS.

3.8.1 Setup

By electrically reconfiguring the three trapping tubes, the axial position of the breeding region was altered such that one of the tubes served as the breeding region, while the other two were integrated into the inner or outer barrier. Voltage amplifiers were used to pulse the outer barrier between breeding and extraction states. Before the run, the voltage amplifiers were calibrated to acquire accurate potential readings. The measurements were carried out with an electron beam current of 200 mA at a gun potential of 5600 V and a period time of 200 ms. Neutral ^{129}Xe gas was injected by connecting a bottle to the gas inlet, which is mentioned in Section 1.4. It should be noted that during the measurement, there was no gas injection tube present that led the gas into the trapping volume. Instead, the gas was directly injected into the gun cross. To be able to account for residual gas in the system due to a non-ideal vacuum, spectra of the residual gas were also measured. To ensure that the neutralization degree did not affect j_{eff} , pressures were monitored during the measurement. To scan the A/Q setting, the magnetic field was varied by adjusting the current supplied to the magnet's power supply.

3.8.2 Measurement procedure

The charge state spectra were obtained by measuring the A/Q intensities for a given breeding time t_{breed} , ranging from 5-195 ms, for each trap configuration. A schematic representation of the setup is shown in Figure 3.16. The total intensity I_{tot} was registered on FC3, located in front of the separator magnet, after each magnet scan, i.e. for every breeding time. The separated A/Q intensity was measured for every setting with FC4, which is located downstream of the separator magnet. Both FC locations can be seen in Figure 1.3 in Section 1.4. With this procedure, complete charge spectra could be extracted for eight breeding times and for the three trap configurations.

A scripting engine allowed automatising the measurement through a list of commands, and a simplified version of the commands given in Python is expressed below.

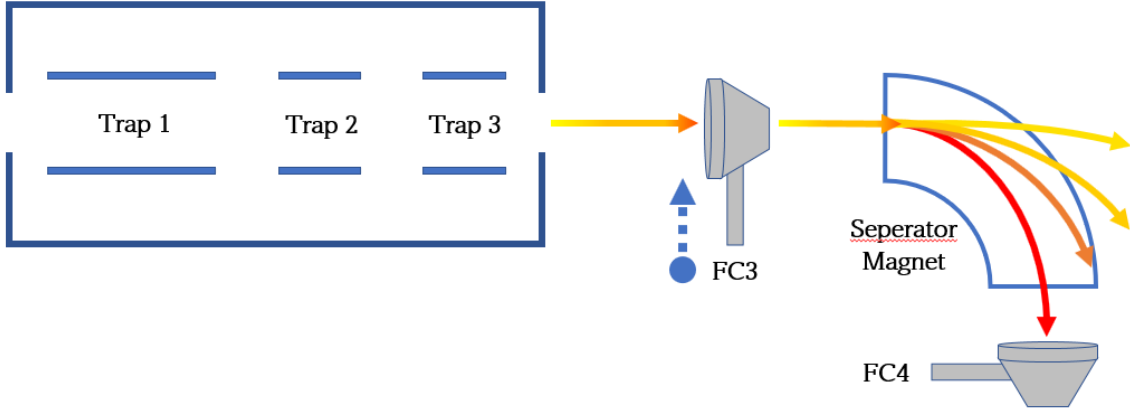


Figure 3.16: Schematic representation of the measurement setup. The three trap configurations are shown. The total current is measured by FC3, which is moved into the beam path after every A/Q scan. The separated current is measured by FC4, right after the separator magnet.

```

trap_configurations = ["config1", "config2", "config3"]
breeding_times = [5, 10, 15, 25, 45, 75, 125, 195]
# Loop over all trap configurations
for trap_config in trap_configurations:
    # Loop over all breeding times
    for breeding_time in breeding_times:
        # Measure the total intensity
        itot = measure_total_intensity(breeding_time)
        # Measure the separated A/Q intensity for the given trap
        # configuration
        isep = measure_separated_qa_intensity(trap_config)

```

Data analysis

Data analysis of the 24 charge state spectra were carried out in Python. The data was offset (to obtain only positive currents) and the background subtracted. To obtain j_{eff} , the charge state spectra were fitted to a theoretical model embedded in the Python package called EBISIM, developed by H. Pahl [66]. The EBISIM package is able to simulate EBIS charge state distributions. The basic simulation model is based on the rate equations mentioned in Section 2.4, however, it only considers EI and RR effects to calculate the charge state distribution. Moreover, a perfect temporal overlap between electron beam and ions ($\kappa = 1$) is assumed in the model. For our measurement evaluation, this leads to an underestimation of the electron current density, as the ions may partly reside outside the electron beam. The current density is extracted from the fitting procedure as one of the fitting parameters. To test the robustness of the fitting algorithm, the fitting was performed and compared with inclusion of all charge states, or with only three of the most abundant charge states. Furthermore, since the energy of the electron beam in the trapping region is not exactly known (due to space charge effects), a 500 eV energy spread was imposed and indicated by uncertainty bands in the plot. An example of the measurement of the charge state distribution and subsequent fit can be seen in Figure 3.17.

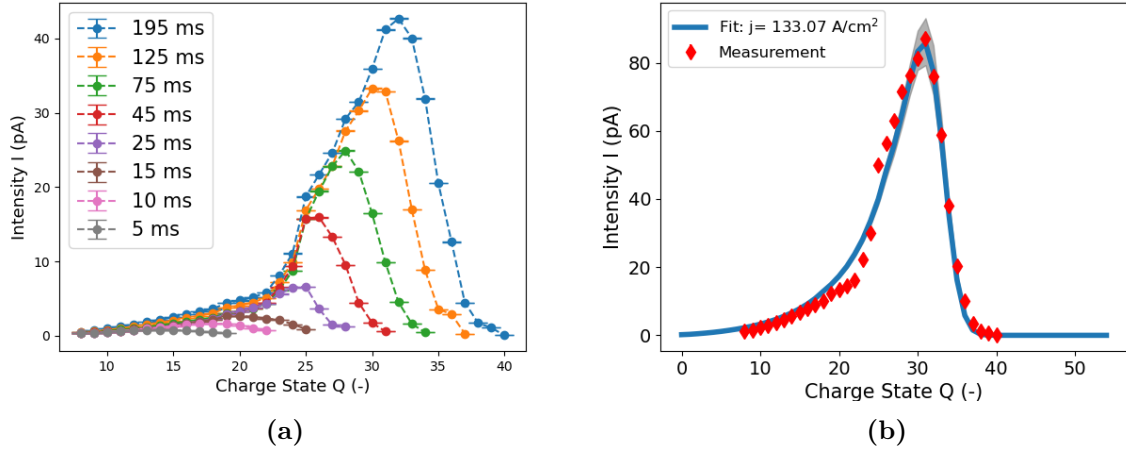


Figure 3.17: (a) The charge state spectra for Trap 3. Lines between point are there to guide the eye. (b) Charge state distribution for Trap 1 and $t_{breed} = 195$ ms with the resulting fit from the EBISIM simulation. The grey band indicates an uncertainty in electron beam energy of ± 500 eV.

Chapter 4

Results & Discussion

This chapter presents the primary outcomes of this study, which are categorized into three sections, with each section addressing one of the three principal objectives, as outlined in Chapter 1. Section 4.1 focuses on the findings regarding the impact of asymmetry on ion extractor losses. This section includes the initialisation of the electron beam, benchmark simulation of the collector region, analysis of simulations with different asymmetric configurations, power deposition inside the collector and a visual inspection of the extractor. It also includes a discussion on the initial launching conditions of the ions and on the uncertainty of the simulations. The second section, Section 4.2, provides a study on the possible formation of a virtual cathode. Results from the REXEBIS measurements are presented in Section 4.3.

4.1 Effect of asymmetry on ion losses

4.1.1 Initialisation of the electron beam

Simulations studies of the MEDeGUN were performed and validated against previously performed measurements and an analytical expression of the radial field. The electron beam from this simulation was subsequently used in the simulations of ion extraction in the collector region. A description of the MEDeGUN geometry and the parameters are previously given in Section 3.5. The precision and relative errors of the simulations were discussed in the convergence study in Section 3.6. A detailed description of the resulting potential and trajectories is given below.

Gun potential surfaces

The space charge of the electron beam is responsible for radial confinement of the ions, as discussed in Section 2.1, and therefore, crucial for shaping the ion beam in the collector region. A cross-sectional view of the radial potential (top figure in 4.1a) from the electron beam at -16 mm, shows a symmetric field map with a large depression. As a first step to validate the simulations of the electron gun, the analytical expression (Equation 2.5) was used to calculate the radial space charge potential and compared to simulation, as can be seen in the bottom figure in Figure 4.1a. The simulation results agreed well ($<0.5\%$)

with the calculated electric potential, providing a solid validation. The minor discrepancy is most likely the result of a non-uniformity of the electron beam in the simulation, for which Equation 2.5 is not valid. The cross section view of the axial potential (Figure 4.1b), exhibits a rapid increase between the anode and cathode, from 0 V (outside the displayed range) to 9320 V, owing to the 10 kV potential difference applied between these components and the space charge potential of the electron beam. The space charge potential gradually decreases throughout the anode structure due to the decreasing beam radius, as shown in Figure 4.2.

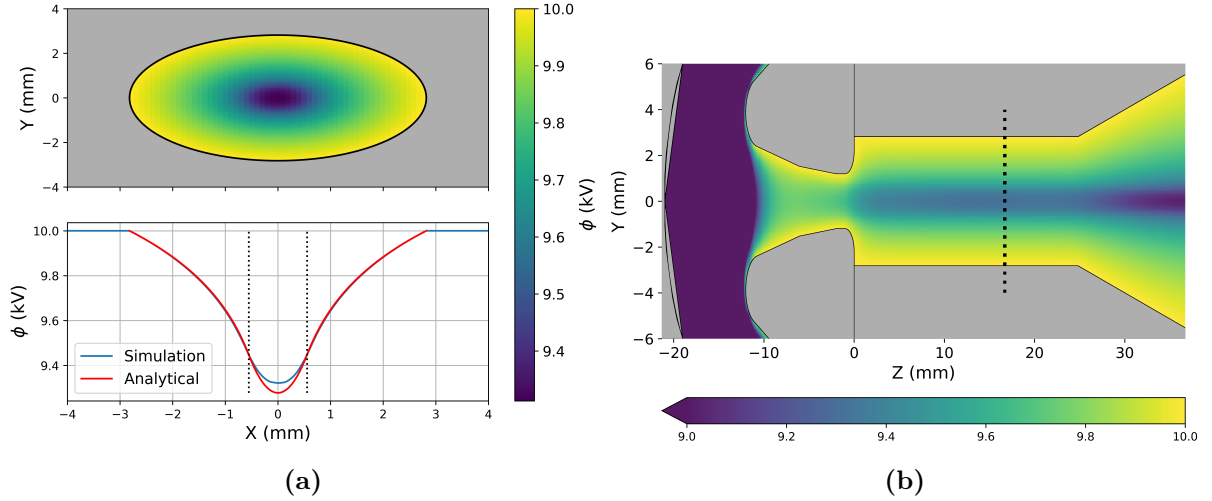


Figure 4.1: (a): Radial cross section at $Z = -16$ (see dotted line in (b)) and a 1D plot, evaluated at $Y = 0$, comparing simulation and analytical results. (b): Axial potential at $X = 0$. The cathode is seen on the left and the anode on the right (both in grey).

Electron trajectories

By analysing the trajectories, we can evaluate whether the conditions are met to obtain the desired Brillouin electron beam. A total of ~ 21 k particles were tracked throughout MEDeGUN, of which a selection of 2500 random particles can be seen in 2D in Figure 4.2. A 3D rendering of the geometry where all trajectories can be seen is displayed in Figure 4.3. It is evident from these figures and Figure 4.1 that the electron beam is initially focused by the electric field inside the shielded gun before it enters the magnetic field region outside the gun shielding, where the magnetic field increases rapidly (at ~ -46 mm). Trajectory crossing still occurs and the flow is not perfectly laminar, which most likely is due to a simulation error that occurs for a finite number of particles tracked. Nevertheless, the resulting space charge potential, which holds greater significance, remains largely unaffected by the number of simulated particles (N_p). This was expected and previously addressed in Subsection 3.5.2. Scalping of the beam can be observed during propagation through the anode, also suggesting that the Brillouin condition may not be met. Numerous efforts to mitigate beam scalping were undertaken by re-positioning the magnetic field in the simulation, however, this did not result in a significant improvement. The simulations yield a perveance of $1.083 \text{ uA/V}^{3/2}$, which is in good agreement with the perveance value obtained during MEDeGUN commissioning ($1.1 \pm 0.002 \text{ uA/V}^{3/2}$), further confirming the validity of the simulation. The 1.5% variation between simulation

and measurement is presumably caused by electrons being emitted from the sides of the cathode or by a different anode-cathode distance [21].

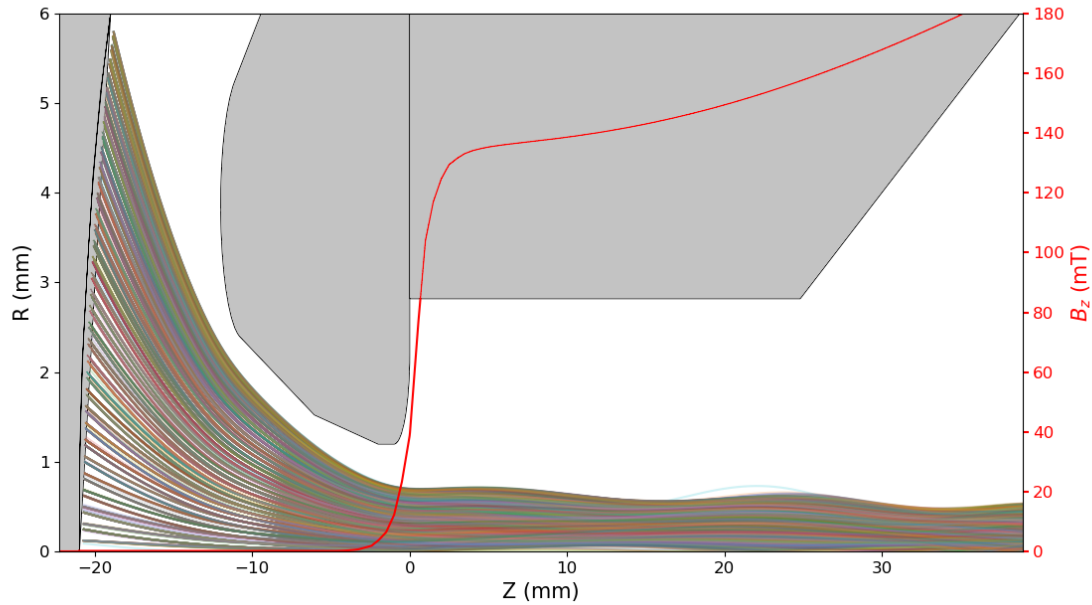


Figure 4.2: Trajectories of 2500 random electrons in MEDeGUN. The magnetic field strength is indicated by the solid red line. The cathode and anode are indicated in grey.

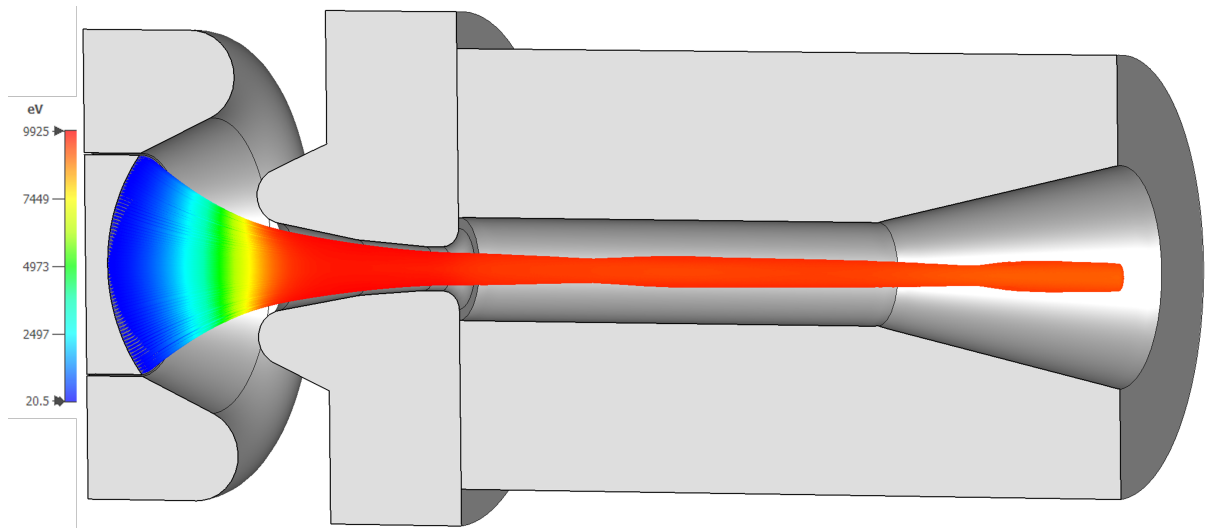


Figure 4.3: 3D rendering of the geometry including approximately 21 k electron trajectories. The color indicates the energy of the particles.

4.1.2 Ion launching conditions

After successfully validating the electron beam simulations, the electron beam can be exported from the gun to the LDT in the collector region, in order to investigate ion trajectories. Upper limits on the radius and energy of the ions inside the trap, originating

from the measurements, were used to determine the ion beam radius and energy in the LDT (discussed in Subsection 3.7.1). Here it was assumed that the momentum of the ions was distributed isotropically. If, however, the ions gain additional energy through ion heating, which is described in section 2.4.4 and the heating occurs more rapidly in the radial direction compared to the axial direction, the ions will spread out. Hence, less collisions will occur and a non-isotropic momentum distribution might be maintained. If this is the case, the upper limit on the radius and energy is violated, and the initial conditions of the ions are not representative anymore.

4.1.3 Collector simulations with ideal alignment

Prior to assessing the propagation of the electron beam and transmission of ions in an asymmetric field, it is crucial to establish a benchmark, using symmetric fields. This benchmark provides us with information about extractor losses and margins in an ideal scenario. The propagation of the electrons and ions in the collector region are discussed in the section below. The resulting trajectories for an ideal scenario in 2D and 3D can be seen in Figure 4.4 and Figure 4.5a, respectively. After leaving the LDT, the electrons (in blue) spread out in the collector and eventually collide with the wall, as can be seen in Figure 4.4. The electrons close to the axis, and with small angles in the vicinity of the extractor, fold backwards towards the LDT. However, if the electrons start with small radii but with substantial divergence, they will instead end up in the dense region at lower values of z (early on inside the electron collector). In the LDT region, the electron beam has a relatively small radius owing to the remaining magnetic field, which leads to significant space charge effects that effectively confine and guide the ions (in red). The ion beam expands, as it progresses the collector region, and to a lesser degree inside the extractor (Figure 4.5a). In this ideal alignment case, all ions are successfully extracted, and no losses are observed on the extractor. It appears that the small size and low divergence of the ion beam provides a considerable margin for extraction as the beam only occupies 25 % of the extractor.

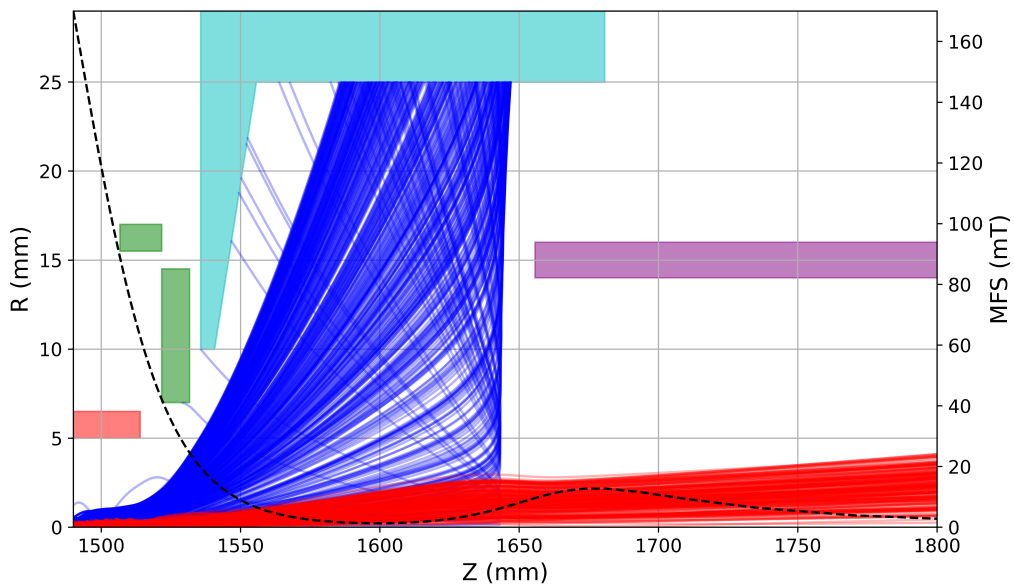


Figure 4.4: Electron (Blue, $N=500$) and ion trajectories (Red, $N=200$) in the collector region for TB2, without displacement. The black dotted line indicates the magnetic field strength.

4.1.4 Collector simulations with misalignment

In the case of TB2 with an asymmetric geometry and a 1.75 mm displacement, illustrated in Figure 4.5b, the shift of the components becomes apparent as the starting position for of the ions (as well as electrons) is no longer located on the central electric axis. This is natural, as the ions are mainly confined by the space charge field of the electrons, that in turn follow the magnetic field lines. The ion beam expands in the collector region, similar to what happens in the benchmark simulation. Upon entering the extractor, the beam is further accelerated, and all ions are extracted without losses. The beam approaches the extractor tube and therefore, the extraction margin is clearly smaller.

If we now consider the same test beam (TB2), but with a 3.5 mm displacement in the electrostatic field, the deviation towards the central axis just after the LDT is more pronounced, as can be seen in Figure 4.5c. However, it appears that the (fringe) fields between the extractor and collector assist in focusing the ions back into the extractor before entry. Although the beam visually appears smaller than the 1.75 millimeter case, the beam profile is now more elongated (elliptical) instead of circular, see Figure 4.6. Despite the perturbation caused by the significant displacement, reducing the extraction margin even more, the ion beam is successfully extracted and no losses occur. The imposed asymmetry affects the beam profile at the end of the extractor mostly in the x direction and slightly in the y direction, as can be seen in Figure 4.6. A summary of the results for the TB2 simulation is shown in Table 4.1. The extraction margin is reduced with increasing field displacement as the ion beam approaches the extractor, for both test beams. Furthermore, the elongated profile of the ion beam appears to be a result of its close proximity to the extractor entry, where it is affected by fringe fields. In none of the displacement cases losses occur on the extractor, as the ion beam is successfully extracted. This does not reflect the losses observed in measurements, as discussed in Section 1.1 and seen in Figure 3.12. It is likely that either the initial conditions of the ions in the LDT are not accurately represented, causing a underestimation of the losses.

For simulations performed with the other test beam (TB1) with a displacement of 3.5 mm, the ion beam closely approaches and collides with the extractor, seen in Figure 4.7. It exhibits a much greater divergence than TB2 and 43% of the total current is intercepted on the extractor. This shows that for a very large displacements, using an ion beam with a higher current and high neutralisation degree, the losses observed in measurements (Figure 3.12) can be reproduced. In case the displacement is only 1.75 mm for TB1, no losses are observed on the extractor. A summary of the results for TB1 can be seen in Table 4.2.

Table 4.1: Results for different displacements with TB2. The definition for R_1 , R_2 and extraction margin m_r can be seen in Figure 4.6 and δ is the charge residual

dy (mm)	R_1 (mm)	R_2 (mm)	$\bar{x}$ (mm)	$\bar{y}$ (mm)	m_r (mm)	Loss (%)	δ (dB)
0	3.5	3.3	0.0	0.1	10.6	0	-55
1.75	4.1	4.2	-2.4	0.1	7.0	0	-89
3.5	4.6	2.7	-5.5	1.0	2.4	0	-67

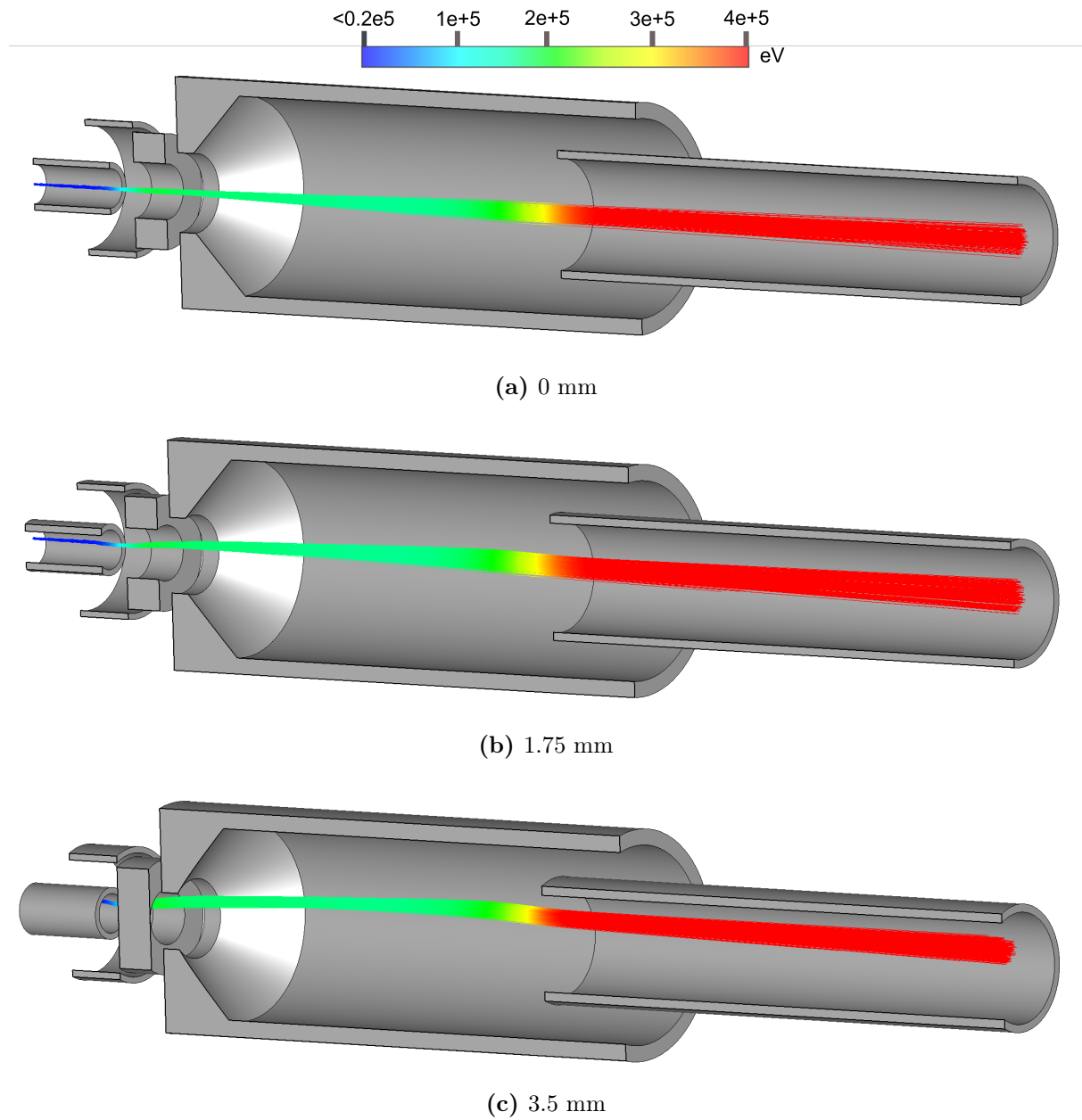


Figure 4.5: Simulations of the electron collector for TB2 with (a) 0 mm (b) 1.75 mm and (c) 3.5 mm displacement. Electrons are not shown. The color scale indicates the energy.

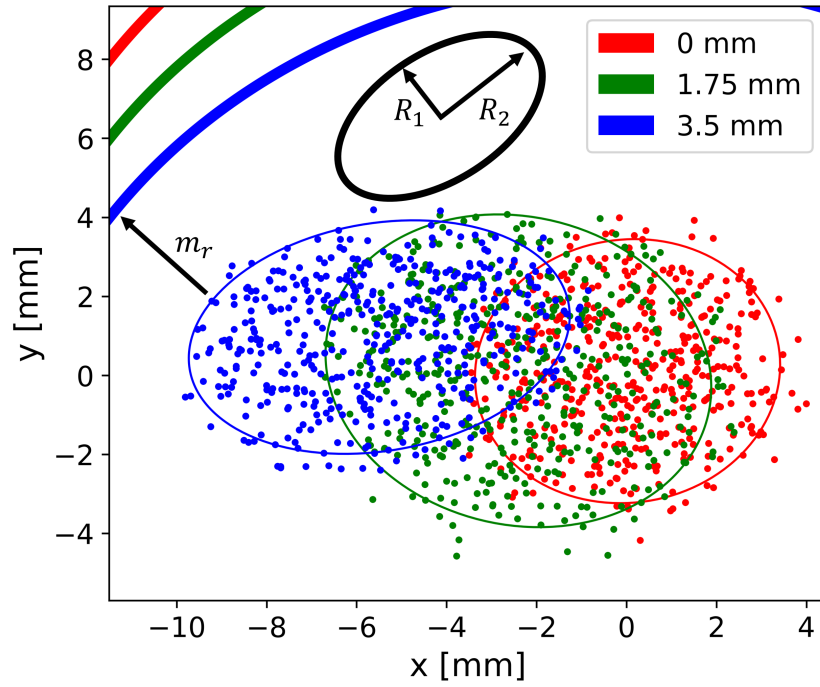


Figure 4.6: Ion beam profile at the end of the extractor tube ($\sim Z=1800$ mm). An ellipse is fitted to the data at 2σ . The extractor boundary ($r=14$) is indicated by the thick colored solid lines. The ellipse parameters and margin (m_r) are also indicated.

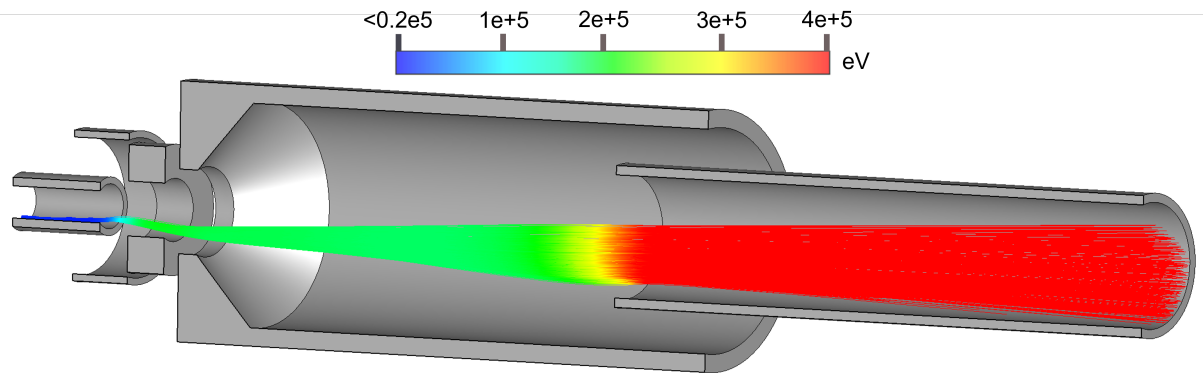


Figure 4.7: 3D ion trajectories for TB1 with a displacement of 3.5 mm. The collector was rotated to display the significant losses on the extractor.

Table 4.2: Results for different displacements with TB1. The definition for R_1 , R_2 and extraction margin m_r can be seen in Figure 4.6 and δ is the charge residual.

dy (mm)	R_1 (mm)	R_2 (mm)	$\bar{x}$ (mm)	$\bar{y}$ (mm)	m_r (mm)	Loss (%)	δ (dB)
0	10.0	8.8	-3.3	-1.7	3.5	0	-11
1.75	6.2	10.1	-3.8	-1.6	3.4	0	-15
3.5	9.8	11.9	-3.4	-1.4	0	43	-23

4.1.5 Electron power deposition inside the collector

In the benchmark simulation, the electron deposition on the collector exhibits radial symmetry, and can be represented as a function of z alone. Two distinct maxima in N_{hit} and power density (PD) can be seen at approximately 1585 mm and 1645 mm in Figure 4.8. The former peak results in a PD of almost 200 W/cm². Although this peak has a very high power density, it is likely that the actual power deposition inside the collector is distributed more uniformly due to the presence of back-scattered electrons. When primary electrons collide with the collector walls, approximately 50% of the electrons are back-scattered, carrying $\sim 80\%$ of the energy. The second peak at ~ 1645 mm indicates a very high particle density at the end of the collector, which is supported by Figure 4.4. Nevertheless, the magnitude of the peak does not offer any valuable insights since it is influenced by a binning artifact. A small increase in particle deposition is apparent in the region at ~ 1550 mm, caused by 'folding' of electrons which was discussed above, however, due to the slanted surface of the collector at this position, the power density is very low. The collector is at a potential of 3400 V and the electron beam carries a current of 1.083 A (assuming no electron loss), hence the total deposited power should be in range of 3691 Watt. This is confirmed by the simulations as the cumulative power deposited in the collector was found to be 3689 Watt.

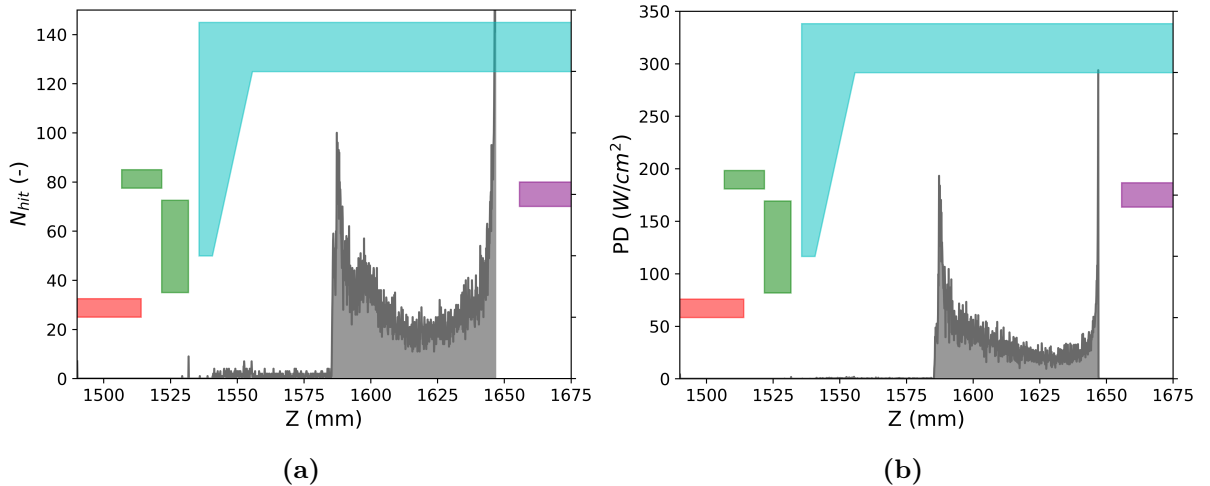


Figure 4.8: (a): Histogram of electrons hitting the collector wall for TB2 (peak at $Z=1645$ mm is truncated). (b): Power density (PD) induced by the electrons on the collector for TB2.

Any asymmetry in the potential field in the collector will express itself in a distorted PD on the collector wall. The deposition will no longer be just depending on the axial position z . Instead, due to the symmetry breaking, the deposition will now also depend

on the azimuthal angle θ , which is defined as $\arctan(y/x)$. The results for TB2, with a displacement of 1.75 mm, can be seen in Figure 4.9. It is clear that the asymmetry has been broken because the distribution as a function of θ is no longer uniform. A counter-intuitive local maximum in the particle deposition can be seen at angle of 180° , however no power is deposited here as it does not show up in the PD, shown in Figure 4.10. A more important local maximum can be seen in the angle ranging from 60° - 130° , which is also apparent in the PD. This asymmetric power distribution of the electron beam inside the collector suggests that the ions are also radially guided by the electron space charge. This asymmetric guiding of the ions as a function of the azimuthal angle is also evident in the beam profile, expressed in Figure 4.6. As previously stated, the presented power density values are significantly higher and less uniform than in reality due to the absence of back-scattered electrons in the simulations.

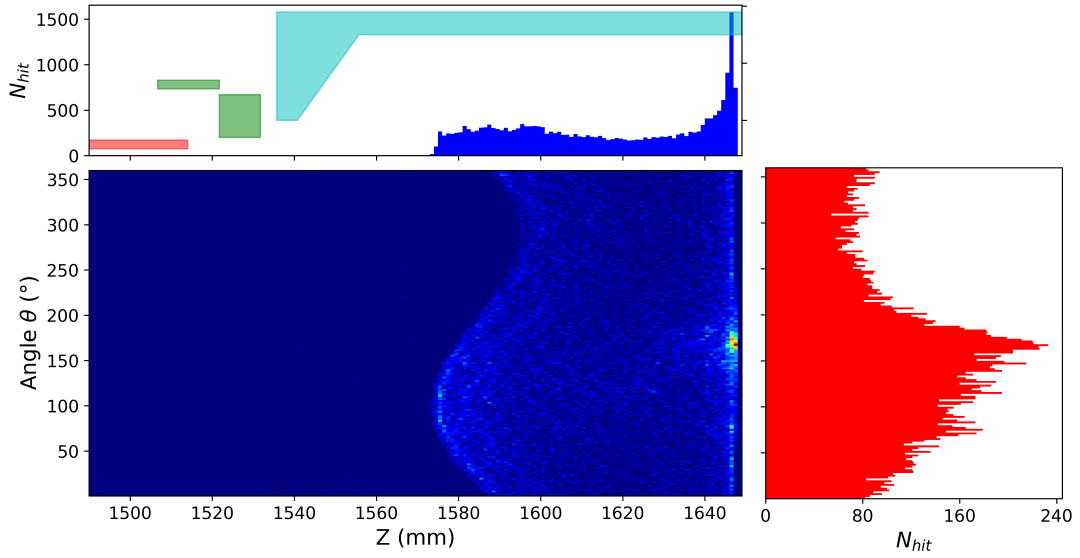


Figure 4.9: Particle hits in the collector region for TB2, with 1.75 mm displacement. The blue 1D histogram shows particle hits as a function of Z , the red 1D histogram shows particle hits as a function of the angle θ .

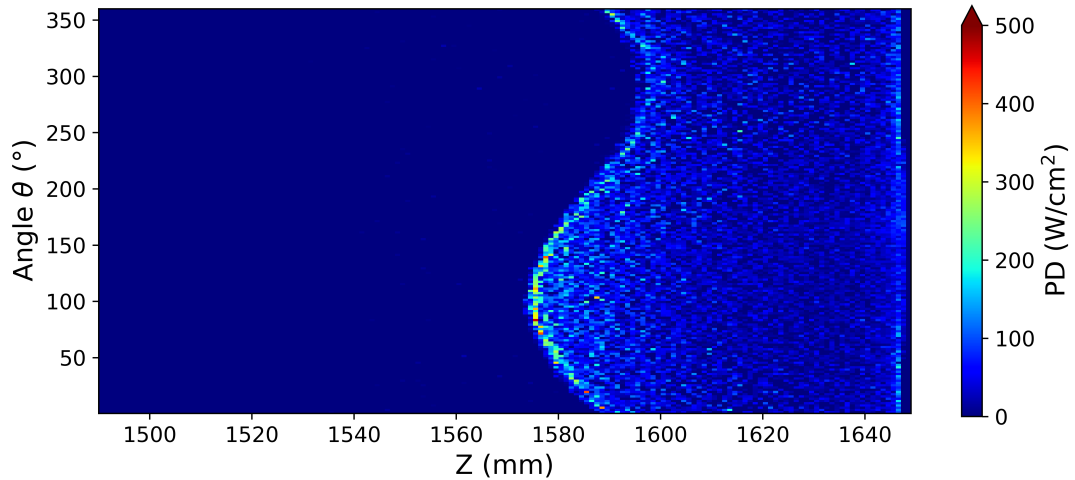


Figure 4.10: Power density in the collector, expressed as a function of z and θ , for TB2 with 1.75 mm displacement.

4.1.6 Simulation uncertainty

The results of the simulations with TB2 are deemed to be highly reliable due to the obtained charge residual error of less than -55 dB for all cases. However, the results of a test beam with higher current (TB1) and thus, higher neutralisation, have to be interpreted with caution as the charge residual error was found to be in the order of -10 to -20 dB (Section 3.6). The lower extracted current for TB2 is more in line with measured current values.

4.1.7 Visual inspection of the extractor

During the disassembly of the collector cross, a visual inspection of the collector was carried out. In a large area of the ion extractor, Newton rings were observed, seen in Figure 4.11a. These rings could be produced by ion bombardment on the extractor walls, but it is also likely that this is the result of the machining process during fabrication. The deposition of 'dust', seen at the end of the ion extractor in Figure 4.11b is more convincing evidence that the extractor was bombarded by ions. However, the deposition inside the extractor tube is rather symmetric, suggesting a good alignment of the extractor with respect to the magnetic field axis.

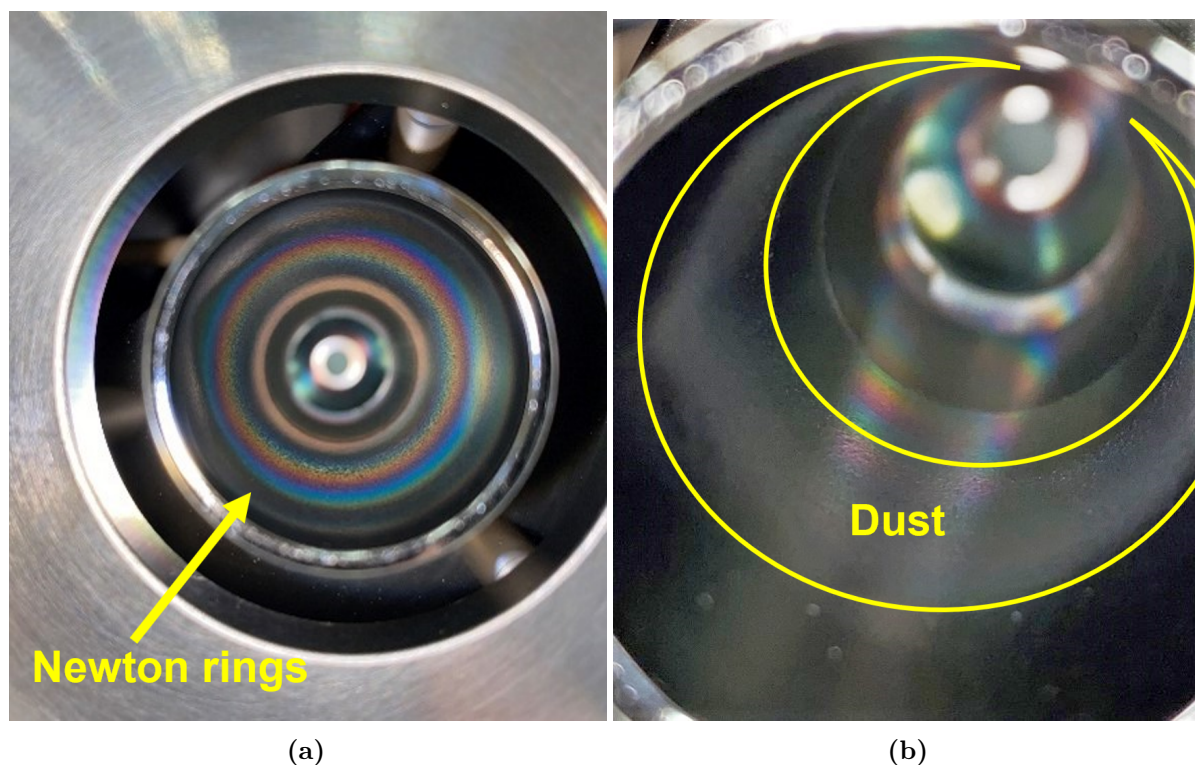


Figure 4.11: (a) Newton rings visible in the extractor tube. (b) 'Dust' on the extractor tube.

4.2 Formation of virtual cathode

Simulations with varying suppressor potentials were carried out to explore the limits of virtual cathode formation. The axial potential with (ϕ_{ESGUN}) and without space charge (ϕ_{ES}) can be seen in Figure 4.12, for an applied suppressor potential (ϕ_{supp}) of 2800 V (with respect to the cathode potential). A depression in the on-axis potential, caused by the space charge, can be seen in the LDT (red), where the potential drops from 10 kV to 9.18 kV. This effect can also be seen between 1515-1525 mm, where the suppressor (in green) is located, however, in this case the central potential without space charge included is 3 kV, while with electron beam space charge present the potential drops to 1.95 kV. This drop in potential caused by a superposition of the space charge potential with the suppressor potential could at some point stall the electron beam and cause a virtual cathode to appear.

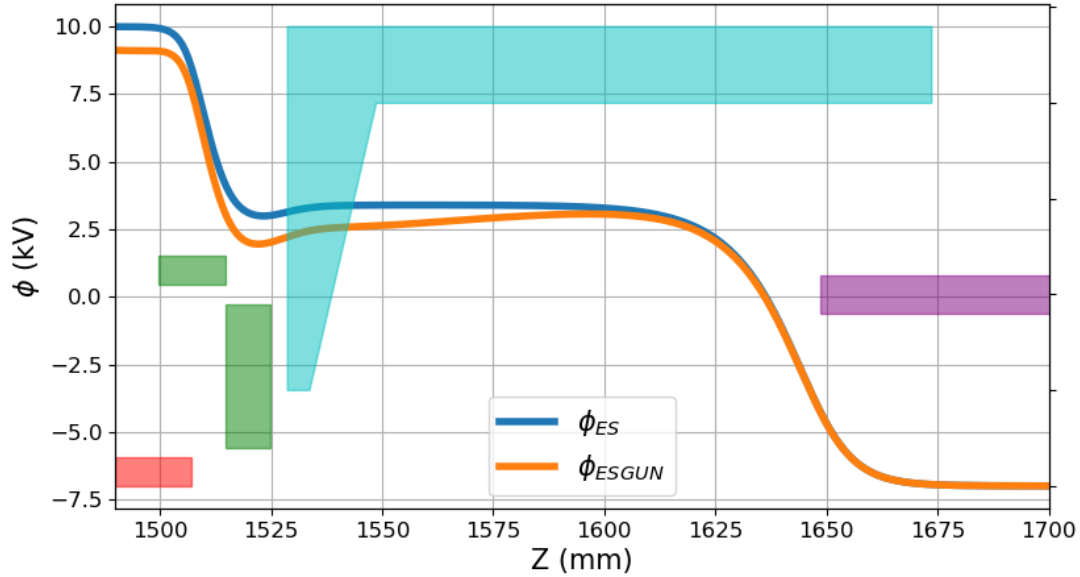


Figure 4.12: Axial potential plotted without (ϕ_{ES}) and with space charge (ϕ_{ESGUN}) included for $\phi_{supp}=2800$ V. The space charge of the electron beam causes a depression well in the suppressor region, located at approximately 1520 mm.

According to the Bursian criterion (Equation 2.8), a virtual cathode appears for any value within the region of the forbidden zone in Figure 4.13. The case for $\phi_{supp} = 2800$ V (described above) is also included in the figure, resulting in a space charge potential of $\phi_{SC} = \phi_{ES} - \phi_{ESGUN} = 1050$ V. In the critical region of the suppressor, the Bursian limit is onset at a suppressor voltage of approximately 1870 V, thus far outside the operational regime of 2600 V to 3000 V. Therefore, it is unlikely that the ion beam will be over focused by the local potential drop in the suppressor region, leading to beam losses on the extractor. This is supported by the simulations presented above, as there were no visual signs of over focusing of the ion beam. Despite simulations with very low suppressor potentials, such that the Bursian limit is surpassed ($\phi_{supp}=[1500, 1800]$), no visual signs of electron reflections caused by a virtual cathode were seen. This discrepancy can be understood, because the expressions for the Bursian limit assume a mono-energetic and

uniform beam, which was not the case in the simulations. Eventually, at a suppressor potential of 1200 V, a virtual cathode formed and the beam was completely reflected.

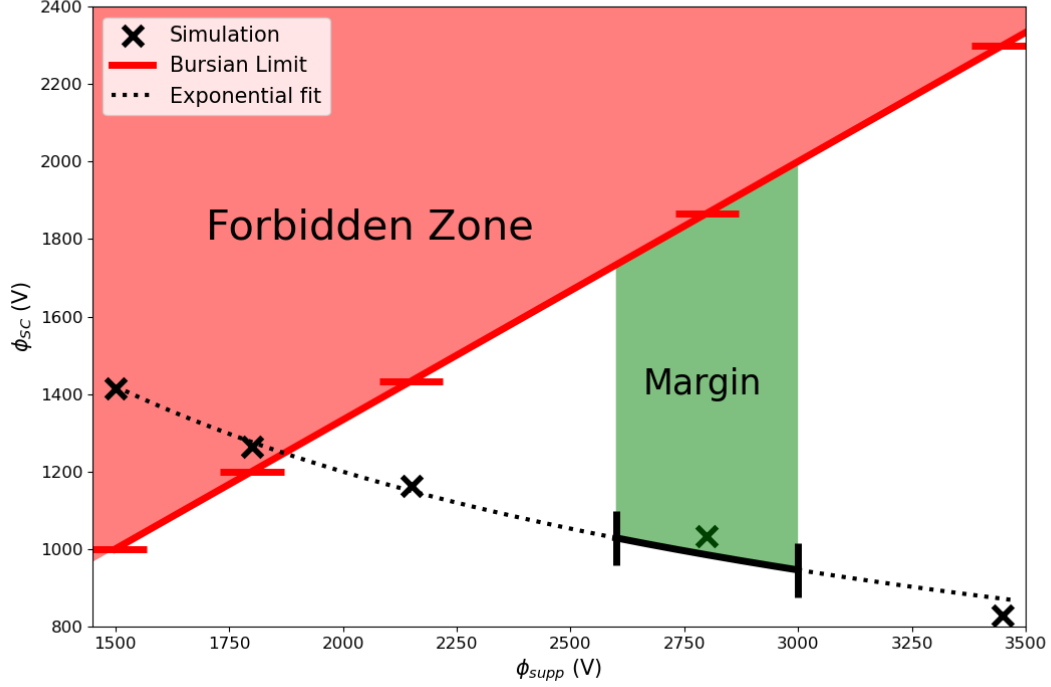


Figure 4.13: Comparison between the simulations and the Bursian limit, expressed in the space charge potential ϕ_{sc} for different suppressor potentials ϕ_{supp} . The forbidden zone is indicated by the red shaded area and the operating range for the suppressor by the solid black line. The green shaded area indicates margin between simulation and the Bursian limit. The exponential fit is described by $a \cdot \phi_{supp}^b$, with fitting parameters a ($1 \cdot 10^5$ V) and b (-0.59).

4.3 REXEBIS current density measurements

In this section, we present the results of measurements designed to evaluate the presence of an electron-ion two-stream instability, that might lead to ion heating at REXEBIS as outlined in Section 1.1. A decrease in the effective current density as a function of breeding time (from 25 ms and onwards) is observed for all three trap configurations (see Figure 4.14). For very short breeding times, the uncertainty in the measurement result blurs the trend. A similar decrease, but as a function of the neutralisation, is seen in Figure 4.15, here with added uncertainty bands for the predicted current densities taking into account a possible error in the electron beam energy.

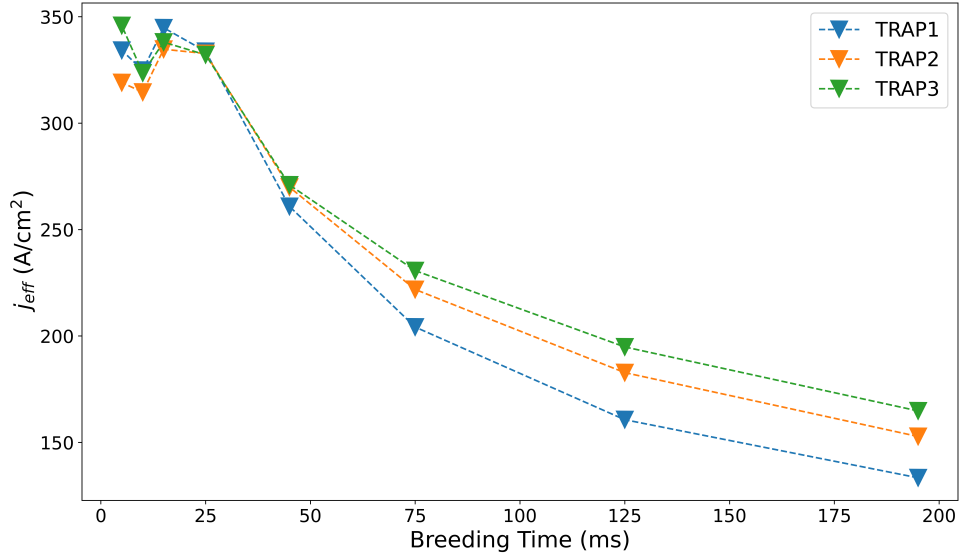


Figure 4.14: The effective current density as a function of the breeding time for the three different trap configurations. Trap 1 is closest to the electron gun, while Trap 3 is located closer to the collector.

The decrease in current density can be attributed to either neutralisation and/or ion heating, as both are time-dependent. However, from Figure 4.16, we can conclude that the former is the driving factor (for neutralisation $>10\%$), as the effective current density is comparable for similar degree of neutralisation, even though the breeding time (and thereby also heating) is different.

Contrary to the measurements performed at TwinEBIS, the effective current density at REXEBIS appears to increase with the distance between electron gun and breeding region. As seen in the plots, this is specifically notable for longer breeding times. However, the change in effective current density between the gun and the last trap is less pronounced than the decrease observed at TwinEBIS (see Figure 1.5).

Given the observed increasing current density with the distance, it is concluded that the electron beam at REXEBIS is not prone to electron-ion two-stream instability, at least not for these operational parameters. Nevertheless, it is atypical that the current density increases from Trap 1 to Trap 3 at REXEBIS. Neutralisation fails to provide an explanation, given that the degree of neutralisation, in fact, increases with the distance from the gun for every breeding time. Presently, we can only speculate about the cause:

- Noisier electron beam, and therefore more energy transfer to the ions, when the trap

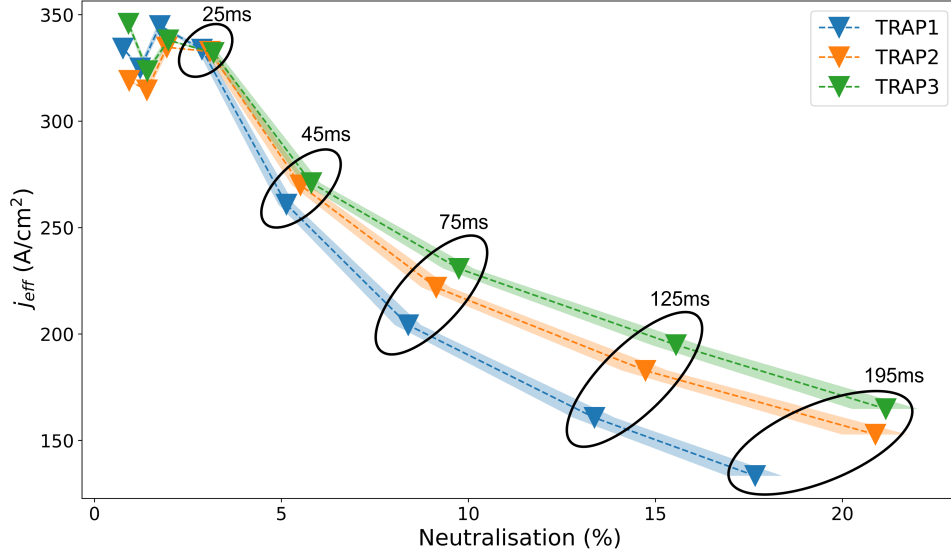


Figure 4.15: The effective current density as a function of the neutralisation for the three different trap configurations. The shaded area indicates the uncertainty band if a 500 eV electron beam energy error is imposed in the fitting routine.

region is configured near the gun. Although, this is contradicted by measurements of the electron losses that appear to increase further away from the gun.

- The release of ions from the trap during extraction moment could be less efficient near the collector region due to a misalignment of the drift tube structure with respect to the magnetic axis. This would leave a fraction of the ions (the cold ones) trapped in a 'macro-trap' for multiple breeding cycles. On the other hand, one would expect to see multiple charge state distributions then, and not only a continuous shift of a single distribution to higher charge states.
- Due to the varying lengths of the outer barrier for the different trap configurations, the extraction optics may influence the A/Q-values differently.

There may also exist certain parameters that are beyond control, and therefore further measurements are required.

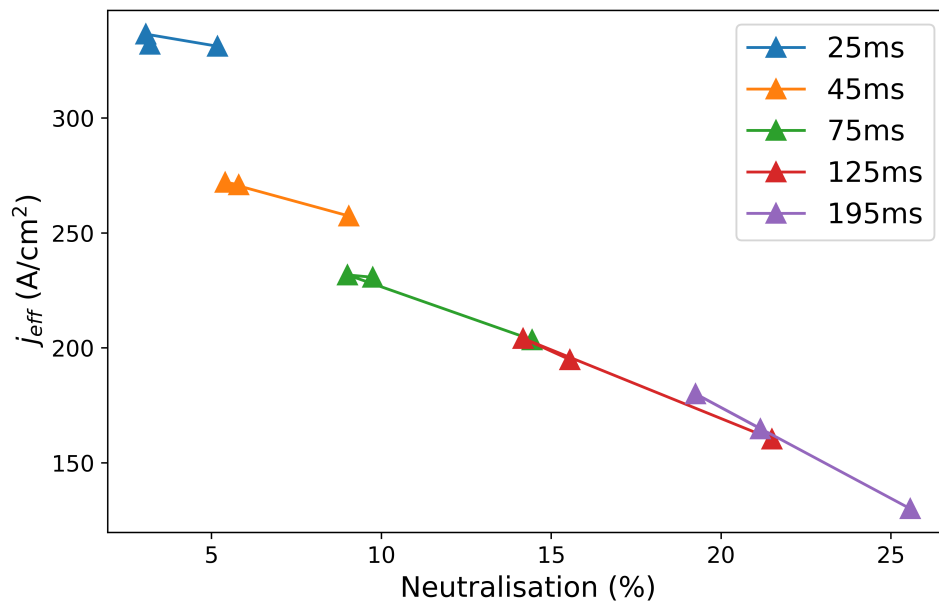


Figure 4.16: Effective current density in Trap 3 plotted as function of neutralisation degree. The data was obtained by varying the Xe injection pressure between three levels, and for each level estimate the current density for the different breeding times. There is a clear overlap between green and red, and red and purple curves, even though the breeding times (and thereby electron-ion heating) are different.

Chapter 5

Conclusions & Outlook

5.1 Ion losses on the ion extractor

For combined electron/ion beam simulations in the collector region, the electron beam was initialized at the gun and consequently translated to the collector region for tracking. Simulations of the electron gun yielded a perveance value of $1.083 \mu\text{A}/\text{V}^{3/2}$, which is in very good agreement with the measurements (accuracy of 1.5%). The observed beam scalloping was slightly larger compared to the findings presented in ref. [56], and crossing of trajectories was still present due to the limited number of tracked particles. Nonetheless, the reliability of the simulations was thoroughly assessed through convergence studies, where the precision of the potentials between simulations was found to be better than $\sim 3\%$. Furthermore, the simulated radial potential exhibited a discrepancy of less than 0.5% from the analytical calculation. These results demonstrate that the MEDeGUN was modelled with a sufficiently high degree of accuracy to provide input for the consecutive ion beam simulations.

An initial study of ion extraction for an electro-magnetostatic symmetric system provided a benchmark for subsequent simulations of asymmetric field configurations. This benchmark showed that no ions were recorded on the ion extractor, as the ion beam diameter only occupied $\sim 25\%$ of the extractor diameter.

By imposing a displacement of the electric field with respect to the magnetic field, the starting position of the electrons and ions were shifted radially in the LDT, emulating a misalignment. This caused a deformed and radially displaced ion beam entering the ion extractor and the available margins for ion extraction decreased as expected. Test beam TB1, with higher neutralisation and extraction current, displayed a large divergence and ions started to impinge on the extractor for a displacement of 3.5 mm. The losses were significant, and in the order of $\sim 40\%$, comparable to the measurements. The much lower precision for the simulation of the large current case, may cast some doubt on the reliability of the exact values. On the other hand, for the lower current beam (TB2), the precision was excellent, but neither a 1.75 mm nor a 3.5 mm displacement of the electrostatic axis yielded any losses, and all ions were successfully extracted. Simulations of TB2 are not in agreement with measurements presented in Section 3.7, where losses as high as 50% were observed on the extractor, also for low extracted amount of charge. Inaccurate initialization of the ions may yield an underestimation of the losses, also for the symmetric case, and this will briefly be discussed in the Outlook below.

An additional consequence of the non-symmetric field configuration was an azimuthally non-homogeneous power deposition from the electrons on the collector surface. Electrons that enter the collector region close to the axis with small angles appear to be reflected backwards to the LDT and the trapping region by the negative potential of the ion extractor. This is confirmed by measurements with MEDeGUN during the commissioning phase, where losses were mainly identified on the LDT and anode. The collector power density study indicates very high power densities ($>100 \text{ W/cm}^2$) at the beginning and end of the collector, however, the actual values will be lower due to a redistribution of the power density by back-scattered electrons.

What opposes the argument of a non-symmetric field configuration causing excessive losses, are visual observations of ion bombardment on the ion extractor. The ion deposition seems to be more or less evenly distributed azimuthally inside the ion extractor.

Simulations were performed with different suppressor potentials to assess if a virtual cathode could arise in the vicinity of the suppressor, leading to an over-focusing of the ion beam. A virtual cathode situation only occurred at a suppressor voltage of 1200 V, far outside of the operational region of 2800-3000 V. Therefore, a strong lens effect for the ions is not expected, and neither can deposited electrons onto the LDT and anode be explained by a virtual cathode situation.

5.2 REXEBIS current density measurements

In the REXEBIS measurements, investigations were conducted to confirm the presence of an electron-ion two-stream instability, that would cause significant ion heating. The measurements were carried out with different trap configurations to explore the effects of the breeding location on the effective current density. The results indicate a trend of an increasing current density with the distance between the electron gun and the location of the breeding region, which is not consistent with an electron-ion two-stream instability. Moreover, the results are in direct contradiction with results obtained at TwinEBIS, where the effective current density reduces farther from the gun. The measurements at TwinEBIS also show a much stronger dependence on the distance to the gun than at REXEBIS.

5.3 Outlook

The asymmetric ion extraction simulations have so far not explained the large fraction of ion current being intercepted by the ion extractor. Evidence for ion losses caused by the formation of a virtual cathode were also not found. Instead, the focus should be redirected towards the starting conditions of the ions inside the trapping region. If, for example, an electron-ion two-stream instability can cause a rapid heating only in radial direction, and the redistribution of the momentum into the axial direction is slow due to a low ion-ion collision rate, one can end up with an ion cloud that has a large transverse momentum and radial distribution. Then, the assumption that all ions are confined within the electron beam is no longer valid ($k>1$). An example of an ion beam with a radius and energy larger than the simulations presented so far in this work (TB1 and TB2), can be seen in Figure 5.1. This ion beam, with $k=1.5$, can be seen propagating

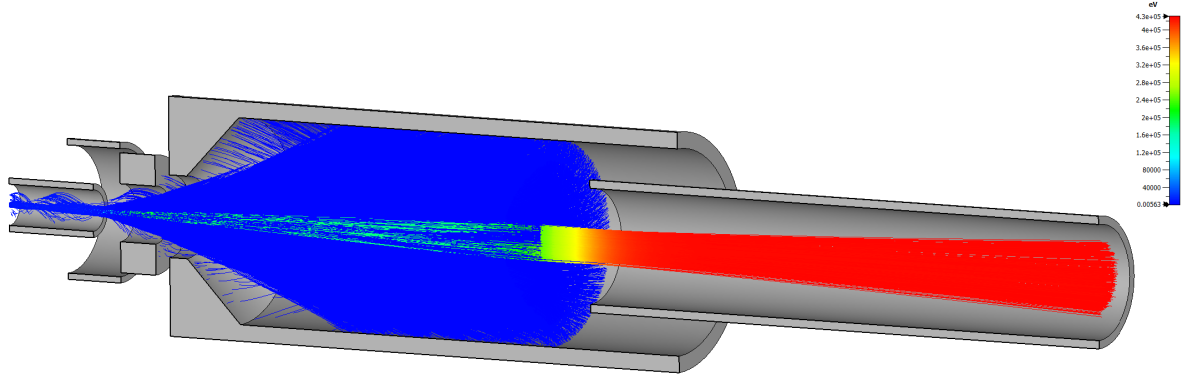


Figure 5.1: Simulation of an enlarged beam, $k=1.5$ and $\eta=0.5$ in trap. In LDT: $r_{ion}=452 \mu\text{m}$ and 1.44 mA

with a very large divergence, almost hitting the extractor for a symmetric scenario. Still, this may not be an exceptionally large ion distribution, in the case an electron-ion two-stream instability is present. Calculations suggest (see Figure 2.3) that the instability ceases to push the ions to even larger radii if an ion temperature as high as $12 \cdot 160 \text{ eV/Q}$ is reached. Such a high temperature is similar to the radial holding voltage from beam axis to the drift tube ($\sim 1300 \text{ V}$), and thereby the ions will occupy more or less the full drift tube. It should be noted that at this stage the electron-ion two-stream instability is not confirmed for TwinEBIS, and if present, if it would heat the ions preferentially in radial direction. VUV or x-ray spectroscopy could potentially be used to determine the electron beam profile and ion distribution, providing insight into the initial conditions in the LDT. However, geometrical constraints hinder the use of direct methods, enforcing indirect methods.

Concretely,

- a theoretical study of the electron-ion two-stream heating was launched with the aim of calculating ion heating rates and distributions, after the instability has settled,
- alternative ion extractor designs are foreseen, with larger diameter and shorter length. Once installed, transverse emittance measurements of the beam in the ion extraction line could give further insight about the ion energy,
- one could consider abandoning the pure Brillouin type gun and instead use a gun as recently presented by A. Pikin [67], where the current density, and current, can be tuned on-line. With such a design, one can explore the electron-ion stability region and find an operational point where the current and current density are maximized, without compromising the beam stability and ion extraction efficiency.

The ion translation from the trapping region to the LDT may merit further investigations, particularly since the ion transport takes place at low beam energies (typically $< 1000 \text{ eV/Q}$). The positive ion current is therefore high, and even though the electron current is significantly higher, the local current densities of the positive and negative charges may be similar, and a proper tracking including space-charge may be required in order to determine the correct starting conditions of the ions in the LDT.

Consequently, it is recommended to,

- perform slow ion extraction over the outer barrier in order to indicate if longer pulses, and therefore lower ion current, can potentially reduce the losses.
- track the ions all the way from the trapping region to the collector, in conjunction with the electrons. However, alternative simulation methods are required due to the elongated geometry, resulting in a slow convergence and low precision.

Further efforts into improving the convergence and precision of extraction simulations with high currents and neutralisation are also recommended. Additionally, back-scattered electrons could significantly change the outcome of the simulations in terms of neutralisation in the collector region, virtual cathode formation, and also power density on the collector.

Considering the electron current density measurements at REXEBIS, the recommendations for future work would be to,

- move the gas injection point to the center of the trapping region, to facilitate comparison with TwinEBIS measurements. A gas tube has been installed during the winter shutdown.
- evaluate the individual contributions of the ion heating and neutralisation in the reduction of the effective electron current density.

Appendix A

Space charge calculations

Iteration scheme

Calculation of the space charge potential of a uniformly charged particle beam requires an iteration scheme because the experienced potential (hence energy) of the particle beam is dependent on its own space charge. The space charge is in turn dependent on the energy of the particle and therefore, we have to make iterations recalculating the energy of the particles. To include compensation by ions we also have to solve the potential functions for the ions.

The energy can be recalculated by using the potential ϕ in iteration t as,

$$\phi_t = \phi_{ext} - \phi_{sc,t}, \quad (\text{A.1})$$

where ϕ_{ext} is the external applied potential, and for the first iteration $\phi_{sc,0} = 0$. Thus, calculation of the energy in the first iteration, only considers the applied external potentials.

To calculate the corrected energy, we first calculate the perveance in the i -th iteration,

$$P_t = \frac{I}{\phi_t^{3/2}}, \quad (\text{A.2})$$

then we calculate the Brillouin radius with (Equation 2.3),

$$r_{B,t}[\text{cm}] = \frac{147.6[\mu\text{m}]}{B_z[\text{T}]} \sqrt{\frac{I_t[\text{A}]}{\sqrt{E_i[\text{keV}]}}, \quad (\text{A.3})$$

where E_t (in eV) is given by the potential $\phi_t e$.

Thereafter, we calculate the corrected Herrmann radius with (Equation 2.4),

$$r_{h,t} = r_{b,t} \left(\frac{1}{2} + \frac{1}{2} \left(1 + 4 \left(\frac{8kT_c r_c^2 m_e}{e^2 B_z^2 r_B^4} + \frac{B_c^2 r_c^4}{B_z^2 r_B^4} \right)^{1/2} \right)^{1/2} \quad (\text{A.4})$$

and we define a constant for convenience as,

$$S = \frac{\sqrt{m}}{\sqrt{2e} \cdot 4\pi\epsilon_0}. \quad (\text{A.5})$$

In the case of a neutralised beam, the negative charge is compensated by the positive charge of the ions. Consequently, the experienced potential for a particle is a superposition of the space charge potential produced by the ions ($\phi_{sc,i,t}$) and by the electron beam ($\phi_{sc,e,t}$), expressed as,

$$\phi_{sc,t} = \phi_{sc,e,t} + \phi_{sc,i,t}, \quad (\text{A.6})$$

using the general form of the space charge potential as expressed in Equation 2.6 and rewriting using the perveance and the introduced constant S , we obtain:

$$\phi_{sc,t}(r) = S \cdot P_t \frac{\phi_t^{3/2}}{\sqrt{\phi_t}} = S \cdot P_t \cdot \phi_t \begin{cases} \frac{r^2}{r_e^2} & \text{for } r \leq r_e. \\ (2\ln \frac{r}{r_e} + 1) & \text{for } r \geq r_e. \end{cases} \quad (\text{A.7})$$

Equation A.7 is used to recalculate the space charge potential $\phi_{sc,t}$, based on the latest obtained perveance P_t , potential ϕ_t , $r_{h,t}$ and $r_{ion,t}$. The solution converges rather quickly, which can be seen in Figure A.1, that shows the error between iterations.

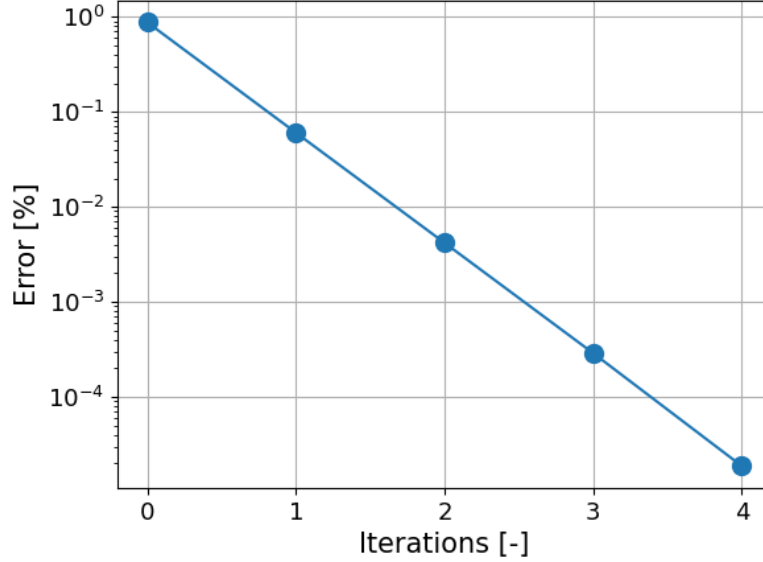


Figure A.1: Relative error in energy compared to the final iteration.

Space charge within ion beam boundary and drift tube

Now we give an example of calculating the potential within the ion beam boundary, by using the equations described above. For the electron space charge, within the boundary of the ions, we set $r = r_i$ (assuming that $r_i > r_e$),

$$\phi_{sc,e,r=r_i,t} = S \cdot P_t \cdot \phi_t \left(2 \ln \frac{r_i}{r_e} + 1 \right). \quad (\text{A.8})$$

Then, for the ions we define a neutralisation factor η ,

$$\eta = \frac{v_e I_{ion}}{v_{ion} I_e}. \quad (\text{A.9})$$

In the same way as in Equation A.8, we can now express the ion potential within the ion boundary ($r = r_i$) by using Equation A.9 to obtain,

$$U_{sc,i,t,r=r_i} = \frac{\sqrt{m_i}}{\sqrt{2e} \cdot 4\pi\epsilon_0} \frac{\eta I_e \sqrt{\frac{2E_t}{m_i}}}{\sqrt{\frac{2\phi_t}{m_e}} \sqrt{E_t}} \cdot \left(2 \ln \frac{r_i}{r_e} + 1 \right), \quad (\text{A.10})$$

which simplifies to,

$$U_{sc,i,t,r=r_i} = S \cdot P_t \cdot \phi_t \cdot \eta. \quad (\text{A.11})$$

To obtain the total space charge potential within the ion beam boundary, we substitute Equation A.8 and Equation A.11 into Equation A.6 and define a factor describing the ion and electron radii $k = r_i/r_e$,

$$\boxed{\phi_{sc,total,t,r=r_i} = S \cdot P_t \cdot \phi_t ((2 \ln k + 1) - \eta)}. \quad (\text{A.12})$$

which expresses the total space charge potential within the ion beam boundary r_i , neutralised by ions with a neutralisation factor η . This equation is only valid for $k > 1$.

With the same approach, the total space charge potential with respect to the drift tube radius can be evaluated by setting $r = r_{dt}$ to acquire,

$$\boxed{\phi_{sc,r=r_{dt}} = S \cdot P_i \cdot \phi_i \left[\left(2 \cdot \ln \left(\frac{r_{dt}}{r_{h,i}} \right) + 1 \right) - \eta \cdot \left(2 \cdot \ln \left(\frac{r_{dt}}{r_{ion,i}} \right) + 1 \right) \right]}. \quad (\text{A.13})$$

An example is given in Figure A.2, where the total experienced potential with respect to the LDT can be seen for typical TwinEBIS parameters. Additionally, the space charge within the ion beam boundary is also given in the cutout for $k < 1$.

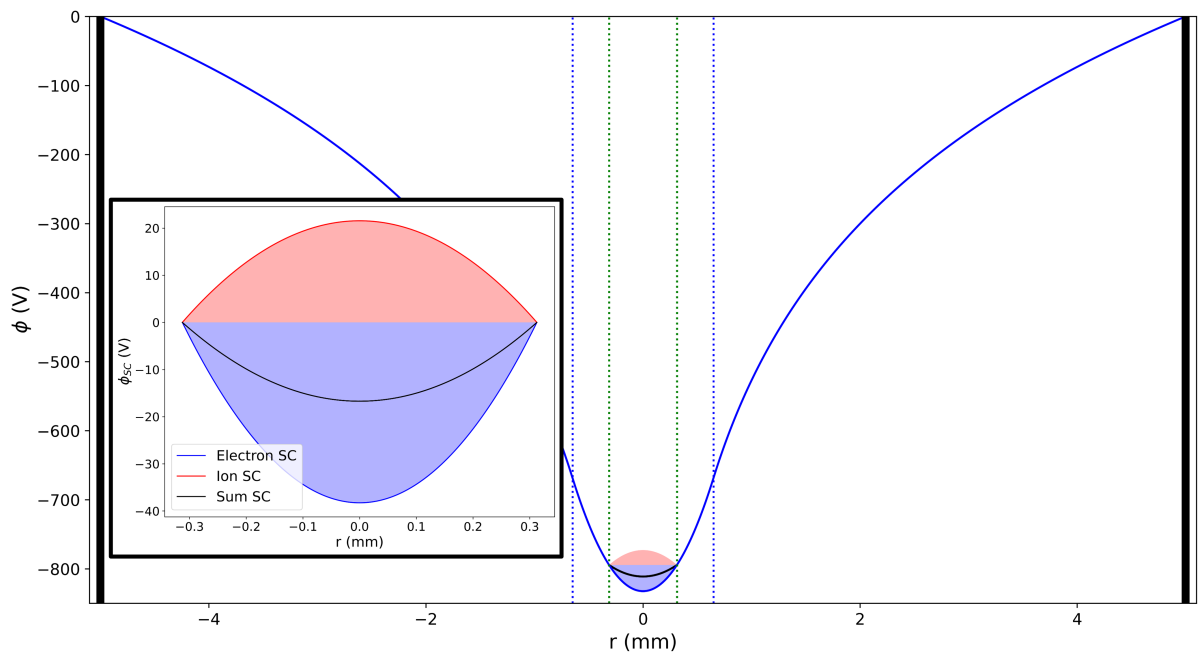


Figure A.2: The calculated space charge potential in the LDT for typical TwinEBIS parameters. The electron beam and ion beam radius is given by the blue and green dotted lines respectively. The cut-out shows the calculated space charge potential (Sum SC) within the ion beam boundary for $k < 1$.

Appendix B

Magnet dismantling

After a cool-down to 4.2 K, the superconducting solenoid at TwinEBIS showed an excessive liquid helium (LHe) boiling-off rate. After a second attempt, the holding time was down to around 24 hours, compared to the specified holding time of 14 days. This corresponds to a heat load of approximately 3 W at 4.2 K. As the insulation vacuum was good ($<10^{-7}$ mbar), a mechanical thermal bridge was suspected being the reason.

In Figure B.1 one can see a schematic drawing of the onion-like design of cryostat from Oxford Instruments, that provides the thermal insulation of the 4.2 K cold mass (indicated as 4 K He in Figure B.2a), including the coil. From outside to the center one passes the room-temperature cryostat envelope, providing the vacuum insulation. Several layers of multilayer insulation (MLI) follows, before the 77 K liquid nitrogen jacket appears. Between the inner side of the nitrogen jacket and the cold mass, an intermediate 20 K shield is installed. On the inner side of the 4 K cold mass, there is no intermediate shield, but a very small gap to the 77 K bore tube. To reduce the radiation heat loss between cold mass and the 77 K bore tube, highly reflective aluminium scotch is taped on the inner side of the cold mass (in cyan), while the 77 K bore tube has a highly reflecting aluminized mylar sheet attached to it (in orange). Inside of the 77 K bore the magnet bore tube inserted, which is at room temperature. The latter ensures the vacuum enclosure, and to reduce the heat load on the 77 K bore tube, several layers of MLI are wrapped around the magnet bore tube. The helium jacket is suspended inside the cryostat using thin stainless steel rods that can be manipulated from outside.

To identify the cause of the thermal bridge, the magnet was dismantled and the internal structure and tolerances were examined. No misalignment of the elements was observed, neither any direct thermal bridges outside of the intermediate shield. However, after the removal of the 77 K bore tube, one could notice that the applied scotch tape on the inside of the He jacket was wrinkled at several locations, see Figure B.2b, and even one thin flake was hanging down. Due to the tight space, the wrinkled scotch caused a thermal bridge between 4.2 K and 77 K. This problem has occurred before, both at the TwinEBIS and REXEBIS solenoids, in spite of different ways of applying the scotch has been tried out.

In the end, it was decided to remove the scotch completely, and instead mechanically polish the inner surface of the He jacket (stainless steel), see Figure B.3. This was done using Scotch brite together with a polishing powder. One can by mechanically polish stainless steel obtain an emissivity value of 0.07 (for radiation from a 77 K source).

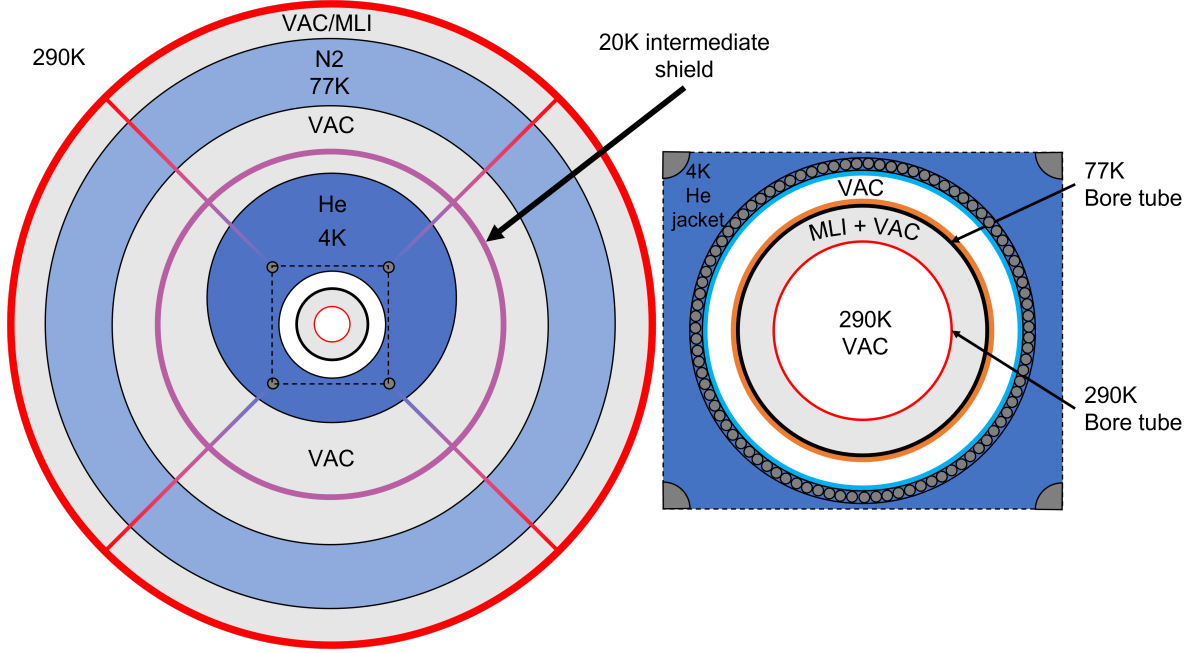
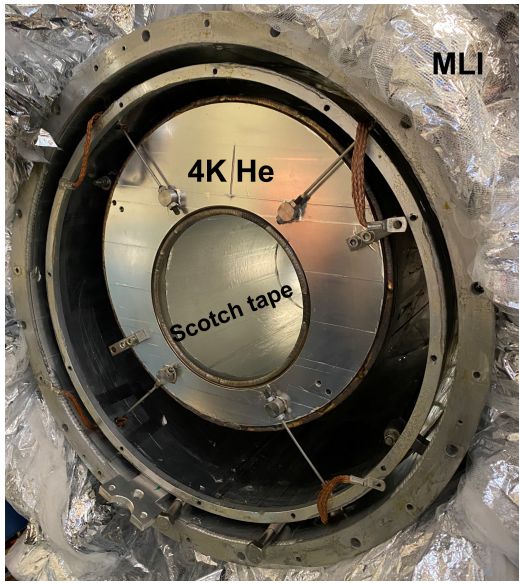


Figure B.1: Thermal structure of the superconducting 2 T magnet at TwinEBIS. The scotch tape is indicated in cyan while the aluminized mylar sheet is indicated in orange. Insulation is provided by vacuum (VAC) and multilayer insulation (MLI). The solenoid is indicated around the helium jacket.

We do not have any figures for the emissivity of the applied aluminium tape at these temperatures, but the values for mechanically and electro-polished aluminium is 0.06 and 0.04, thus not so far away. If we apply Lemmen's formula for radiative heat transfer between surfaces, taking an emissivity of 0.07 for the polished stainless steel and 0.04 for the aluminized mylar sheet (located at 77 K), one obtains a heat load of 0.07 W, which translates to 2.3 litre liquid helium per day.

In spite of the initially expected reduced holding time compared to initial specifications, the TwinEBIS now demonstrates an excellent liquid helium holding time in excess of 20 days, which is very encouraging. A similar good result was also obtained at REXEBIS after an identical modification. As also the REXEBIS magnet had to be opened up during the past shutdown, a similar modification was applied, with an equally good result concerning the holding time.



(a)



(b)

Figure B.2: (a): View of the TwinEBIS magnet showing the 4 K He jacket. (b): Loose scotch tape inside of the He jacket.



Figure B.3: The polished surface where scotch tape used to be.

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