

Experimental and numerical studies on the proposed application of hollow electron beam collimation for the LHC at CERN

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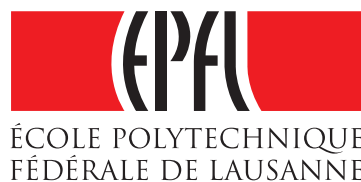
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Abstract

This thesis work was carried out in the framework of the *U.S. LHC Accelerator Research Program (US-LARP)*, a collaboration between the *European Organization for Nuclear Research (CERN)* and the U.S. Department of Energy. The first half of the work was completed at Fermilab (USA), the location of the Tevatron, a proton-antiproton collider and the second largest particle collider in the world. The second half was completed at *CERN* (Switzerland), the location of the largest proton collider in the world (*Large Hadron Collider (LHC)*).

This thesis characterizes a *Hollow Electron Beam (HEB)* for possible usage at the *LHC* to enhance its collimation through *Hollow Electron Beam Lenses (HEBLs)*. Collimation is a long established principle in high energy particle accelerators. *Hollow Electron Beam Collimation (HEBC)* aims to enhance current collimation systems by controlling diffusion of primary halo particles into the limiting aperture. It works on the principle of a transverse radial electric field that kicks the primary halo particles outwards upon each pass in a multi-pass system. The transverse field is produced by a *HEB* that is coaxially aligned with the accelerator beam, producing a negligible electric field in the center and a strong transverse electric field at amplitudes higher than the inner radius of the electron beam. Ideally, halo particles are affected without perturbation of the beam core. One of the main advantages of this system is to decrease the dependence on instantaneous loss spikes and beam jitter. A solid experimental basis of *HEBC* was accumulated at the Tevatron. The application of this technique at the LHC is now under investigation.

The aim of this thesis is to present a preliminary report to support a future optimal conceptual design report. It characterizes the available hardware in order to facilitate the design of a *Hollow Electron Gun (HEG)* for the LHC, characterizes the effect on beam diffusion by determining the transverse electric fields of the electron beam and initiates 3D simulations in order to determine the effect of the *HEBL* on the beam core. Experiments were conducted in the *Tevatron Electron Lens Test Stand (TELTS)* at *Fermi National Accelerator Lab (Fermilab)* (USA) in the lower *Linear Accelerator (LINAC)* gallery.

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Acronyms

Notation	Description	Page List
ACL	Accelerator Command Language	29–31
ACNET	Fermilab Accelerator Control System	20, 29, 30
BNL	Brookhaven National Laboratory	6
CERN	European Organization for Nuclear Research	I, 1, 5, 56, 57
CGM	Computer Graphics Metafile	49
COM	Center Of Mass	4
DTL	Drift Tube LINAC	3
EGR	Emittance Growth Rate	44, 47
Fermilab	Fermi National Accelerator Lab	I, 1, 4, 9, 12, 23, 48
GNU	GNU's Not Unix	31
HEB	Hollow Electron Beam	I, 1, 6, 7, 14, 15, 20, 33, 40, 41, 47, 55–57
HEBC	Hollow Electron Beam Collimation	I, 1, 3, 7–10, 20, 57
HEBL	Hollow Electron Beam Lens	I, II, 1, 2, 7, 8, 11, 18, 20, 29, 41, 43, 48, 50, 56, 57
HEG	Hollow Electron Gun	I, 1, 8, 42, 56, 57
HG06	0.6 inch Hollow Electron Gun	1, 8, 9, 11–14, 22, 56
HG1b	1 inch Hollow Electron Gun	1, 9, 11–15, 21, 22, 25, 49, 56
HL-LHC	High Luminosity LHC	5
IR	Interaction Region	5, 14
LHC	Large Hadron Collider	I, 1, 2, 4, 5, 8, 9, 11, 14, 41, 55–57
LINAC	Linear Accelerator	I, 4
PIC	Particle-In-Cell	48, 49, 57
RHIC	Relativistic Heavy Ion Collider	6
RMS	Root Mean Square	5, 43, 44
SCLER	Space Charge Limited Emission Region	15, 16, 18, 19, 23, 24, 26

Notation	Description	Page List
TEL1	Tevatron Electron Lens 1	6, 8, 9
TEL2	Tevatron Electron Lens 2	1, 6, 8, 9, 11, 48, 55
TELTS	Tevatron Electron Lens Test Stand	I, 9–11, 20, 24, 29, 31, 43, 54, 56, 57
TEV	Accelerator Simulations Cluster	48, 52, 54
TLER	Temperature Limited Emission Region	15–19, 24, 26
US-LARP	U.S. LHC Accelerator Research Program	I, 1
VLHC	Very Large Hadron Collider	5

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Chapter 1

Introduction

This work was completed in the framework of the U.S. Department of Energy collaboration with the *Large Hadron Collider (LHC)*, the *U.S. LHC Accelerator Research Program (US-LARP)*. The experiments were completed between February and May 2013 at *Fermi National Accelerator Lab (Fermilab)* in Illinois, USA. Simulations were done at the *European Organization for Nuclear Research (CERN)* in Switzerland in June and July 2013. The work incorporates aspects of the Tevatron, a proton and antiproton collider, and the LHC, a proton-proton collider.

This thesis addresses the characterization of a new *1 inch Hollow Electron Gun (HG1b)* tested at *Fermilab* for *LHC* collimation purposes in the framework of *Hollow Electron Beam Collimation (HEBC)*. Considering successful soft collimation experiments using a *0.6 inch Hollow Electron Gun (HG06)* in the *Tevatron Electron Lens 2 (TEL2)* at the Tevatron, this thesis outlines important design parameters for a *Hollow Electron Gun (HEG)* and an electron lens for the LHC. It measures the transmission, yield and transverse profiles of the new *HG1b*, which fits the general *LHC* requirements. Furthermore it determines the transverse electric fields and the beam evolution of the *Hollow Electron Beam (HEB)*. Additionally upper limits for the emittance growth of the proton core due to the *HEB* are determined.

The first Tevatron electron lens was installed in 2001. It was used on a daily basis for abort gap cleaning for a period of 10 years until the recent shutdown of the Tevatron in 2011. A second Tevatron electron lens was installed in 2006 as a backup for the first lens. It was mainly used for research on beam-beam force compensation and space charge compensation [1]. More recently, the lens has been tested as a soft collimator by installing a *HEG*. Considering the 10 years of prolonged stable operation at the Tevatron, electron lenses have established themselves as a mature technology for beam manipulation.

HEBC is designed to be used together with current collimation systems in order to control the diffusion of halo particles into the limiting aperture through transverse electric fields. The proton core at the same time remains unaffected due to the negligible electric field that is found in a cylindrical hollow electron beam.

HEBC studies have been part of *US-LARP* since 2009. There is a strong interest to implement two electron lenses in the *LHC*. The aim is to provide a solid basis for the design of those lenses, in case these are needed when the *LHC* reaches nominal energy. The *TEL2* is now available for use at the *LHC*, but constraints such as cryogenics and a long installation time make this a difficult task. Therefore the plan is to design two new electron lenses, optimized specifically for operation at 7 TeV, with improved integration possibilities and instrumentation [2, S.27-28].

The *CERN* strategy for the *Hollow Electron Beam Lens (HEBL)* was presented at the 20th *US-LARP* collaboration meeting in Napa Valley, CA, USA, in April 2013, it was agreed that *Fermilab* would work on an optimum conceptual design for an implementation in the LHC. This study would entail a discussion of the hardware parameters and optimal design parameters for the LHC, the effect of the *HEBL* on beam dynamics and beam core (luminosity) and the enhancement of collimation performance. The effect on beam dynamics was addressed in [3]. This recent paper shows that with an AC beam mode operation, a scraping of 75% of the halo particles was possible in 20 s[3].

This thesis will address the hardware and optimal design parameters as well as the effects of *HEBC*

on beam dynamics and the beam core. This is done by discussing current Tevatron hardware, measuring the yield and transverse profiles of the electron beam and determining the transverse electric fields of the electron beam. Additionally this thesis initiates a 3D simulation using WARP which will be used in order to obtain a 3D non-linear kick model for implementation in Lifetrack or SixTrack. This will allow the integration of proton trajectories in the *LHC* passing through the *HEBL* and thus a analysis of the effect of the electron lens on beam halo diffusion and on the beam core. An overarching aim of this thesis is to present a first study that will support a future optimal conceptual design report.

Chapter 2

Particle Accelerators and Collimation

This chapter introduces particle collimation as a necessity for current high energy particle accelerators. It discusses the limitations of classical collimation systems and elaborates on *Hollow Electron Beam Collimation (HEBC)*.

2.1 Accelerators and Particle Collimation

The origin of particle accelerators can be traced back to Rutherford's 1910 scattering experiment of α particles on gold foil at Cavendish at Cambridge University in England. In 1927, Ernest Rutherford addressed the Royal Society of London, expressing his desire for the development of a device that could continuously produce α and β particles at energies much larger than their natural decay energies. His goal was to disintegrate nuclei with binding energies that exceed that of nitrogen [4]. In 1930, the first particle accelerator was conceived by John D. Cockroft and E.T.S Walton at the laboratory [5]. Since it was yet impossible to accelerate particles such as α particles to energies beyond their radioactive equivalents, Cockroft and Walton decided to work with lighter particles, accelerating protons through a linear discharge tube with a potential of 200 kV. Lacking results with such "low energy" particles, they conceived a voltage multiplier, called the Cockroft-Walton generator (See fig. 2.1), allowing them to accelerate protons to 800 keV, which subsequently allowed them to force the decay of Lithium into two α particles, using protons at 500 keV.



Figure 2.1: *Cockroft Walton Generator*¹

In 1931, Van der Graaf and Wideröe followed suit. Especially Rolf Wideröe's design, the *Drift Tube LINAC (DTL)*, was a cornerstone for the development of today's particle accelerators. It accelerated particles through axially aligned drift tubes, separated by strong electromagnetic fields. By applying an AC current, he could tune the frequency of the field, such that the particles would be boosted upon every exit of a drift tube (see fig. 2.2). This design removed the need to store huge electric charges, which limited Cockroft and Van der Graaf's designs. While Wideröe's design was limited to around 50 keV of energy, it was his design that inspired Ernest Lawrence to develop the cyclotron, a device that is widely known as the forerunner of particle accelerators (see fig. 2.3). In effect, the cyclotron is equivalent to winding Wideröe's design around and around itself to create a magnetically confined beam orbit with an alternating electric field.

In recent years, the spectrum of different applications of particle accelerators has widened. Leading-edge accelerators are driven by particle physics requirements (beam energy, high luminosity and intensity), but the majority of operating accelerators serve other purposes such as chemical or material research and medical treatments. For a history on particle accelerators, see [6].

¹http://www.visualphotos.com/photo/1x6033020/cockroft-walton_generator_fermilab_a090057.jpg

²<http://www.fnal.gov/pub/science/experiments/energy/images/95-1039-small.jpg>

Today's state of the art accelerators reach energies that are approximately 10^5 times higher. The highest to date recorded acceleration energy was observed at the *Large Hadron Collider (LHC)* with a value of 4 TeV, giving 8 TeV in the *Center Of Mass (COM)* frame. It is designed to hold a stored energy of ≈ 360 MJ for each beam [7]. Such energies require the use of superconducting magnets to steer the beam, resulting in the need for strong collimation. Even under good stable operational conditions, particles will leave the optimal design path of the accelerator due to beam-gas interactions, intra-beam scattering, beam-beam interactions, RF noises, ground noises and resonances due to imperfections in the accelerator elements [8]. The main process of intra-beam interactions results in a slow diffusion of protons from the axial path and a subsequent growth of the emittance. These particles together form the halo, a set of off-axis particles whose betatron amplitudes increase gradually until they are caught by collimators or other limiting apertures.

The beta function is the envelope around all particle trajectories in the accelerator. The betatron amplitude is the transverse amplitude with respect to the nominal beam orbit of individual particles in the accelerator. The collision of particles with the limiting aperture causes hadronic and electromagnetic showers, which can negatively affect accelerator components and detectors with different severities.

Collimation refers to the spatial alignment and the reduction of the spatial cross-section of a beam halo. It is the removal of the beam halo, in order to protect components against excessive irradiation, prevent quenches in the superconductors, minimize background noise in the detectors and reduce the radiation on personnel and the environment [9, 10, p. 3, p. 297]. Collimators can act as diagnostic tool for accelerator admittances, beam vibrations and diffusion rates [11].

2.2 Beam Collimation Systems

Collimation of beam halo particles is achieved by limiting the physical aperture of the accelerator beam using solid blocks of absorbing material. Through scattering, a small fraction of halo particles can escape these blocks. We call such particles out-scattered particles. The cleaning inefficiency, the leakage of halo protons to sensitive equipment, of the collimation system is improved by using several collimation stages. Such a system consists of primary collimators, whose purpose is to intercept the primary beam halo through multiple Coulomb scattering. Secondary collimators are used to intercept the secondary halo particles which are out-scattered from the primary collimators at higher amplitudes [12]. The LHC uses a complex four stage collimation system. A list of the current *LHC* collimators is given in tab. 2.2.

2.2.1 Tevatron Collimation System

Tevatron had two Collider Runs. Inbetween the two runs, the collimation system of the Tevatron was upgraded [9]. During Collider Run I, the Tevatron used a single stage collimation system that consisted of 1 m long solid absorbers which allowed the *Fermi National Accelerator Lab (Fermilab)* to raise the Tevatron efficiency of the fast resonant extraction system by a factor 5 [13]. Using this system at Tevatron, one obtained a low cleaning efficiency close to 0.5 [13]. This system was insufficient and caused operational limitations, such that in Collider Run II, a two-stage automated collimation system was implemented [9]. At Tevatron collimation is a discrete process in which the beam halo is regularly removed. The new design required that the entire halo removal could be conducted in approximately 5 min. The system incorporated four primary collimators (targets) and eight new 1.5 m long secondary



Figure 2.2: Drift Tubes in the LINAC facility at Fermilab²



Figure 2.3: Ernest Lawrence with his cyclotron design³

³<http://newscenter.lbl.gov/wp-content/uploads/lawrence-cyclotron.jpg>

Interaction Regions	Purpose Purpose	Collimator Types
IR1	ATLAS experiment	TCT, TCL
IR2	ALICE experiment & Injection Beam 1	TCLI, TCT, TDI
IR3	Momentum cleaning	TCP, TCSG, TCLA
IR4	RF cavities	-
IR5	CMS experiment	TCT, TCL
IR6	Beam Dump	TCSG, TCDQA
IR7	Betatron Cleaning	TCP, TCSG, TCLA
IR8	LHC-b experiment & Injection Beam 2	TCLI, TCT, TDI

Table 2.1: The 8 interaction regions, their purpose and collimator types.

Functional type	Name	Plane	Num.	Material
Primary IR3	TCP	H	2	CFC
Secondary IR3	TCSG	H	8	CFC
Absorbers IR3	TCLA	H,V	8	W
Primary IR7	TCP	H,V,S	6	CFC
Secondary IR7	TCSG	H,V,S	22	CFC
Absorbers IR7	TCLA	H,V	10	W
Tertiary IR1/2/5/8	TCT	H,V	16	W/Cu
Physics debris absor.	TCL	H	4	Cu
Dump protection	TCSG	H	2	CFC
	TCDQ	H	2	C
Inj. prot. (lines)	TCDI	H,V	13	CFC
Inj. prot. (ring)	TDI	V	2	C
	TCLI	V	4	CFC
	TCDD	V	1	CFC

Table 2.2: Current LHC Collimators. For a complete list of Acronyms, visit the Acronym website of the LHC⁴.

collimators. The primary collimators are 5 mm tungsten plates, placed at 5σ . σ is the standard deviation of the Gaussian distribution of the accelerator beam. They create a *Root Mean Square (RMS)* transverse kick of $17\ \mu\text{rad}$ at 980 GeV [11]. The secondary collimators are 1.5 mm steel blocks placed at 6σ [9]. Additionally a new control system was implemented that would allow the fast processing of beam loss monitor data and a fast beam intensity feedback control, in which the full travel of the collimator took 15 sec [9]. Next to this major upgrade, the system was upgraded on a regular basis, including the installation of a tertiary collimator in 2003.

Measurements have shown that the cleaning inefficiency was 0.001. At the Tevatron collimation is primarily used for background reduction in physics, which was of the order of 6.7×10^{-3} , defined as the ratio of background noise with and without collimation [9, p. 7]. The estimated evolution of beam losses due to $\bar{p}p$ collisions, losses in the RF-bucket and beam-gas scattering are reviewed in [13, p. 14].

2.2.2 LHC Collimation System

Particle accelerators such as the *LHC*, with a nominal stored energy of 360 MJ require more collimation systems. At the *LHC*, the beam is continually cleaned. Even small losses in the *LHC* of the order of 4×10^7 protons, could cause quenches in the superconducting magnets through a deposition of energy in the order of $30\ \text{mJ cm}^{-3}$ [14].

The beam cleaning system at the LHC requires a cleaning efficiency of 99.998%. The *LHC* has two cleaning regions in *Interaction Region (IR)3* and *IR7* and several additional collimators in the other sections, with a total of 100 collimators, absorbers and similar devices [7]. There are 8 *IRs* in the LHC with different purposes. The *IRs* and their purposes are listed in table 2.1. The cleaning insertions have primary (TCP), secondary (TCS) and absorber (TCLA) collimators. Tertiary collimators (horizontal TCTH and vertical TCTV) are placed upstream of the experiments in *IR1*, *IR2*, *IR5*, and *IR8*. The machine is protected in *IR6* against beam dump failures through dump protection devices (TCS6 and TCDQ) [7].

2.3 Hollow Electron Beam Collimation (HEBC)

Considering projects such as the *High Luminosity LHC (HL-LHC)* at *European Organization for Nuclear Research (CERN)*, which aims at increasing the luminosity of the *LHC* by a factor 10, or the *Very Large Hadron Collider (VLHC)*, designed to operate at 20×20 TeV in Stage 1 and 88×88 TeV in Stage 2 [15], new innovative collimation techniques are required.

Some of the limitations of classical collimators is that they can not operate arbitrarily close to the beam orbit, due to impedance effects and instantaneous loss rates [11]. Additionally, beam loss rates

⁴<http://lhccwg.web.cern.ch/lhccwg/Bibliography/UsefulAcronyms.htm>

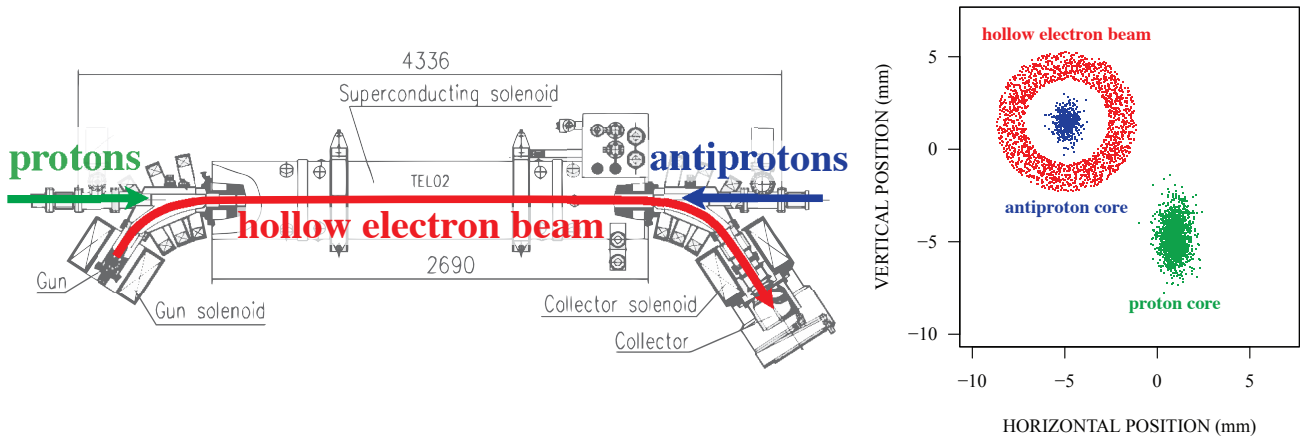


Figure 2.4: Technical Drawing of TEL2 Setup. Source: [8]

increase dramatically when moving collimator beam jaws inwards. Furthermore, classical collimators are affected by beam jitter, oscillations of the accelerator due to mechanical noise or ground motion [8]. Even with active stabilization, periodic bursts at the beam aperture are caused.

Electron lenses employ transverse fields of electron beams to interact with high energy bunches. An electron gun is used to produce an electron beam that is steered into the accelerator beam tube. It is aligned with the proton beam orbit, overlapping over a given length L_e , after which it is extracted from the accelerator beam tube into a collector. The electron beam is magnetically confined through solenoids. The electron gun and therefore the beam can be pulsed. All current electron lenses have the electron gun and the collector positioned outside the accelerator beam tube. A sketch of the *Tevatron Electron Lens 2 (TEL2)* is given in fig. 2.4.

An electron lens can produce different transverse profiles. For example, a Gaussian profile was used for non-linear beam-beam force compensation in the Tevatron and a flat-top profile was used for bunch by bunch tune correction. Further profiles are explained in [16]. An important advantage of the electron lens is that the electron beam current can be adjusted between individual bunches at the Tevatron, allowing single bunch manipulations. A normal figure of merit for electron lenses with Gaussian profiles is the shift of the accelerator beam tune due to the lens. A perfectly steered round electron beam, shifts the betatron tune by [17]

$$dQ_{x,y} = \pm \frac{\beta_{x,y} L_e r_p}{2\gamma e c} j_e \left(\frac{1 \mp \beta_e}{\beta_e} \right) \quad (2.1)$$

where $\beta_e = v/c$ is the electron beam velocity, γ the Lorentz factor and $r_p = e^2/mc^2 = 1.53 \times 10^{-16}$ is the classical proton radius. The plus sign represents focusing for protons and defocussing for anti-protons.

There are two electron lenses installed in the Tevatron, *Tevatron Electron Lens 1 (TEL1)* and *TEL2*. Both operate around 10 keV and at a couple of amperes. They can produce a tune shift of $dQ_{x,y}^{\max} \approx 0.008$ [16]. They were installed for research on beam-beam compensation [17, 16]. *TEL1* was installed in 2001. It has since been used in normal operation procedure for abort gap cleaning [18]. *TEL2* was installed in 2006 as a backup for *TEL1*. Beam-beam compensation was observed, but was not needed after the installation of electron cooling for antiprotons in the recycler ring. Due to the reliability of *TEL1*, *TEL2* was rarely needed for normal operations and thus used for further experiments on beam-beam compensation with different electron guns [19, 11]. Electron lenses for beam-beam compensation are currently being commissioned at the *Relativistic Heavy Ion Collider (RHIC)* at *Brookhaven National Laboratory (BNL)* [20].

With an appropriate gun design, *Hollow Electron Beams (HEBs)* can be produced. Such a beam can be used for enhancing collimation. The *HEB* is aligned coaxially with the proton beam, such that the proton beam core travels through the negligible electric field in the hollow space of the *HEB*. Halo particles of the proton beam at transverse amplitudes bigger than the inner radius R_i experience near-

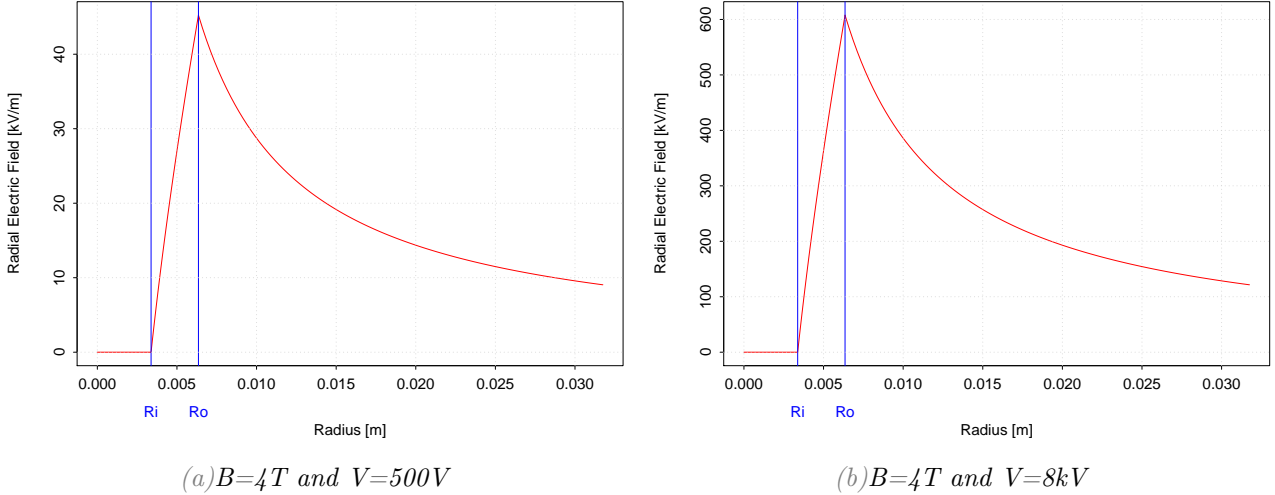


Figure 2.5: Radial electric field for profiles corresponding to $V=500V$ and $8kV$, $I=0.073A$ and $3.88A$, $R_i=3.4mm$ and $R_o=6.4mm$.

linear transverse radial kicks up to the outer radius R_o . Particles above R_o experience a non-linear decay of the transverse kicks with respect to amplitude due to the Biot-Savart decay of the transverse electric field of the *HEB* above its outer radius. A typical electric field profile is shown in fig. 2.5. Its derivation is discussed in chap. 6.

Assuming a cylindrical symmetry of the current density profile, transverse kicks are very controllable and given by [11]:

$$\Theta = \frac{1}{4\pi\epsilon_0} \frac{2I_r L(1 \pm \beta_e \beta_p)}{r\beta_e \beta_p c^2 (B\rho)_p} \quad (2.2)$$

where $\beta_e c$ is the electron velocity, $\beta_p c$ is the particle velocity, I_r is the enclosed electron current, L is the interaction length of the *Hollow Electron Beam Lens (HEBL)* and r is the distance from the axis of the beam. The $+$ applies when the magnetic and electric forces have the same direction. For typical Tevatron parameters, the transverse kick given to 980 GeV particles in Tevatron is $0.2 \mu\text{rad}$.

The magnetic fields in the gun, collector and main solenoid can be varied individually. This allows the operator to compress the *HEB* in the main solenoid. The compression follows the scaling law $\sqrt{B_{main}/B_{gun}}$ and the decompression law $\sqrt{B_{coll}/B_{main}}$. The magnetic field in each solenoid has an upper limit of 6 T, which is easily attainable by superconducting magnets. It has a lower limit of ≈ 0.1 T due to scalloping of the beam. Scalloping refers to transverse oscillations in the beam due to transverse electric fields. Scalloping is reduced by magnetically confining the particles stronger. When increasing the *HEB* size, it becomes necessary to compress the beams. This is shown in sec. 5.2.

The basic concept of the *HEBC* is that R_i is chosen to be smaller than the half gap of the primary collimators (TCP). It then causes the diffusion of particles into the limiting transverse aperture between R_i and the transverse aperture. A sketch is shown in fig. 2.6. The proton beam is represented through the blue curve with long tails representing the halo. The diffusion coefficient is represented by the green curve. *HEBC* allows the cleaning of the long tails of the transverse proton beam distribution. This makes the system less dependent on loss spikes such as those caused by beam jitter [8]. It is important to note that *HEBC* requires that the current collimation system is kept in place.

Various effects can reduce the effectiveness of *HEBC*. Important requirements are: a sufficient beam current to produce significant transverse kicks, a negligible electric field in the center to reduce emittance growth and a symmetric beam distribution. Beam current should be above 1 A, as was seen from experiments at the Tevatron [11]. The electric field is strongly affected by radial symmetry of the *HEB*. Furthermore bends in the electron lenses can adversely affect the electron beam distribution and the proton core as it pierces through the *HEB* wall in the bend (see fig. 2.4.) The effectiveness of *HEBC* depends furthermore on the time structures of the pulsed electron beam. Valentina Previtali recently

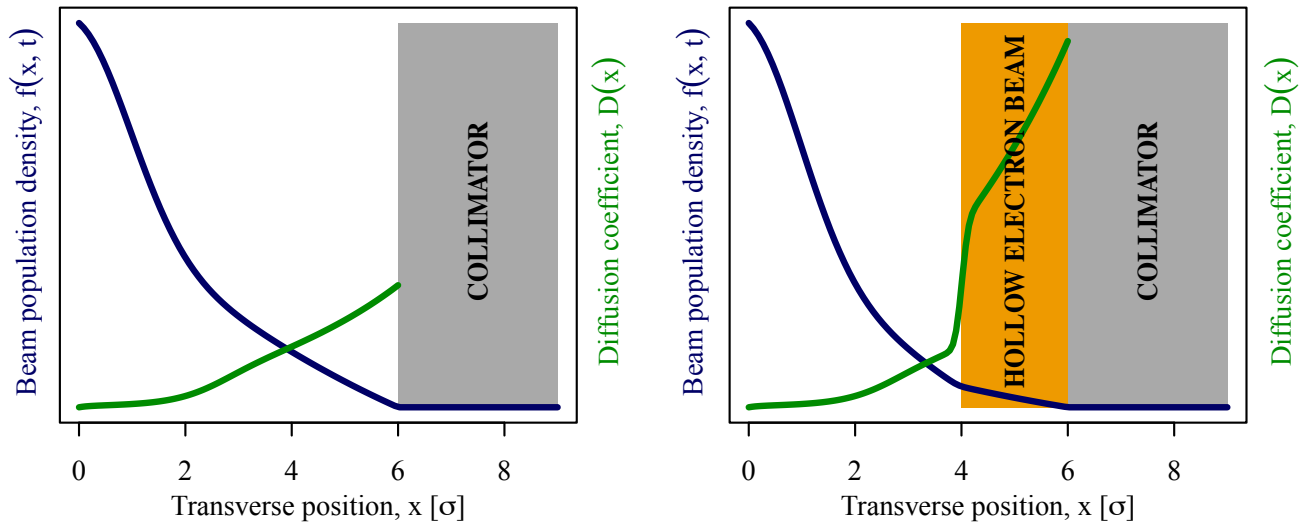


Figure 2.6: Schematic representation of the effect of the HEBE on the diffusion model of collimation. Source: [8].

completed a study of 3 different time structures; DC current, AC current and a "diffusive" current. These are possible, because the cathode has a rise-time short enough to allow turn by turn modulation in the *LHC*. Her studies show that the AC beam mode is the most efficient with a scraping of 75% of halo particles in less than 20 s. For more details refer to [21].

2.3.1 Tevatron experience for HEBE at LHC

Tevatron experiments from October 2010 to September 2011 gave an experimental foundation for the *HEBE* concept in the context of beam studies for the LHC collimation purposes. They were done using a *0.6 inch Hollow Electron Gun (HG06)* in the *TEL2*. The experiments showed that *HEBLs* are compatible with collider operations and that the alignment of the electron and proton beam is reliable and reproducible. It could be shown that the effects on the beam core were negligible, while a smooth halo removal was observed. Furthermore the loss-rate fluctuations due to beam jitter were reduced. Overall a transverse diffusion of the beam halo was observed. These achievements of the *TEL2* at the Tevatron are explained in more detail in [11, 22, 8]. After 10 years of stable Tevatron electron lens operation in the Tevatron (*TEL1* and *TEL2*), it is clear that the technology is reliable and thus ready for operation in the LHC. The *HEBLs* which were used for *HEBE* and its characterization are discussed in sec. 3.1. Furthermore a conceptual design of a *HEBL* where the *Hollow Electron Gun (HEG)* and the collector are coaxially aligned with the accelerator beam is discussed. *HEGs* are an important part of the *HEBLs* and are discussed in sec. 3.2.

Chapter 3

Tevatron Electron Lenses and Guns

The *Tevatron Electron Lens 2 (TEL2)*, installed in 2006, was used as a backup for *Tevatron Electron Lens 1 (TEL1)* for abort gap cleaning and for studies on beam-beam compensation and *Hollow Electron Beam Collimation (HEBC)*. The *HEBC* studies at the Tevatron were done using a *0.6 inch Hollow Electron Gun (HG06)*. Since 2012 a new *1 inch Hollow Electron Gun (HG1b)* has been used in the *Tevatron Electron Lens Test Stand (TELTS)*, which is used for yield and transverse profile measurements. It was designed specifically for the *Large Hadron Collider (LHC)*. This chapter discusses the electron lenses and electron guns that have been used for the development of *HEBC* at *Fermi National Accelerator Lab (Fermilab)* in the context of collimation studies for the LHC. It furthermore outlines design parameters for the *HEBC* studies at Tevatron and proposes design parameters for the use of the *HG1b* at the LHC at CERN.

3.1 Tevatron Electron Lenses

3.1.1 Tevatron Electron Lens 2 Design Considerations

The *Tevatron Electron Lens 2 (TEL2)* is one of two electron lenses installed in the Tevatron. It was used for beam-beam force compensation and for experimentation with *HEBC*. A sketch of the *TEL2* is shown in fig. 2.4. Unlike the LHC, the Tevatron circulates a proton and an antiproton beam in opposite directions in the same vacuum pipe. An electron gun, situated left next to the accelerator beam tube, produces an electron beam that is sent on an arc through 3 short solenoids into the accelerator beam tube. After traveling a distance of 2 m, during which the electron beam interacts with the (anti-)proton beam, the electrons are again extracted from the accelerator beam tube using 3 more solenoids [16]. The lens operates with a few amperes and at an energy up to 10 keV [16]. The gun, the interaction region and the collector have 3 separate solenoids, used for the magnetic confinement of the electron beam. Their magnetic field strengths are designated B_{gun} , B_{main} and B_{coll} respectively. Inside the main solenoid, 6 superconducting dipole correctors are found. They are used to align the beam with the (anti-)proton beam. This requires five degrees of freedom, three for the axial position of the electron beam upstream of the main solenoid and two for its angle.

Since the shutdown of the Tevatron at Fermilab, the *TEL2*'s hardware has become available for use. Its efficiency as a scraper was proven through extended tests at the Tevatron collider, driving the halo of a 980 GeV anti-proton beam onto the collimators[23]. The *TEL2* (using the *HG06*) was used for *HEBC* at currents up to 1.2 A. *TEL2* parameters used in the Tevatron are given in tab. 3.1.

$I_{max} \pm (\Delta I/I)_{max}$	1.2 A \pm 2%
V_{max}	5 kV
R_1/R_2	4.5 mm/7.5 mm = 0.6
R_{1min}	0.58 mm
Δt_{min}	250 ns

Table 3.1: Design parameters of *TEL2* in Tevatron with *HG06*: maximum electron beam current I_{max} and current jitter $(\Delta I/I)_{max}$, maximum extraction voltage V_{max} , ratio between inner and outer cathode radius R_1/R_2 , minimum achievable inner radius for the electron beam R_{1min} and cathode modulator rising time Δt_{min} [21]

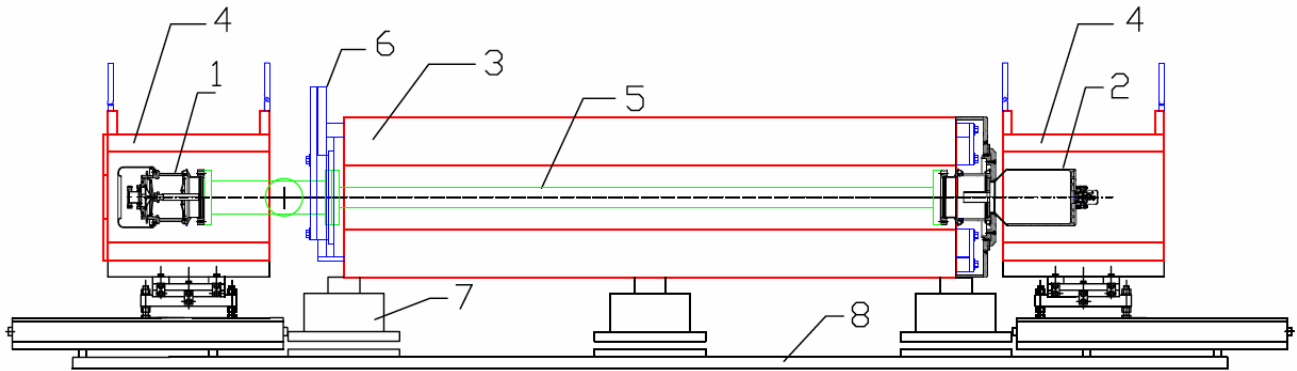


Figure 3.1: Sketch of TELTS. [24]



Figure 3.2: Photo of TELTS. Source: Valentina Previtali

Significant scraping could be observed at this current [11]. Similar currents are thus desired for new design considerations. For further information on the scraping studies refer to [23, 8, 11].

3.1.2 Tevatron Electron Lens Test Stand Design Considerations

While *HEBC* tests with a proton beam in an accelerator are crucial, they are not intended for the characterization of the electron beam parameters. For the study of the transverse profile, the *Tevatron Electron Lens Test Stand (TELTS)* is used. A sketch is shown in fig. 3.1 and a panoramic photo in fig. 3.2. The *TELTS* is a linear test bench, where the pulsed electron gun (1) sends an electron beam downstream through a straight beam tube (5) with pickup electrodes to a water cooled collector (2). The whole beam tube is in a vacuum and is surrounded by 3 solenoids. The gun is placed in a gun solenoid (4) which is followed by a short drift space and the main solenoid (3). The collector (2) at the end of the drift tube is placed in the collector solenoid (4). Magnetic correctors (6) are used to control the beam inside the beam tube. The device is supported on a test bench (8) [24].

The distance between the gun cathode and the collector downstream is 2.86 m. Thereof 35 cm are in the gun solenoid, 23 cm in the first drift space, 192 cm in the main solenoid, 15 cm in the second drift space and the remaining 21 cm in the collector solenoid. The magnetic fields in the 3 solenoids can be set independently. The gun and collector solenoid are 50 cm long. The inner diameter of the two short solenoids is 28 cm and the main solenoid is 20 cm [24].

For detailed information on the power supply, the water cooling system and the vacuum system, please refer to the Electron Lens Test Stand Wiki page¹. The *TELTS* was used for all measurements in chap. 5 and implemented in the simulations in chap. 7.

3.1.3 Straight Hollow Electron Beam Lens Design

The straight hollow electron beam lens design eliminates the bends required to steer the electron beam into the accelerator beam tube in the usual electron lenses. It is thus no longer necessary for the proton

¹https://cdcv.s.fnal.gov/redmine/projects/elens/wiki/Test_Stand

beam to pass through the hollow electron beam edge when entering the *Hollow Electron Beam Lens (HEBL)*. A sketch of such a device is shown in fig. 3.3. No such device has been built to date. In the straight hollow electron lens design, the electron gun itself is hollow, not just the cathode, and is coaxially aligned with the hadron beam of the accelerator. The electron beam is coaxial to the proton beam, focusing shortly before the main solenoid and expanding again just after. It is extracted by being radially deflected at the electron collector.

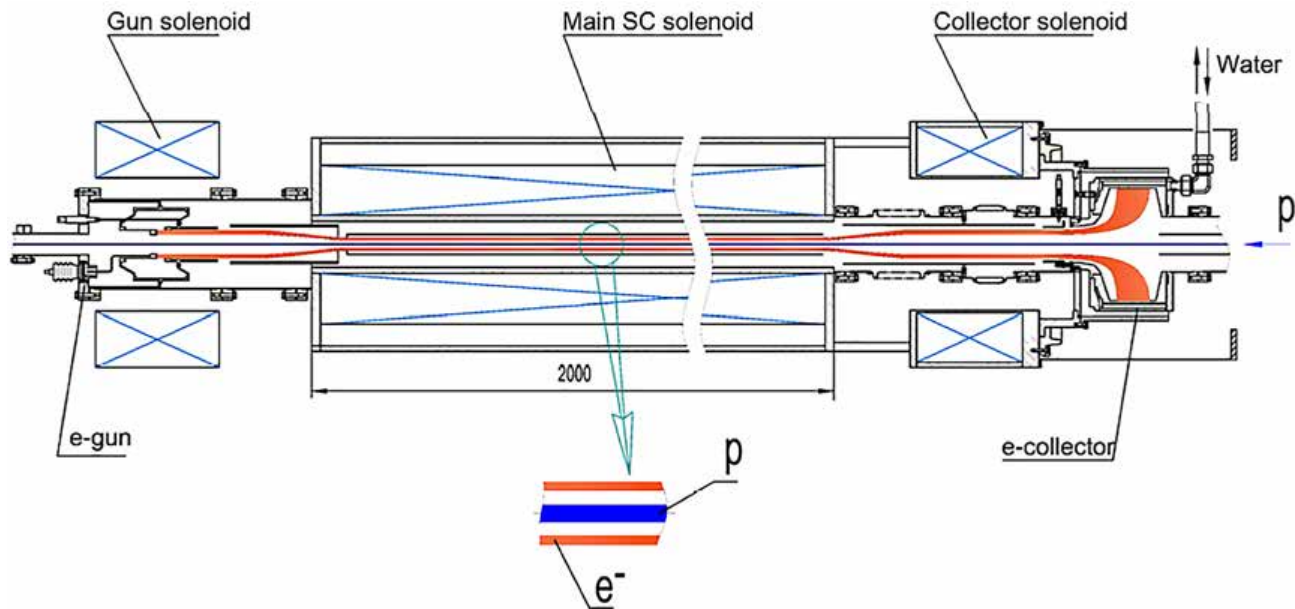


Figure 3.3: Sketch of straight HEBL setup. Source: Gennady Kuznetsov (Fermilab)

3.2 Design of the Electron Guns

An electron gun emits free electrons with a specific energy spectrum. The most common application is the cathode ray tube used in old television sets. Among many different electron sources, the simplest is the planar diode, consisting of two oppositely charged electrodes. The cathode emits the electrons, which are accelerated to the anode via a potential difference. The anode contains a hole or a mesh type structure to allow the electrons to pass and continue downstream of the electron gun [25, p. 7].

The most vital part of the *HEBL* is the electron gun. Two guns were produced for the *TEL2* and *TELTS*. First a *HG06*, which was used in the *TEL2* setup. Second a *HG1b* was acquired for testing in the *TELTS* and subsequent installation in the *LHC*.

Both cathodes are made out of an 80% density porous tungsten matrix, impregnated with $3\text{BaO}-1\text{CaO}-1\text{Al}_2\text{O}_3$. At a cathode temperature of about 2500 K ($k_B T \approx 0.2$ eV), the work function of pure tungsten is 4.5 eV and it produces a current density of about 0.5 A cm^{-2} [25, p. 9]. The work function is the minimum energy required to remove an electron from a solid to a point immediately outside the solid surface in vacuum. Using tungsten cathodes which are impregnated with barium or strontium oxides, considerably higher current densities of 10 to 20 A cm^{-2} can be achieved. Such cathodes are typically operated at 1400 K ($k_B T \approx 0.12$ eV) and have a work function of 1.6 eV [25, p. 9]. Pure barium cathodes are not used due to their low melting point of 725°C .

3.2.1 0.6 Inch Hollow Electron Gun

HG06 was manufactured by Hi-Tech Manufacturing, LLC (Shiller Park, IL, U.S.A). The model number is 101507. The cathode is commercially available from Heat Wave Labs, Inc. (Watsonville, CA, U.S.A) [26]. It has an outer diameter of 15.24 mm (0.6 in) and a radius of curvature of 10 mm [26]. A 9 mm hole was drilled into the center of the cathode [26]. The gun is equipped with two control electrodes,

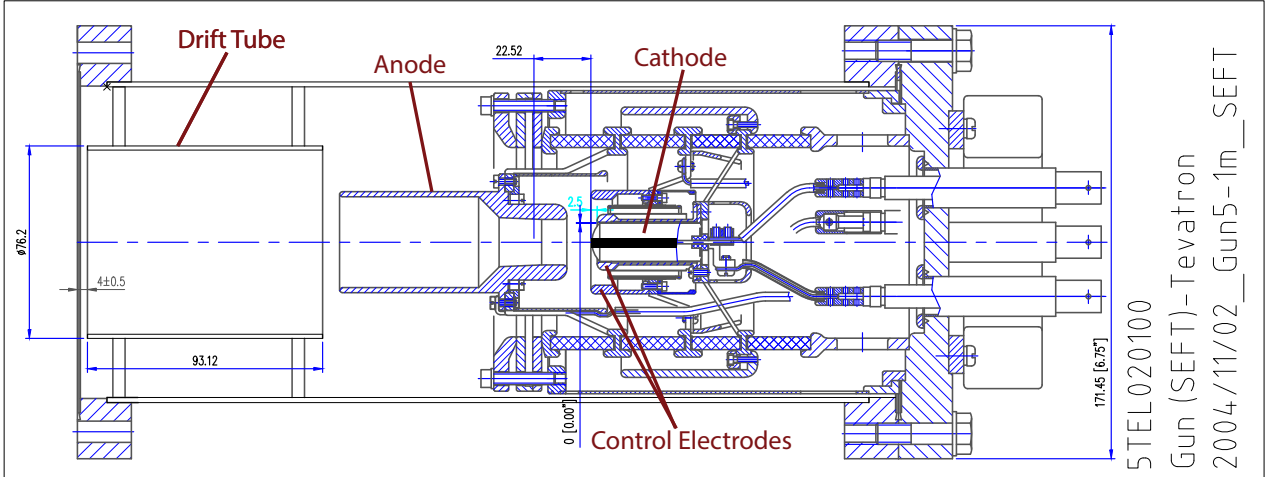


Figure 3.4: Technical Drawing of HG06. Source: Gennady Kuznetsov (Fermilab)

situated 0.28 mm and 9.38 mm from the cathode. The anode is 9.84 mm downstream of the cathode and has an aperture of 9 mm at the front. Downstream of the anode is a drift pipe with an aperture of 36.5 mm and a length of 93.1 mm. Fig. 3.4 gives a technical drawing of the gun.

This gun was used for the Tevatron scraping experiments [23]. Through magnetic compression it could be scaled to a minimal inner radius of the electron beam of 0.58 mm. The gun has a perveance of $3.20(7) \times 10^{-6}$ perv (see fig. 3.5) and an optimal operating temperature above 1100°C as seen in fig. 3.6. The unit perv is equivalent to the SI units $\text{A V}^{-\frac{3}{2}}$. Perveance is defined as the scaling factor between the beam current, I , and the cathode potential to the power of 1.5, $V_a^{1.5}$. The calculated current density distribution is negligible between $0 < r < 4.5$ mm, rising sharply at the inner edge, and falling gradually back to 0 at the outer edge [26].

3.2.2 1 Inch Hollow Electron Gun

Given a maximum current of the *HG06* in the Tevatron of 1.2 A, a new gun was designed specifically for LHC parameters. The diameter of the cathode was increased to 1 inch in order to allow higher currents. *HG1b*, custom designed by *Fermilab* and built by Heat Wave Labs Inc., is made out of the same material as *HG06*. It has an outer diameter of 25.4 mm (1 inch), an inner diameter of 13.5 mm and a radius of curvature of 10.0 mm between the outer and inner radius. The gun is equipped with two control electrodes, situated 0.4 mm and 7.8 mm from the cathode. The anode is 9.8 mm downstream of the cathode and has an aperture of 14.3 mm upstream. Downstream of the anode is a drift pipe with an aperture of 36.5 mm and a length of 93.0 mm. Fig. 3.7 gives a technical drawing of the gun.

The new gun can use higher magnetic fields up to 6 T in the beam solenoid, to improve transport of the electrons through the lens, by reducing space charge expansion and taking advantage of the $\mathbf{E} \times \mathbf{B}$ drift on the electrons. One should note that design plans place the inner radius of the *Hollow Electron Beam (HEB)* at $\approx 4 \sigma$ of the *LHC* proton beam. The proton beam σ was estimated in sec. 6.3 to be ≈ 0.5 mm at the possible installation site of *Interaction Region (IR) 4*. Positioning the beam at 4σ requires a magnetic compression of the electron beam inner radius from 6.75 mm to 2.0 mm by

I_{max}	≥ 3.88 A
V_{sug}	3-4 kV
R_1/R_2	$6.75 \text{ mm}/12.7 \text{ mm} = 0.53$
f_{comp}	3.4
B_{sug}	0.43-5-0.43 T

Table 3.2: Design parameters for the e-lens installed in the Tevatron: maximum electron beam current I_{max} , suggested voltage V_{sug} , ratio between inner and outer cathode radius R_1/R_2 , compression required to place inner beam radius at 4σ f_{comp} and a suggested magnetic field at the LHC.

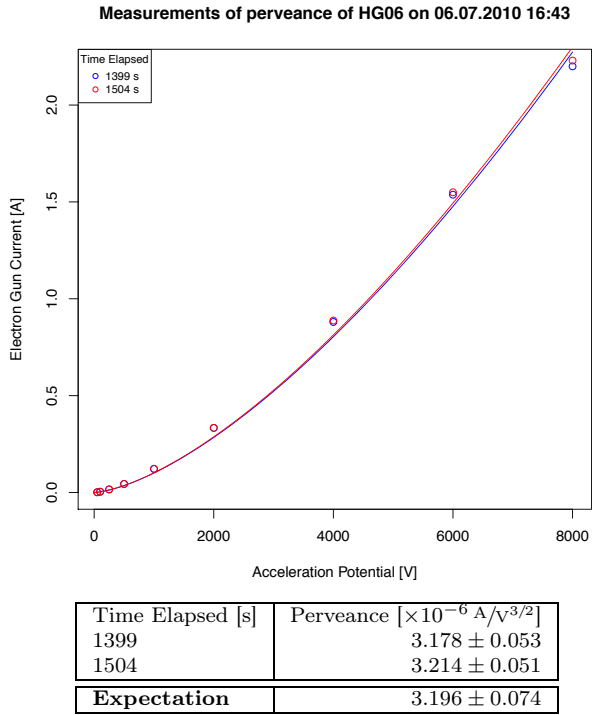


Figure 3.5: Perveance of HG06 on 06.07.2010. The perveance is $(3.20 \pm 0.07) \times 10^{-6}$. Time elapsed is measured since heating of the cathode.

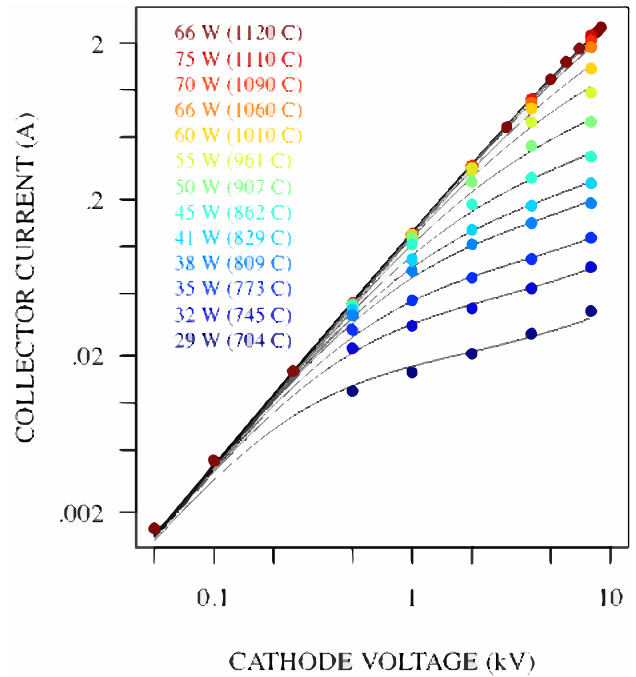


Figure 3.6: Performance of the HG06 gun with respect to cathode voltage and filament power. Source: [26]

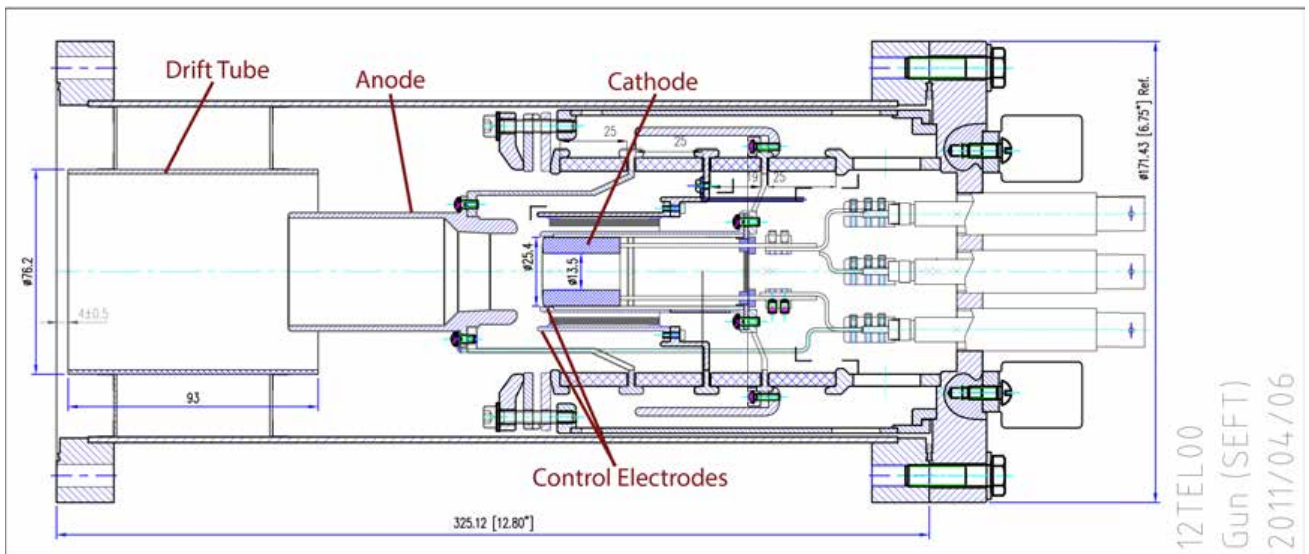


Figure 3.7: Technical Drawing of HG1b. The center of the drawing shows the cathode with the two electrodes around it and the anode and the drift pipe to its left. Source: Alexander Didenko (Fermilab contractor)

a factor of 3.4 in the main solenoid. Given that the magnetic compression scales as $\sqrt{B_{main}/B_{gun}}$ a ratio between the magnetic field in the gun solenoid and main solenoid of ≈ 11.5 is recommended. Given an upper limit of the magnetic field in the LHC of 6 T, a possible magnetic configuration of the electron lens at the LHC is 0.43-5-0.43 T. A high main solenoid magnetic field of 5 T is chosen for its magnetic rigidity. Given this compression, the outer beam radius would be at ≈ 3.7 mm or 7.4σ . Since primary collimators are placed at 6σ [7], a large portion of the beam is shielded by the primary collimators. It might thus be possible to retract primary collimators up to 7.4σ , reducing the impedance on the proton beam. In order to obtain a similar scraping effect as was seen at the Tevatron, a cathode voltage of 3-4 kV is recommended, which provides a beam current of 1-1.5 A as can be seen in appendix tab. B.1. Furthermore, tab. 3.2 provides a list of suggested design parameters for the usage of the *HG1b* at the LHC.

This gun is the focus of this thesis and was used for all subsequent measurements. *HG06* was mentioned for comparison purposes and due to its significance in the Tevatron scraping experiments.

Chapter 4

Thermionic Emission

This chapter introduces the concept of thermionic emission in *Temperature Limited Emission Region (TLER)* and *Space Charge Limited Emission Region (SCLER)*. Thermionic emission governs the emission of particles from the cathode in the *1 inch Hollow Electron Gun (HG1b)* and thus is directly responsible for the production of the *Hollow Electron Beam (HEB)*. There are three main emission regimes, *TLER* where the beam current strongly depends on the cathode temperature, *SCLER* where the beam current is independent of the cathode temperature and depends on the cathode potential through Child-Langmuir law and Field Emission Regime. The latter does not apply to our guns, since it only arises at very high electric fields of $\approx 10^{10} \text{ V m}^{-1}$. Another important parameter for cathode emission is secondary emission, which is induced through the passing of a primary incident particle with sufficient energy through a material. For linear beam tubes only thermionic emission is considered [27, p.39].

4.1 Temperature Limited Emission

With increasing temperature the probability of electrons escaping the cathode surface increases. **Thermionic emission** refers to the process of emitting electrons from a surface by heating that surface. The minimum energy required for an electron to escape an emitter is the sum of the Fermi energy and the work function, $E_0 + e\phi$ [27, p. 42]. The Fermi energy is the energy difference between the highest and lowest occupied single-particle states in a quantum system of non-interacting fermions at absolute zero temperature. The work function is the energy difference between the top of the conduction band in the cathode and the vacuum level adjacent to the cathode [27]. The minimum energy required to escape an emitter is schematically shown in fig. 4.1.

Electrons obey the Fermi-Dirac distribution, meaning that each energy state may only be occupied by

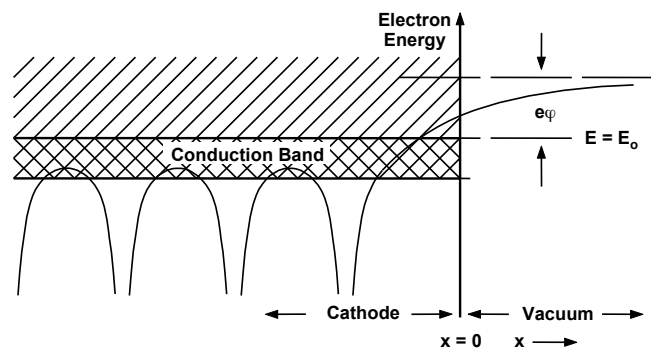


Figure 4.1: Scheme of the energy levels in a cathode. At higher energy, the disjunct energy bands merge to form the conduction band just below the Fermi Energy E_0 . Particles require at least $E_0 + e\phi$ to escape the cathode. [27, p. 42]

one single electron. Electrons emitted from the thermionic cathode are part of the Maxwellian tail of the Fermi-Dirac distribution [25, p. 8]. Their current density is described by the **Richardson-Dushman equation**:

$$J_{therm} = A_0 T^2 e^{-\frac{\varphi}{k_b T}} \quad (4.1)$$

where T is the cathode temperature, φ is the cathode work function and k_b is the Boltzmann constant. $A_0 = \frac{4\pi e m_e k_b^2}{h^3} = 1.2 \times 10^6 \text{ A m}^{-2} \text{ K}^{-2}$ is a characteristic constant, where e is the elementary charge, m_e is the mass of the electron and h is Planck's constant. The regime in which the emission has the above temperature dependence is called **Temperature Limited Emission Regime (TLER)**. The beam current density is exponentially dependent on the temperature of the cathode.

Given eq. 4.1, when designing a cathode, one tries to minimize the work function in order to obtain a higher yield and possibly be able to operate at lower temperatures. The work function of our cathode and its operating temperature were discussed in sec. 3.2.

4.2 Schottky-Effect

Richardson-Dushman provides a simple relationship between the temperature, work function and current density, but it does not consider electric fields at the surface of the cathode. A potential difference between the anode and cathode causes charges to diffuse inside the cathode in order to return the electric field inside the conductor to equilibrium. This has the effect of lowering the effective work function by:

$$\Delta\varphi = \left(\frac{eE_a}{4\pi\epsilon_0} \right). \quad (4.2)$$

E_a is the applied electric field, e is the electron charge and ϵ_0 is the electric permittivity of free space. We refer to the effective work function, since the work function is usually an intrinsic quality of the surface and material. This effect is called the Schottky Effect [27, p. 46]

Incorporating the Schottky Effect into the Richardson-Dushman equation provides the improved emission equation:

$$J = A_0 T^2 e^{-\frac{\varphi}{k_b T} \left[\varphi - \left(\frac{eE_a}{4\pi\epsilon_0} \right)^{1/2} \right]} = J_0 e^{\frac{e}{k_b T} \left(\frac{eE_a}{4\pi\epsilon_0} \right)^{1/2}} \quad (4.3)$$

Here J_0 is the Richardson-Dushman current density. It is used to compare the performance of different cathodes [27, p. 47].

4.3 Space Charge Limited Emission

Given an emitting cathode, a substantial electron cloud can build-up near the cathode. The potential outside the cathode is thus reduced by the negative charge presence of the electrons. This effect is shown in fig. 4.2. The amount of space charge at the cathode is increased when increasing the temperature in the *TLER* and decreased when increasing the cathode potential in the *SCLER*.

The electron emission rate is limited by the point where the space charge is sufficiently large to depress the potential at the cathode below zero, as is the case for (b) in fig. 4.2b. Consequently emitted electrons need to overcome a potential well, allowing only energetic electrons to be emitted from the cathode. Low energy electrons are returned to the cathode by the space charge. This causes the *SCLER* to be lower than the saturated emission rate, which is found exactly when the potential, and therefore the electric field, at the cathode is 0. The saturated emission rate is equal to the Richardson-Dushman emission rate J_0 , mentioned in sec. 4.2. If the potential difference between the diode increases, more electrons are emitted and in turn the potential at the cathode is decreased. If the potential difference decreases, less electrons are emitted, reducing the space charge effect and thus increasing the potential at the cathode. This effect is called the **Space Charge Limited Emission Region (SCLER)**. During

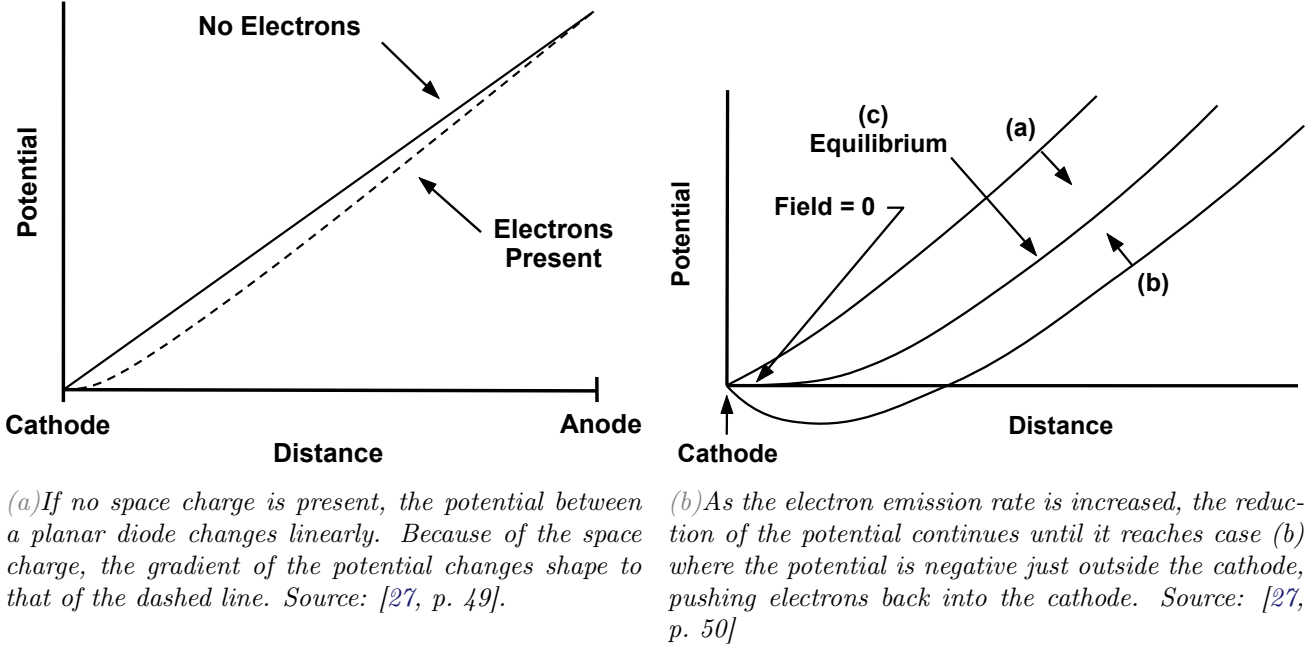


Figure 4.2: Schemes showing the effect of space charge build-up on the potential outside a cathode.

this emission regime, cathode temperature and surface effects no longer play a role in the emission rate [27, p. 50]. This emission regime can be reached by increasing the cathode temperature in the *TLER*, thus increasing the space charge build-up at the cathode. This transition is depicted in figure 4.3b. The space charge limited current density is given by [25, p. 10]:

$$J = 1.67 \times 10^{-3} \left(\frac{q}{mc^2} \right)^{1/2} \frac{V_a^{3/2}}{d^2} \quad [A/m^2] \quad (4.4)$$

where V_a is the potential difference between anode and cathode, d is the spacing between the cathode and the anode, q and m are the particle charge and mass and c is the speed of light. All constants are given in MKS units [27, p. 51]. From eq. 4.4 the beam current of a cylindrical hollow thermionic dispenser cathode can be determined [25, p. 10].

$$I_{beam} = 1.67 \times 10^{-3} \pi \left(\frac{q}{mc^2} \right)^{1/2} \frac{V_a^{3/2}}{d^2} (r_{ext}^2 - r_{int}^2) \quad [A] \quad (4.5)$$

where r_{ext} is the outer radius and r_{int} the inner radius of the cathode. This law is called the **Child-Langmuir law**, from which a quantity, dependent on the electron gun geometry, called the **perveance** is defined as the ratio (distance d is difficult to determine for complex diodes):

$$P = \frac{I}{V_a^{3/2}} = 1.67 \times 10^{-3} \pi \left(\frac{q}{mc^2} \right)^{1/2} \frac{r_{ext}^2 - r_{int}^2}{d^2} \quad \left[\frac{A}{V^{3/2}} \right] \quad (4.6)$$

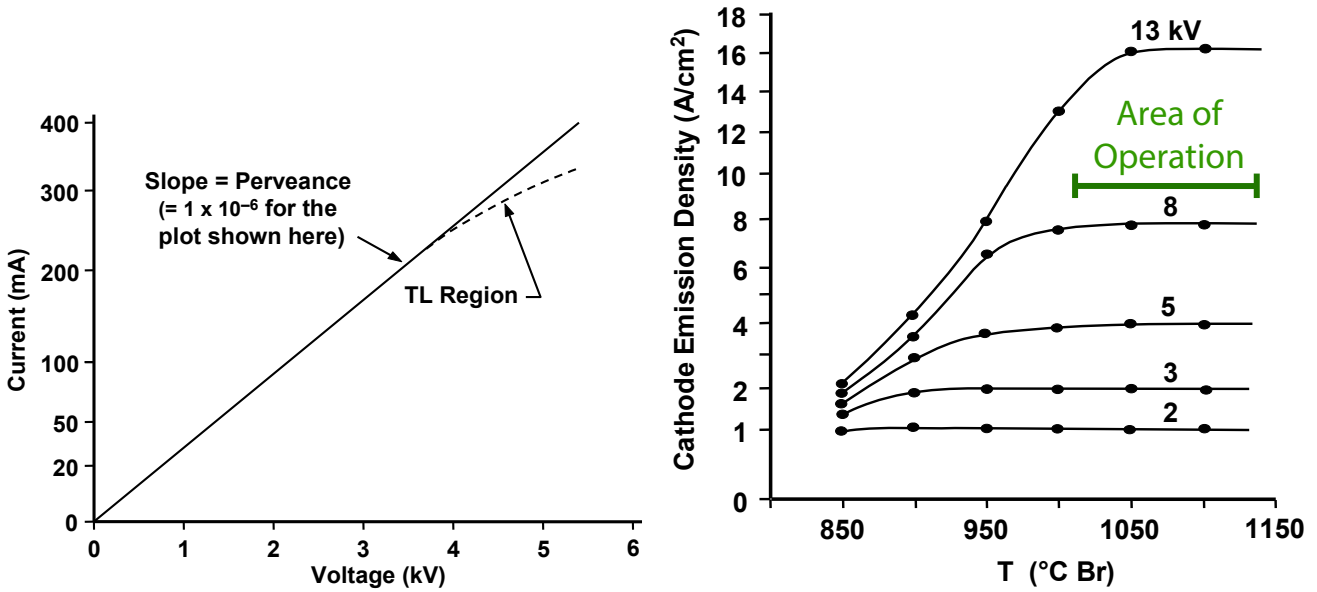
For the purpose of this thesis the unit perv is defined in SI units as $A V^{-3/2}$.

If V_a exceeds a certain level, the space charge condition can not be upheld and the beam enters the temperature limited region, diverging from the Child-Langmuir law. This is depicted in fig. 4.3a.

Considering residual gases in the drift tubes and relativistic effects, the concept of a generalized perveance is introduced [25, p. 196].

$$K = \frac{I}{I_0} \frac{2}{(\beta\gamma)^3} (1 - \gamma^2 f_e) \quad (4.7)$$

where $I_0 = \frac{4\pi\epsilon_0 mc^3}{q} = 17kA$ is the characteristic current, I is the beam current, f_e is the neutralization factor and β and γ are the relativistic factors. Unlike the perveance, the generalized perveance is a



(a) In general the current density is given by the child langmuir law (see eq. 4.6). At high potential differences, the space charge condition is broken and the beam enters the Temperature Limited (TL) region again. Source: [27, p. 53]

(b) With increasing temperature, the emission becomes temperature independent. The higher the cathode potential, the higher the temperature at which this transition occurs. Source: [27, p. 53]

Figure 4.3: Transition from TLER to SCLER

dimensionless quantity. Given that $\beta = \frac{v}{c}$ and $v = \left(\frac{2qV}{m}\right)^{\frac{1}{2}}$, we can relate to P by

$$K = P \times \left[\frac{(1 - \gamma^2 f_e)}{4\pi\epsilon_0\gamma^3(2q/m)^{1/2}} \right] \tag{4.8}$$

Considering a non-relativistic situation equation 4.8 can be simplified to:

$$\frac{K}{(1 - f_e)} = P \times \left[\frac{m^{1/2}}{4\pi\epsilon_0(2q)^{1/2}} \right] = P \times 1.515 \times 10^4 \tag{4.9}$$

Given a neutralization free beam, the correlation is $K = 1.515 \times 10^4 P$ [25].

4.4 Field Emission

For the sake of completion, we also introduce field emission. At electric fields much higher than that of the *SCLER*, $\approx 10^9 - 10^{10} \text{ V m}^{-1}$, electron emission increases rapidly, due to a low work function. Quantum mechanics thus dictates that even particles with insufficient kinetic energy to overcome the barrier by classical theory, have a non-zero probability of passing through the barrier due to the tunneling effect. Such an electron emission is called field emission. This process is schematically shown in fig. 4.4. This type of emission does not play a role in our *Hollow Electron Beam Lenses (HEBLs)*, since we deal with a potential difference of $10^3 - 10^4$ over 1 cm and thus electric fields of $\approx 10^5 - 10^6 \text{ V m}^{-1}$.

4.5 Summary of Thermionic Emission

In summary, at very low temperatures, the cathode operates in the *TLER*. When the temperature is high enough, a substantial space charge builds up and the emission regime transitions into *SCLER*. This is depicted in figure 4.3. The optimal point of operation is given by the green bar and is only considered for voltages up to 8 kV. Figure 4.5 gives a summary of the various emission regions and the respective potential fields needed to achieve them. The emission from the thermionic cathode first enters the *SCLER*, rising with voltage, until the cathode potential is strong enough in order to transport away the space charge. At this point it enters the *TLER*. Ultimately when the voltage is high enough, field emission takes place, since particles have a non-vanishing probability of tunneling through the work function. The optimal area of operation is again indicated by the green bar.

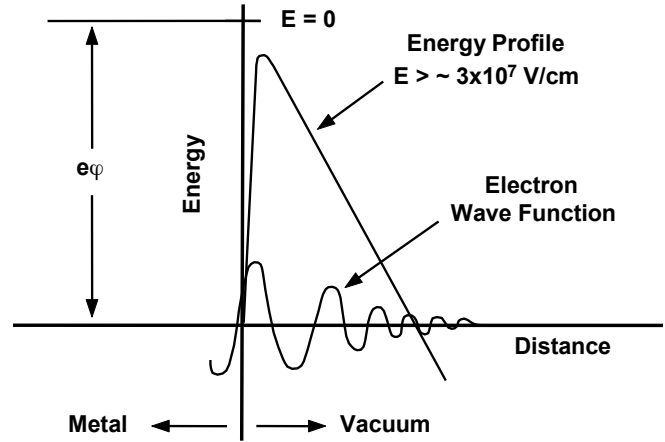


Figure 4.4: An electron with a wave function whose amplitude is lower than the potential barrier at the surface of the cathode, can tunnel through the barrier given a very strong electric field [27, p. 48].

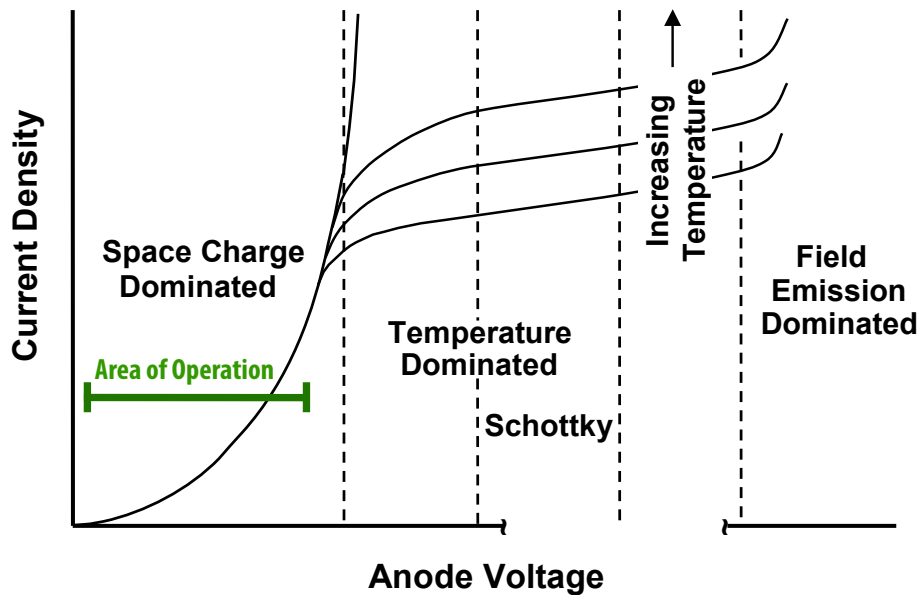


Figure 4.5: Summary of the various thermionic emission regions with increasing anode voltage. The optimal area of operation is indicated by the green bar. Source: [27, p. 55]

Chapter 5

1 Inch Hollow Electron Gun Characterization

Having discussed the necessary theory, explained the terms *Hollow Electron Beam Collimation (HEBC)* and *Hollow Electron Beam Lens (HEBL)* and described the relevant electron lenses and guns, the measurements at the *Tevatron Electron Lens Test Stand (TELTS)* are presented. First transport measurements are discussed, these measurements describe the amount of beam that is transmitted through the main solenoid and arrives at the collectors. Then the yield measurements are discussed, a discussion of the amount of current produced by the gun. Lastly the method of transverse current distribution profile measurement is discussed and the evolution of the profiles through the beam tube with respect to the magnetic field and the cathode potential is presented.

Transport and yield measurements are done using a Tektronix TDS3034B oscilloscope¹. The cathode and collector current are read using 3 induction coils, 2 dedicated to the collector current which shows a systematic error of $\approx 1\%$. Since all induction coils are the same, this systematic error can be transferred to the cathode current readout. Additionally a statistical error on the oscillator readout of a fraction of a percent is observed $\approx 0.5\%$. Profile measurements are made through the average current in a pinhole in the collector. The transverse profile of the beam is scanned by moving the beam over the pinhole using 6 horizontal and vertical magnetic correctors in the beam tube. Profile measurements are explained in detail in sec. 5.4. The transverse fields are calculated using a simulation code called WARP. This is discussed in detail in chap. 6.

5.1 Operational Procedure of the TELTS

All measurements throughout this thesis were made in the *TELTS*. Turning on the test stand can take 1-2 days, due to the long time it takes to heat the cathode and re-establish the vacuum. Before any parameters are changed on the *TELTS*, the vacuum in the beam tube is measured. The vacuum must remain below 10^{-7} mbar. Next the cathode is heated through a filament. The filament current is gradually increased with long pauses inbetween, so that the vacuum can recuperate. It is desirable to leave the cathode at a lower temperature than the operational temperature of $400\text{ }^\circ\text{C}$ in order to evaporate all liquid constituents from the surface. The filament current is then increased to an operational temperature of 9.25 A. Later on we will explain why this should be lowered to 8.5 A. This process can take several days. It is important to keep an eye on the vacuum through the *Fermilab Accelerator Control System (ACNET)*.

For future reference, we also mention the cathode temperature dependence on the filament current used to heat it. The scale of temperature to filament resistance is given in [28] as a linear local approximation:

$$T = \beta R + T_0 \tag{5.1}$$

¹<http://www.tequipment.net/TektronixTDS3034B.asp>

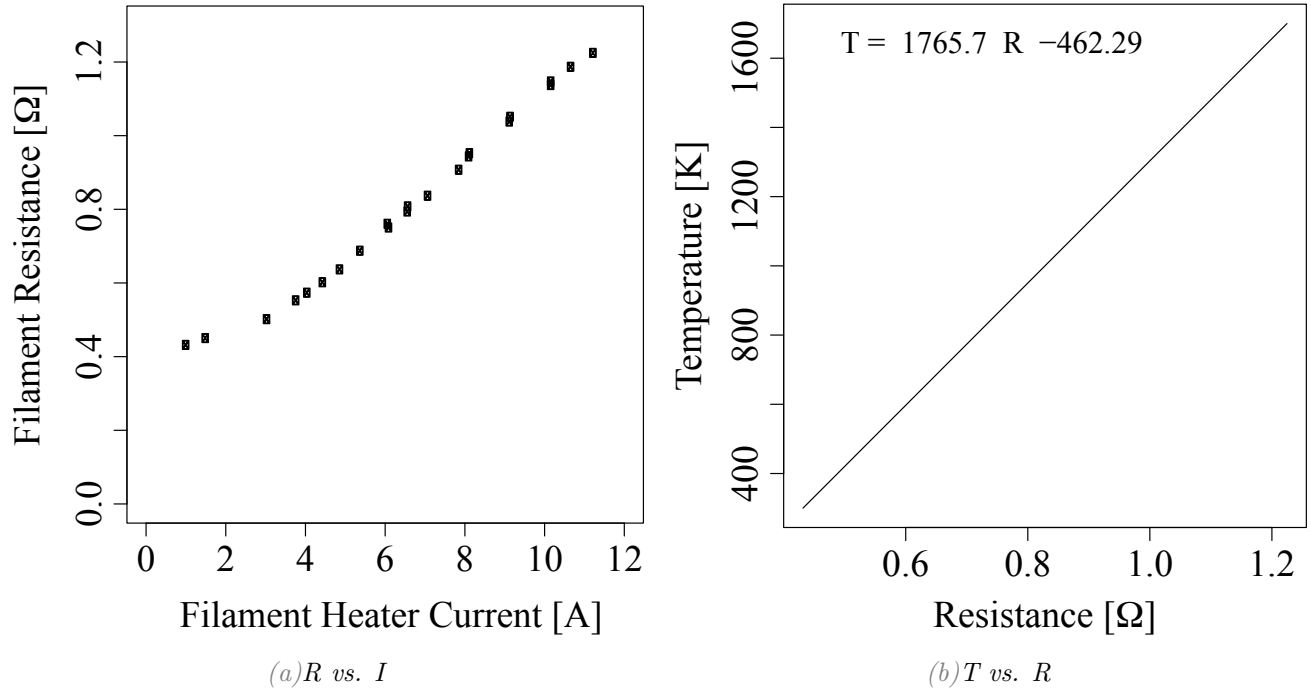


Figure 5.1: Cathode temperature in terms of filament resistance and filament current. [28]

where $\beta=1765.7 \text{ K } \Omega^{-1}$ and $T_0=-462.29 \text{ }^\circ\text{C}$ and R is the filament resistance. The relation of filament resistance vs. filament current is given in figure 5.1a and the relation of cathode temperature to filament resistance in 5.1b.

Next the Tektronix TDS3034B oscilloscope is turned on. The gun, main and collector solenoids are set to the necessary magnetic fields. The main solenoid uses 2 power supplies that are linked to each other. It is thus sufficient to set the current on one of the power supplies to half that which is used to drive the main solenoid. The other power supply is set automatically. Having set the magnetic fields, the cathode voltage is set and a DEI PVX-4110 10-kV modulator is turned on in order to pulse the electron beam. The pulse width and repetition rate are set. The pulse width is usually $8 \mu\text{s}$ and the repetition rate is set such that an appreciable signal is obtained.

During measurements, the pulse from the modulator is measured using 2 induction toroids at the collector, 1 induction toroid at the cathode and the pinhole in the collector of the *TELTS*. The data is recorded through a *Programmable Logic Controller (PLC)* interface for profile measurements. Beam current measurements are done using the oscilloscope.

5.2 Transport Measurements

Transport refers to the migration of particles or energy within a host medium, considering effects such as absorption, emission and scattering. Here the medium is a combination of beam plasma, neutralized particles and a confining magnetic field. We define transmission T as the ratio of beam current at the collector to the cathode:

$$T = \frac{I_{\text{collector}}}{I_{\text{cathode}}} \quad (5.2)$$

This measure should ideally be 100%. The new *1 inch Hollow Electron Gun (HG1b)* is the largest gun that was ever used in the test stand. After a month shut-down of the e-gun in April, profiles taken on 02.05.2013 showed significant asymmetries (see fig. 5.2). Bad conditioning of the cathode surface was suspected. Following 11 additional days of conditioning at 9.25 A and 10.0 A, the profiles only improved slightly.

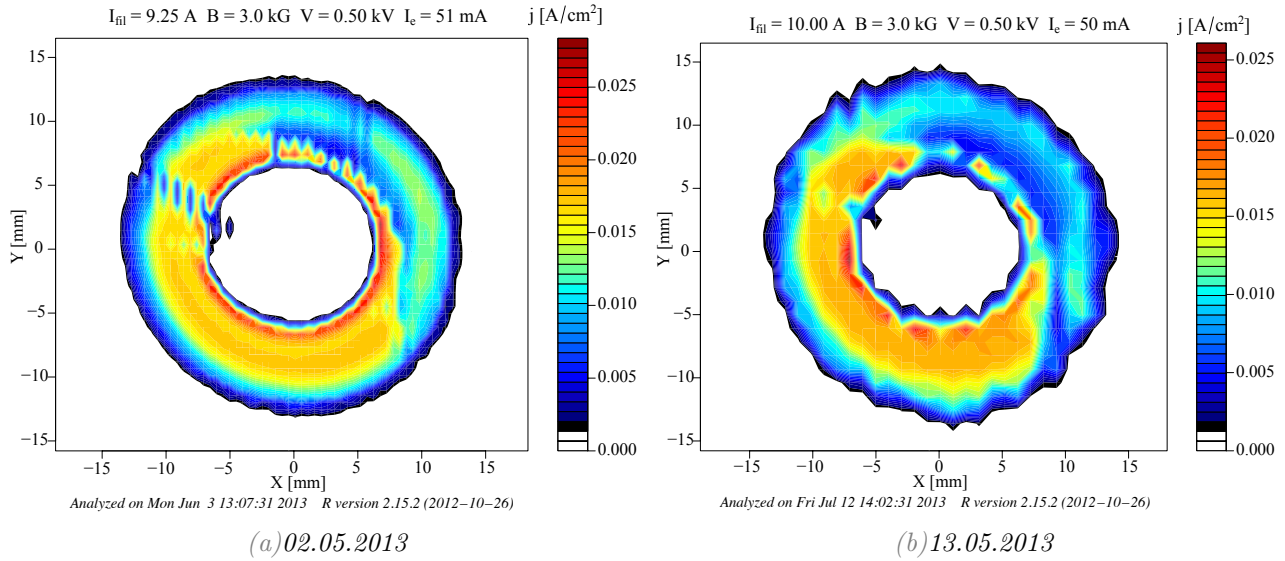


Figure 5.2: The figures show the normalized current density in Acm^{-2} of the measured profiles in the transverse plane. Current densities below $6.25 \times 10^{-4} \text{ Acm}^{-2}$ are negligible and ignored. Profile (a) shows the electron beam distribution on 02.05.2013. It is strongly asymmetric. After 11 more days of conditioning, the asymmetries have not improved as seen in (b). The production of these plots is explained in detail in section 5.4

During the follow-up a discrepancy between collector and cathode current was noted. The cathode and collector current were 68.6 mA and 50.6 mA respectively, giving a transmission of 73.8%. The cathode potential was 500 V and the magnetic field was 0.3 T for this measurement. Causes for the low transmission can either be particle-particle interactions, such as neutralization, or scraping at the beam pipe. To lower the effect of scraping, the beam can be compressed in the main solenoid, and to reduce neutralization, a better vacuum could be provided.

Trying several combinations of B_{gun} , B_{main} , B_{coll} , it was found that transport is best with $B_{gun} = B_{collector} = 0.25B_{main}$. This provides a transport of $\approx 100\%$. Table 5.1 shows the improved solenoid settings that were used. Using the older *0.6 inch Hollow Electron Gun (HG06)*, such transmission issues were not observed and the gun could be used under equal magnetic fields ($B_{gun} = B_{main} = B_{coll}$). Because the improvement in transmission for the *HG1b* was achieved by compressing the beam, the most likely cause of the losses of current using equal magnetic fields is beam scraping.

	B_{gun} [kG]	B_{main} [kG]	$B_{collector}$ [kG]
Pre	1	1	1
	1.5	1.5	1.5
	2	2	2
	2.5	2.5	2.5
Post	3	3	3
	0.4	1.6	0.4
	0.6	2.4	0.6
	0.8	3.2	0.8
	1.0	4.0	1.0

Table 5.1: Pre and post transmission improvement solenoidal magnetic field settings

5.3 Yield Measurements

Yield measurements are made by increasing the potential difference between the cathode and anode in regular steps and using the Tektronix oscilloscope to measure the yield at the collector. The oscilloscope averages results taken during a few seconds, reducing the statistical error significantly to a fraction of a percent. The systematic error is given by about 1%.

The yield at the collector is defined by the acceleration potential V_a , the perveance P and the transmission in the beam tube T as:

$$Y = P * V_a^{3/2} * T \quad (5.3)$$

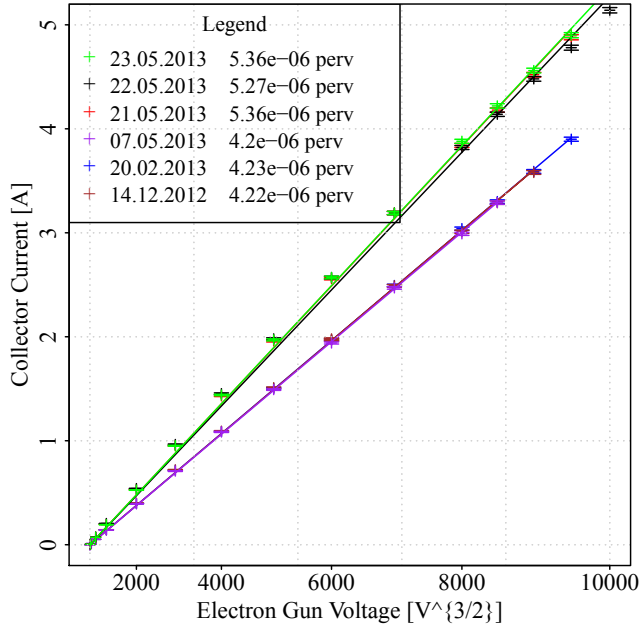


Figure 5.3: Effect of transport improvement on the yield of the test-bench. The yield follows the Child-Langmuir law and measurements are thus taken in SCLER. The statistical error is estimated at 0.5%. Systematic errors are not considered, because they affect each measuring point equally.

Measurement Date	Perveance [$\times 10^{-6} \text{ A}/\text{V}^{3/2}$]
23.05.2013 15:02	5.36 ± 0.03
22.05.2013	5.27 ± 0.04
21.05.2013	5.35 ± 0.03
Expectation	5.33 ± 0.14
07.05.2013	4.20 ± 0.01
20.02.2013	4.23 ± 0.01
14.12.2012	4.22 ± 0.01
Expectation	4.22 ± 0.03

Table 5.2: Measured global perveances and their expectation values. The new measurements are $\approx 26\%$ higher than the old perveance measurements, prior to May 2013. Error estimates are given through the statistical uncertainty and calculated by the fit.

We define the global perveance to be the fit between all data points of the peak collector current and the cathode potential according to the model in eq. 4.6; $I \propto V^{3/2}$. The peak collector current is the highest current obtained from the pulsed beam shape. The pulse shape is shown in [28, p. 13]. This is an overall average which is independent of the cathode potential. In addition to the global perveance we define a quantity called the local perveance which describes the fraction of $I_{peak}/V^{3/2}$ for each measurement point.

5.3.1 Global Perveance

Fig. 5.3 compares the global perveance of measurements made after the transport improvements², $5.33 \pm 0.14 \mu\text{perv}$, and those made before the improvement, $4.22 \pm 0.03 \mu\text{perv}$. Measurements prior to the transport improvement confirm measurements done earlier by Siqi Li [28]. Li obtained a perveance of $4.13 \pm 0.01 \mu\text{perv}$ in February 2012 and $4.15 \pm 0.02 \mu\text{perv}$ during the measurements of June 2012. The gun is relatively stable over long time periods (see fig. 5.3). All global perveance measurements after the asymmetric profiles, experienced beginning of May 2013, seem to show a slight deviation from the Child-Langmuir law. The significance of the transmission improvement is apparent through a yield increase of $\approx 26\%$.

5.3.2 Global Perveance from SAM Simulations

SAM is a code developed at Budker Institute of Nuclear Physics for simulations of stationary axial-symmetric electron optical systems and electron guns. The code distributes a surface charge across electrodes and dielectrics, which are simulated using line and arc segments. A curved mesh is used to describe the space charge density which is constant within one cell. Further information on this code can be found in [29].

²Measurements continued by: G. Stancari, A. Valishev and M. Chung during the days after my departure from Fermilab.

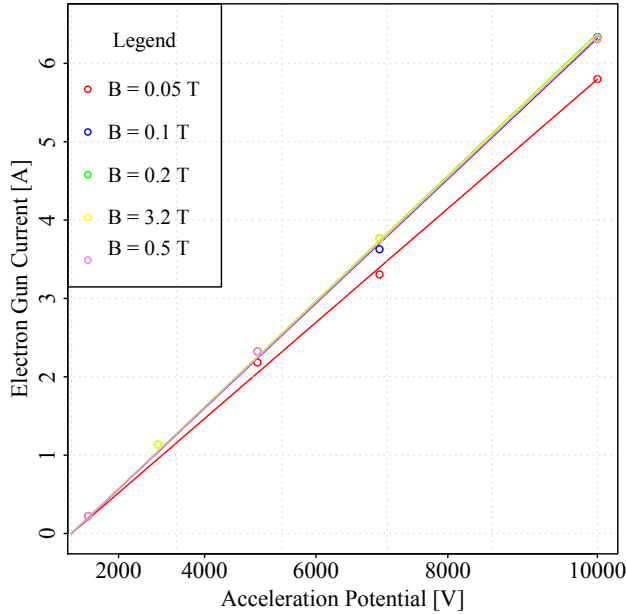


Figure 5.4: Perveance plots for the SAM simulations at 5 different solenoidal field strengths. [30]

Magnetic Field [T]	Perveance [$\times 10^{-6} \text{ A/V}^{3/2}$]
0.05	5.796 ± 0.079
0.1	6.322 ± 0.057
0.2	6.381 ± 0.051
0.32	6.371 ± 0.051
0.5	6.337 ± 0.060
Expectation	6.321 ± 0.110

Table 5.3: SAM simulated perveance and expectation value of $6.3(1) \times 10^{-6} \text{ AV}^{-\frac{3}{2}}$.

In January 2012, using SAM, Leonid Vorobiev at *Fermi National Accelerator Lab (Fermilab)* simulated the electron gun current for a given acceleration potential at a magnetic field of 0.05, 0.1, 0.2, 0.32 and 0.5 T in the gun solenoid. From this, we calculated the global perveance of the electron gun, depicted in fig. 5.4 and table 5.3. Our measurements were within 15% of the SAM simulations and satisfactory.

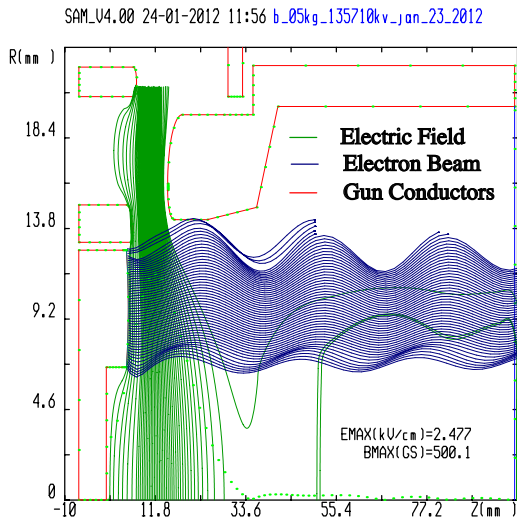
The expectation value of $6.3(1) \times 10^{-6}$ perv includes all magnetic fields except that of 0.05 T, which is insufficient to force the electrons to go on a straight path. The transverse electric fields between the cathode and anode cause the particles to undergo strong transverse oscillations, called scalloping [27, p. 138]. This results in the partial scraping of the electron beam and reduces the yield. The scalloping can be observed in fig. 5.5, where (a) is the electron beam at a solenoidal field of 0.05 T and (b) is at 0.32 T. In the stronger field, the magnetic confining force is too strong to allow scalloping.

5.3.3 Local Perveance

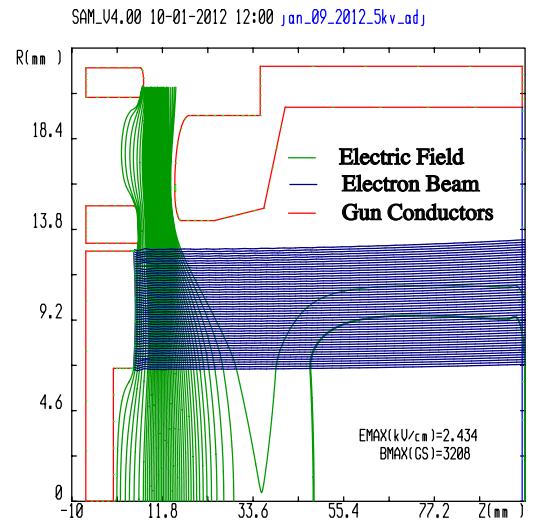
Following the improvement of the transport mentioned in sec. 5.2, yield measurements were taken on 14.05.2013. Fig. 5.6a shows the electron gun peak current as a function of the cathode potential. Fitting a line to all data points (red and blue) provides us with a global perveance of $5.12 \pm 0.03 \mu\text{perv}$. Without a discrepancy from the Child-Langmuir law, this graph should portray a straight line. This is the case up to 4000 V. At higher voltages a gradual deviation from the Child-Langmuir law can be observed. A fit of the data up to 4000 V provides us with a perveance of $5.70 \pm 0.02 \mu\text{perv}$, $\approx 90\%$ of the SAM simulations perveance. The discrepancy between the Child-Langmuir law and the measurement is portrayed through a local perveance plot with respect to the cathode potential in fig. 5.6b.

The yield is measured at the end of the beam tube. Therefore it can be negatively affected by neutralization of the beam by residual gases in the beam tube, scraping of the beam at the beam tube edge and a departure from the *SCLER* to the *Temperature Limited Emission Region (TLER)*.

When the potential is high enough, space charge effects occur further downstream, decreasing the space charge close to the gun. Consequently the *SCLER* cannot be sustained. Under these conditions, the emission returns to the *TLER*. This effect is shown in fig. 4.5 and 4.3a. Sec. 5.3.4 tells us that the voltage at which the *SCLER* transitions into the *TLER*, rises with increasing filament current. Seeing that this break down has not occurred for a filament current of 8.25 A in fig. 5.8c, the drop in yield

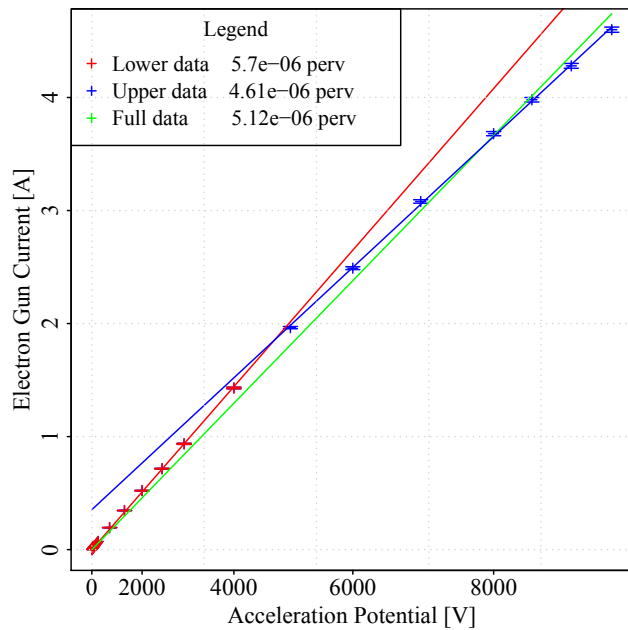


(a) SAM simulation of HG1b gun: $B=0.05$ T, $V=5$ kV

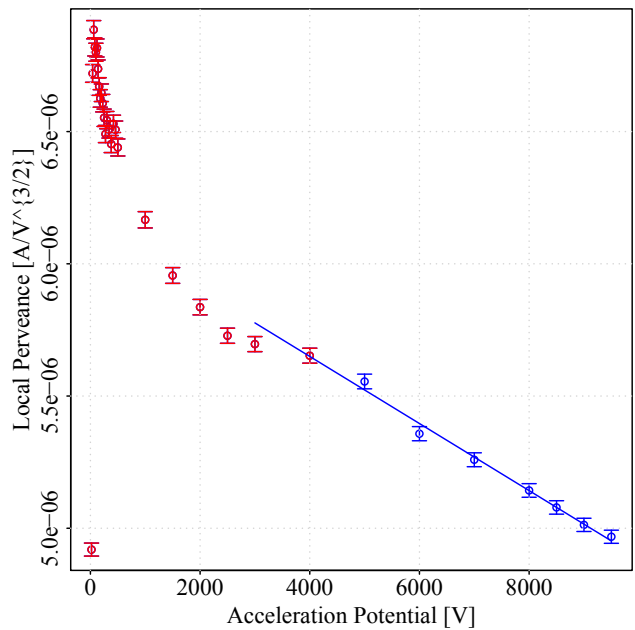


(b) SAM simulation of HG1b gun: $B=0.32$ T, $V=5$ kV

Figure 5.5: SAM simulations of HG1b from January 2012 [30]. The blue lines represent the electron trajectories while the green lines represent the electric field at the cathode.



(a) Collector Yield vs. V



(b) Local Perveance vs. V

Data Set	Global Perveance
Lower data	$(5.70 \pm 0.02) \times 10^{-6}$
Upper data	$(4.61 \pm 0.04) \times 10^{-6}$
Full set	$(5.12 \pm 0.03) \times 10^{-6}$

Data Set	Best fit for data set
Upper Data	$P = -1.27(4) \times 10^{-10} \times V + 6.16(3) \times 10^{-6}$

Figure 5.6: Global (a) and local (b) perveance measurements of the HG1b. A discrepancy was seen in fig. (a) where the perveance departed from the Child Langmuir law at 4 kV. This is most likely due to beam scraping as explained in the text. Fig. (b) shows that the change of local perveance with voltage due to this discrepancy is linear.

seen in fig. 5.6a is probably not due to the transition into the *TLER*.

Neutralization refers to the absorption of electrons by background gases. There are many reasons for background gases [27, p. 173]. In the *TELTS*, the predominant background gas is Hydrogen at 1×10^{-8} mbar. Fig. 5.7 shows the number of ions of various gases formed per $cm \times mbar$ for electron-gas interactions. As can be seen, the cross section drops to values under unity when the electron energy exceeds 10^3 eV. Assuming a pressure of 1×10^{-8} mbar, at 5000 V only 5×10^{-8} ions are formed per cm. We can thus safely assume that neutralization only plays a role for low energy electrons, below 4000 V. This was also confirmed in Siqui's paper [28].

The sudden change of slope between 4 kV and 5 kV in fig. 5.6a is thus likely explained by the scraping of the beam at the beam tube with a radius of 3 cm. The effect thereof seems to be a linear change of perveance with voltage after 4 kV with a slope of $-1.27(4) \times 10^{-10}$ perv V^{-1} , as seen in fig. 5.6b. The linear change could be explained by the beam reaching a transverse beam size at $V_a=4$ kV such that the beam starts scraping on the beam tube edge. As the acceleration potential V_a is increased, more current is produced and the scraping increases, further lowering the perveance.

Assuming that the decrease in yield is mostly due to scraping, the fit for the whole data set (green) in fig. 5.6a is the best assumption for the yield at the collector. This gives a perveance of $(5.12 \pm 0.03) \mu$ perv. The fit for the set of lower data best describes the perveance of the gun itself, which excludes losses downstream of the gun.

5.3.4 Dependence of Perveance on Filament Current

This section discusses the filament current dependence of the perveance. A scaling law between filament current and temperature of the cathode is given in eq. 5.1.

Additional measurements were made at a magnet setting of 1-4-1 kG ($B_{gun} - B_{main} - B_{coll}$) for linearly changing filament currents from 6.25 A to 9.75 A in steps of 0.5 A. Using this data, we expect to be able to validate our current measuring point of 9.25 A and possibly deduce a lower filament operating current, without a significant loss in yield due to the temperature-limited regime. The cathode yield was acquired at a repetition rate of 4 Hz. Fig. 5.8 shows the measurement results.

Fig. 5.8a shows the transition from *SCLER* to *TLER* and the voltage at which this transition occurs. In the *TLER*, the emission current is independent from the cathode potential, when the emission has entered the *TLER* completely. The transition does not take place below 10 kV for a filament current between 8.25 A and 9.75 A. Interestingly, the emission current seems to drop again at higher cathode potentials as one surpasses 8.75 A of filament current. This effect is analyzed more closely in fig. 5.9a.

Fig. 5.8b shows the electron gun current as a function of the filament current. Considering measurements on the full potential voltage scope (0.1-10 kV), the maximum "knee current" is at 8.25 A. The "knee current" is given by the filament current at which the transition into the *SCLER* takes place. If we consider a safety filament current increment of 0.5 A, an operating filament current of at least 8.75 A is recommended. If one wishes to only measure profiles with a cathode potential of up to 7 kV, this recommended filament operating current can be lowered to 8.25 A and for up to 4 kV to 7.75 A. The filament current increment is used, because the yield tends to fall with time as described in [27, p. 73]. By taking a safety filament current increment, we guarantee that the current density produced by the cathode does not fall and measured profiles are consistent.

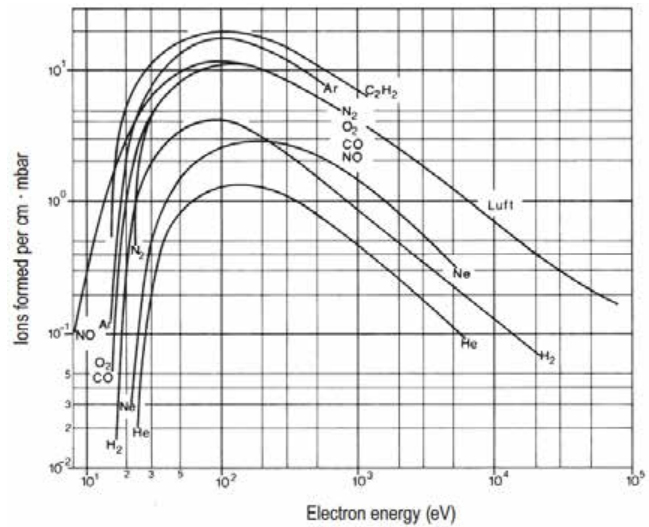
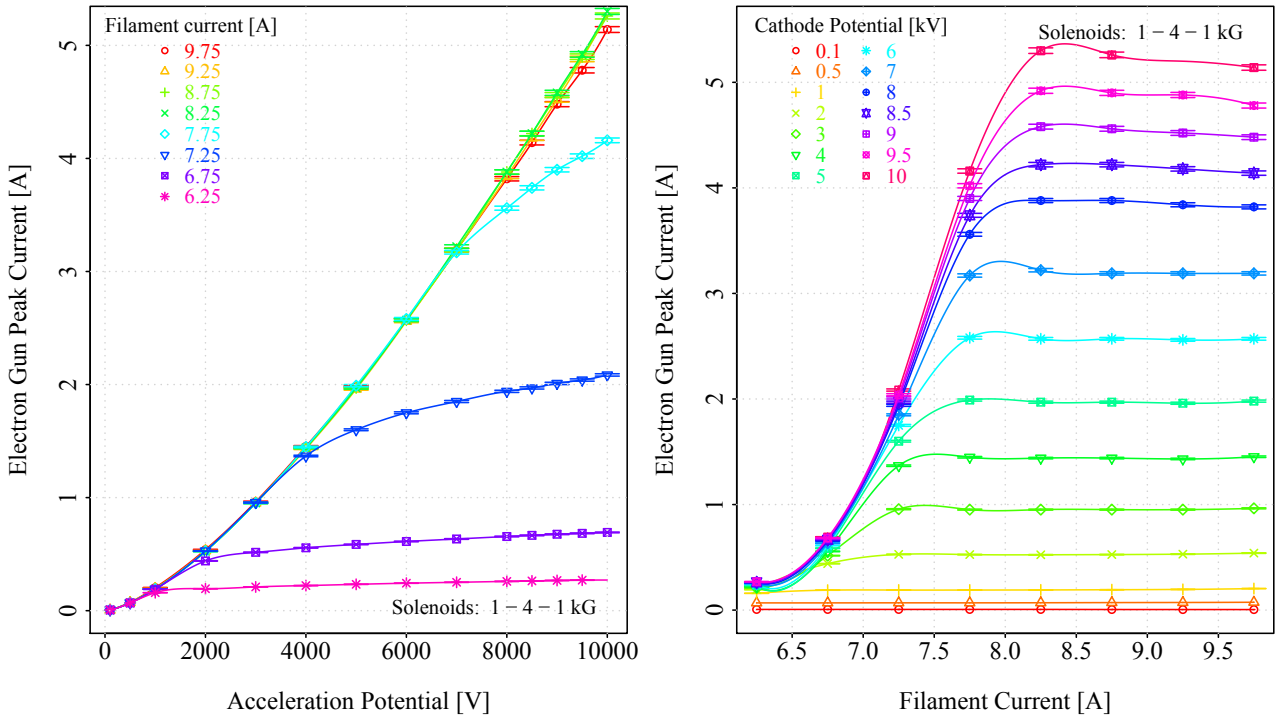
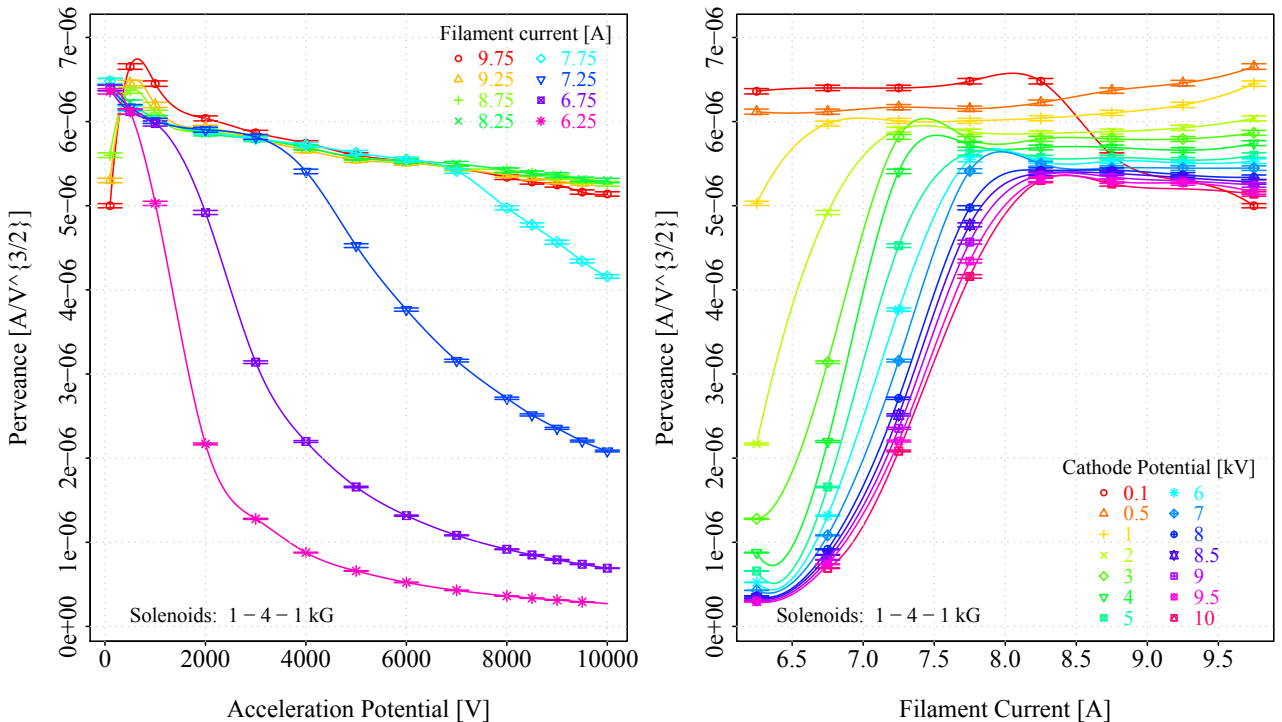


Figure 5.7: Number of ions formed per cm per mbar for various gases. Source: [31, p. 104]

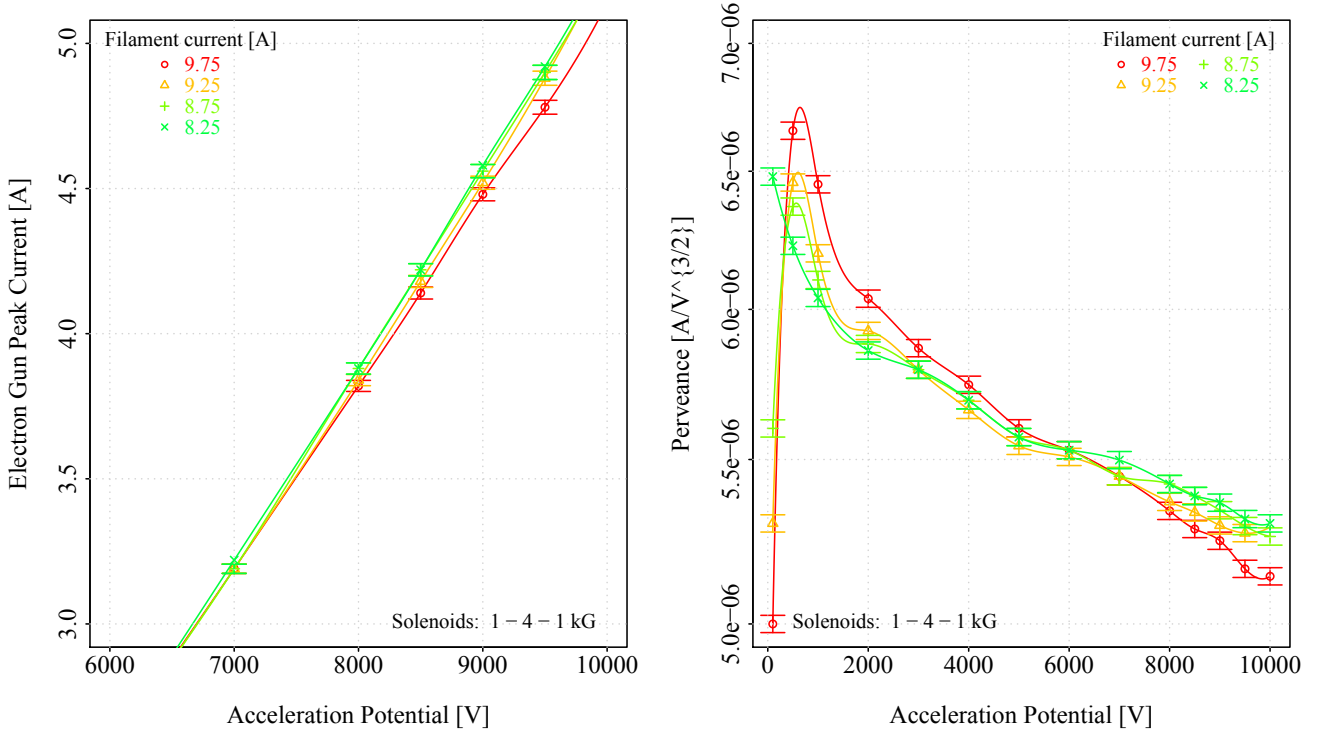


(a) Peak current vs. cathode potential for various filament currents. (b) Peak current vs. filament current for various cathode potentials.



(c) Perveance vs. cathode potential for various filament currents. (d) Perveance vs. filament current for various cathode potentials.

Figure 5.8: Electron gun peak current (top graphs) and perveance (bottom graphs) as a function of acceleration potential and filament current. All measurements were taken at 1-4-1 kG at a repetition rate of 4 Hz.



(a) Close-up of peak current vs. cathode potential for the highest filament currents.

(b) Close-up of perveance vs. cathode potential for various filament currents.

Figure 5.9: Close up of the cathode-potential dependence of the electron gun peak current and the perveance. The left plot shows that the yield is actually lower for the higher temperature cathode with a filament current of 9.75 A. The right plot, allows one to deduce what temperature to use at given cathode voltages. Below 6 kV, the yield is greatest for the highest filament current of 9.25 A. Above 6 kV, the yield is highest for a filament current of 8 to 9 A.

Fig. 5.8c, similar to fig. 5.8a, shows the transition into the *TLER* and the drop in perveance. This plot confirms that the local perveance drops slightly at high cathode potentials when exceeding 8.75 A filament current and that the cathode should be operated above 8 A. Fig. 5.8d shows the transition of the perveance from *TLER* to *SCLER*.

Fig. 5.9 shows that above a given filament current, the yield is lower than for smaller filament currents. The perveance at 9.75 A falls below that of 8.75 A and 8.25 A at 6 kV and the perveance at 9.25 A falls below that of 8.75 A and 8.25 A at 3 kV as seen in fig. 5.9b. Running the cathode at a too high temperature will deplete the BaO in the porous tungsten faster and decrease the lifetime of the cathode [27, p. 63].

The above analysis proposes that one operates the cathode not at 9.25 A, as done up to now, but at a lower filament current of ≈ 8.5 A.

5.3.5 Generalized Perveance

The generalized perveance provides a dimensionless unit used to compare different cathodes (sec. 4.3). In order to calculate this quantity, we first need to assert that we can operate in non-relativistic assumptions. Given the simple relation $\gamma = \frac{E}{E_0}$ one can derive a relation for the velocity of a particle having passed the anode.

$$\sqrt{\frac{1}{1-\beta^2}} = \gamma = \frac{E_0 + qV_a}{E_0} \Rightarrow \beta = \sqrt{1 - \left(\frac{E_0}{E_0 + qV_a}\right)^2} \quad (5.4)$$

E_0 is the rest energy of the electron, γ and β are relativistic parameters, q is the electron charge, V_a is the acceleration potential and E is the total energy of the electron, which is given by the acceleration potential. The electron velocity is given by βc , where c is the speed of light. Using conservative values for V_a of 8000 V, which is the maximum we have measured, we obtain a β of 0.17 and can thus proceed by calculating the general perveance in a non-relativistic manner.

In order to determine the general perveance (see eq. 4.9), we would plot the right hand side of that equation vs. the voltage and see that the right hand side equals the general perveance when the neutralization is 0. Sigi Li's paper [28, p. 15] states that the neutralization approaches 0 at very high acceleration potentials. An upper limit for the generalized perveance is determined by utilizing the local perveances at 10 kV from fig. 5.9b, where neutralization is clearly 0. Averaging these values gives a local perveance of $5.14(5) \times 10^{-6}$ perv. Using eq. 4.9 the generalized perveance is $7.93(7) \times 10^{-2}$. This quantity will be important when comparing the measurements to the numerical simulations in chap. 7.

5.4 Profile Measurements

Transverse profiles are measured in order to analyze the transverse beam distribution and any azimuthal asymmetries in the transverse profile. They are subsequently used to determine the transverse electric fields of the measured profiles and an upper limit for the emittance growth due to the *HEBL*.

5.4.1 Transverse Profile Measurement

Transverse profile measurements are acquired using 6 horizontal and 6 vertical beam correctors that deflect the beam in the transverse plane. A 0.2 mm pinhole at the center of the collector measures the current density as the beam is moved along a grid, defined in the acquisition script (ACL). The readout is then saved as a text file and processed by a R Script. This chapter discusses the profile measurement method and the profile evolution as it travels through the beam tube. Additionally a scaling law is deduced and discussed.

ACL Script

The full Accelerator Command Language (ACL) script is provided in appendix C.1.1.

An *ACL* script [32] controls the *TELTS* through the *ACNET* for profile scans. After initializing the run, the script defines the list of horizontal and vertical correctors that are used and the variables that are to be read (Code Line: 18) For future reference the most important variables are listed in table 5.4. It then defines the extension of the grid over which the scan is to be performed. This grid size is given in units of ampere. It then defines a quantity called *step* which gives the step size made in each direction. The total size in horizontal or vertical direction of the grid has to be an integer multiple of the step size. The variable *dt* defines how much time is spent per measurement point. For post transmission upgrade measurements a 31×31 pixel grid with 2 s interval per pixel were used. Pre-transmission upgrade measurements used a 61×61 pixel grid with a 1 s interval per pixel. The change was made purely for the purpose of reducing measurement time. Table 5.5a shows the optimal grid sizes in A for the various magnetic field configurations. Additionally tab. 5.5b gives the correction parameters for the grid not being centered around (0,0) A.

The script first runs a few safety calculations (Code Line: 55) to see that all entries are correct and physical. After this it proceeds by calculating the expected runtime. For our measurements this was usually of the order of one hour. Lastly the script defines a quantity called *stepsign* (Code Lines:

Variable Name	Variable Descriptor
Z:BC1AD3	probe current
Z:BC1AD5	tube current
Z:BC2AD5	diode pump vacuum
Z:HCORxx	horizontal corrector positions
Z:VCORxx	vertical corrector positions

Table 5.4: List of variables recorded by ACNET and saved during the transverse profile measurements.

Solenoidal configuration [T]	Horizontal settings [A]	Vertical settings [A]
1.0-1.0-1.0	[-1.5,1.5]	[-1.5,1.5]
1.5-1.5-1.5	[-2.25,2.25]	[-2.25,2.25]
2.0-2.0-2.0	[-3,3]	[-3,3]
2.5-2.5-2.5	[-4,3.5]	[-3.75,3.75]
3.0-3.0-3.0	[-4.8,4.2]	[-4.5,4.5]
0.4-1.6-0.4	[-1.8,0.6]	[-1.4,1.0]
0.6-2.4-0.6	[-2.8,0.9]	[-2.1,1.5]
0.8-3.2-0.8	[-3.6, 1.2]	[-2.8,2.0]
1.0-4.0-1.0	[-4.5,1.5]	[-3.5,2.5]

(a) Corrector settings for grid scans.

Solenoid configuration [T]	Horiz. correctors [A]	Vert. correctors [A]
0.4-1.6-0.4	-0.645	-0.2
0.6-2.4-0.6	-0.968	-0.3
0.8-3.2-0.8	-1.290	-0.4
1.0-4.0-1.0	-1.613	-0.5

(b) Corrector center of mass settings.

Table 5.5: The corrector settings in the beam tube and center of mass of the measured profiles for the different magnetic field configurations ($B_{gun} - B_{main} - B_{coll}$).

70-73) which gives the direction of the scan. The script scans one row after the other in the vertical direction, changing scan direction for each row. The directionality of the scan is important and can cause artifacts in the transverse scan profile.

The script then terminates by resetting all the correctors to 0 (Code Lines: 130-132). The measured data is saved in a text file. Code 5.1 is an example of such a text file, for a measurement that was taken on 14.05.13 at a filament current of 9.25 A, magnetic field of 0.8-3.2-0.8 kG, a cathode potential of 500 V and a peak current of 73 mA.

```

1  === Electron lens test stand profile scan ===
2  # 14-MAY-2013 17:47:54
3  # Scan parameters:
4  #   mix = -3.6   A
5  #   max =  1.2   A
6  #   miy = -2.8   A
7  #   may =  2     A
8  #   step = .16   A
9  #   dt  =  2     s
10
11
12 # xset[A] yset[A] Z:BC1AD3[UA] Z:BC1AD5[UA] Z:BC2AD5[MA] Z:HCOR02[A] ... Z:VCORB5[A] ctime[s]
13 -3.6  -2.8  .0012207031 .0001953125 6.51550293 -3.603515625 ... -2.80090332 1368553731
14 ...
15  1.2   2     .0014648437 .0001953125 6.572570801 1.192626953 ... 1.995239258 1368555846

```

Code 5.1: "Sample of profile measurement text file"

The text file first contains a preamble that lists the settings with which the *ACL* script was run. In this case we used a 31 x 31 grid with a 2 s measurement per grid point. Following the preamble, the measurements are listed. First the x and y positions are given. Followed by the probe current, the tube current and the diode pump vacuum. It then lists the positions of all 6 horizontal and 6 vertical correctors. Lastly it provides the time stamp of the measurement.

R Script

The full R Script is provided in app. C.1.2.

R is an open-source *GNU's Not Unix (GNU)* language for statistical computing and graphical output. It is based on the similar S language and environment which was developed by Bell Laboratories³.

The R script starts of with the usual initialization (Code Lines: 8-12), such as the loading of library files, defining very long vectors of all input files, their beam parameters and their transverse offsets. Furthermore some processing and plotting options are set. The script uses two types of color coding

³www.r-project.org

in contour plots. One is the classical MATLAB color series with blue being the lowest value and red the highest. It was found that this color scheme provided too little contrast for the areas of interest. A second scheme named `COLOR.CHART` was created to provide more color contrast in the mid-range (Code Line: 175).

The script calculates a few important global quantities such as the electron frequency, flight time, cyclotron and plasma frequency and evolution number (Code Lines: 321-339). These are printed to the standard output. The R script can also handle measurements made with previous versions of the above mentioned *ACL* script. The new *ACL* script provides vacuum data. The R script thus extracts the data if necessary. The measured data is then stored into 3 arrays: `Zprobe`, `Ztube` and `Zvac` (Code Lines: 421-423). The quantity that is ultimately plotted is `Zprobe`. The background of the measurement is calculated by averaging the fourth lowest quantile of the measurements. It is then subtracted from the measurements. A fake signal often arises in the bottom left corner. This is removed. Next the measurements are normalized and the center of mass of the profiles are calculated. At this point, the transverse grid is still given in units of amperes, which are provided to the correctors to deviate the beam. To convert them to mm, either the calibration coefficients saved in `calx.v` and `caly.v` are used, or they can be recalculated by turning on the option `CALIBRATE.CORRECTORS` (Code Line: 564). This will ask the user to define the outer and inner beam by defining 8 points on each edge. Given the current deviation and the normal beam size, the calibration coefficients are calculated and printed to the standard output.

The major calculations have now been completed and the script creates several plots of the measurements (Code Line: 681). First a 1D cross-section of the beam, showing the variation of current density along the horizontal direction with the vertical position set to 0. It then produces 2D contour plots (Code Line: 720). These come in two variations. One with annotations and one without. Lastly it produces a 3D plot of the profile (Code Line 800).

Having produced all the plots, the script, if the respective options are turned on, outputs; the calibrated profile and a radial plot of current density vs radius from the beam center, which is the average over all azimuthal angles, a particle plot together with a text file containing all the coordinates and if selected a polar decomposition plot (Code Line: 931).

Measured Transverse Profiles

Profiles were measured throughout the course of this thesis in the *TELTS*. For a list of all measured profiles, see appendix B.1. Profiles can be sorted by the magnetic fields in the three big solenoids and the cathode voltage. The cathode current is dependent on the cathode voltage through the Child-Langmuir law. In general it was observed that profiles were reproducible when measured with the same parameters. Considering space charge evolution and the angular rotation of the profiles, a chart of all profiles with respect to the magnetic field in the main solenoid and the cathode potential was made. This allows us to uniquely observe profile evolution through these two parameters. Fig. 5.10 depicts such a chart with profiles made after the transmission upgrade mentioned in sec. 5.2. The red lines indicate the expected scaling laws for a constant ratio of pinhole current to total current, which is discussed in section 5.4.3. We can compare this to the profiles that were measured before the transport upgrade, which are depicted in fig. 5.11. It is important to recollect that measurements after the transmission upgrade had a magnetic configuration of $B_{gun} = B_{coll} = 0.25B_{main}$ while measurements before the transmission upgrade had equal magnetic fields in all 3 solenoids. The lack of magnetic compression in the main solenoid has prevented the rapid space charge evolution seen in fig. 5.10 in the measurements made before the transmission upgrade shown in fig. 5.11.

The profiles that are of interest to us are those in the top left corner. Profiles below 0.5 kV tend to become unstable, due to insufficient removal of space charge from the surface of the cathode. At the LHC, the maximum magnetic confinement will be of the order of 6 T, which is the easy attainable magnetic field with today's superconducting magnets. Given this and the assumption that the red lines in fig. 5.10 hold, we see that the profiles in the top left corner are those that represent the profiles that will ultimately scale to LHC parameters. The cathode potential at the LHC will most likely be

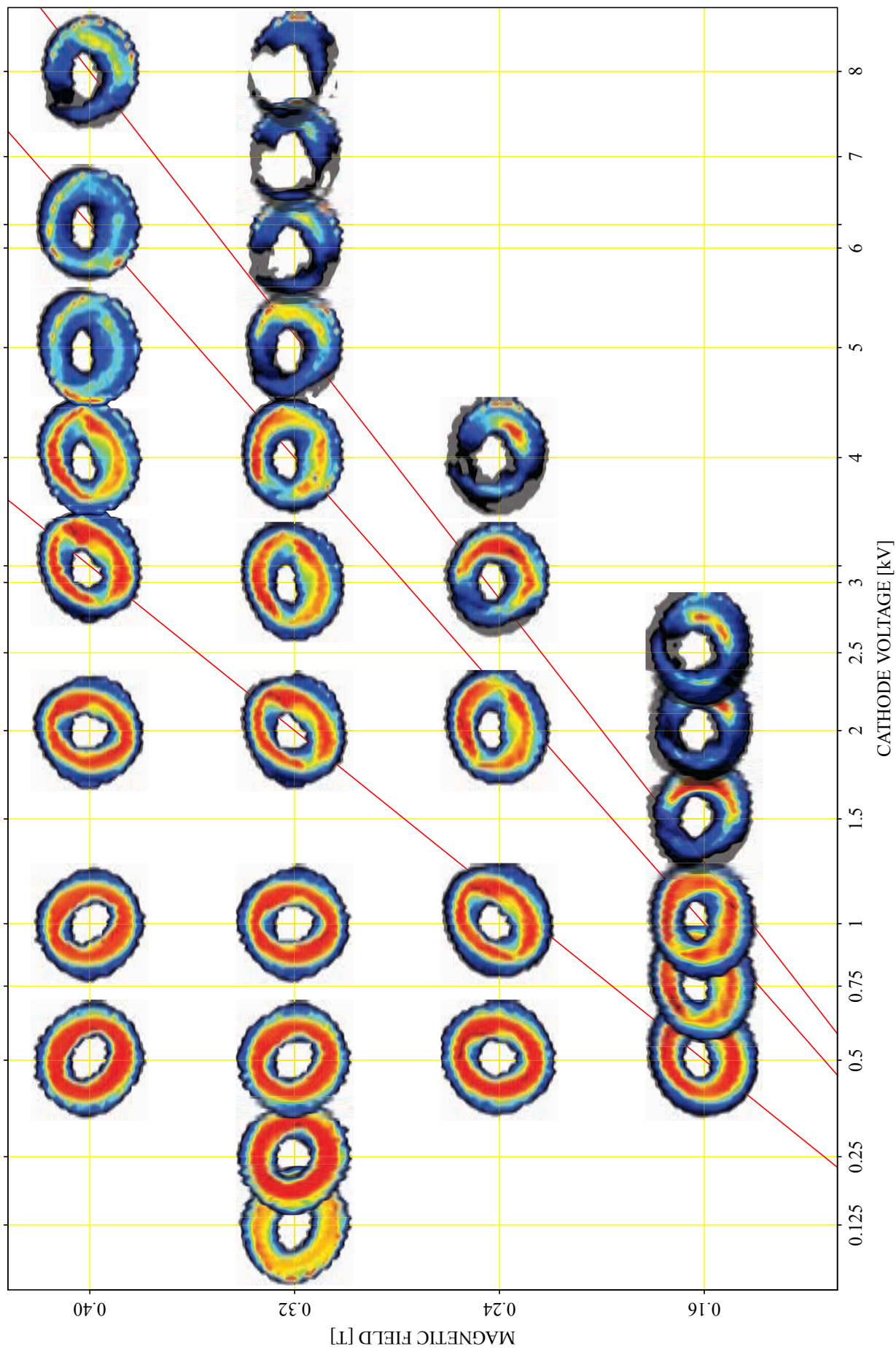


Figure 5.10: Profiles measured after the improvement of the transport (see section 5.2). They are ordered by the magnetic field of the solenoids and the cathode voltage. The red lines indicate scaling lines discussed in section 5.4.3. The same color coding was used for all profiles.

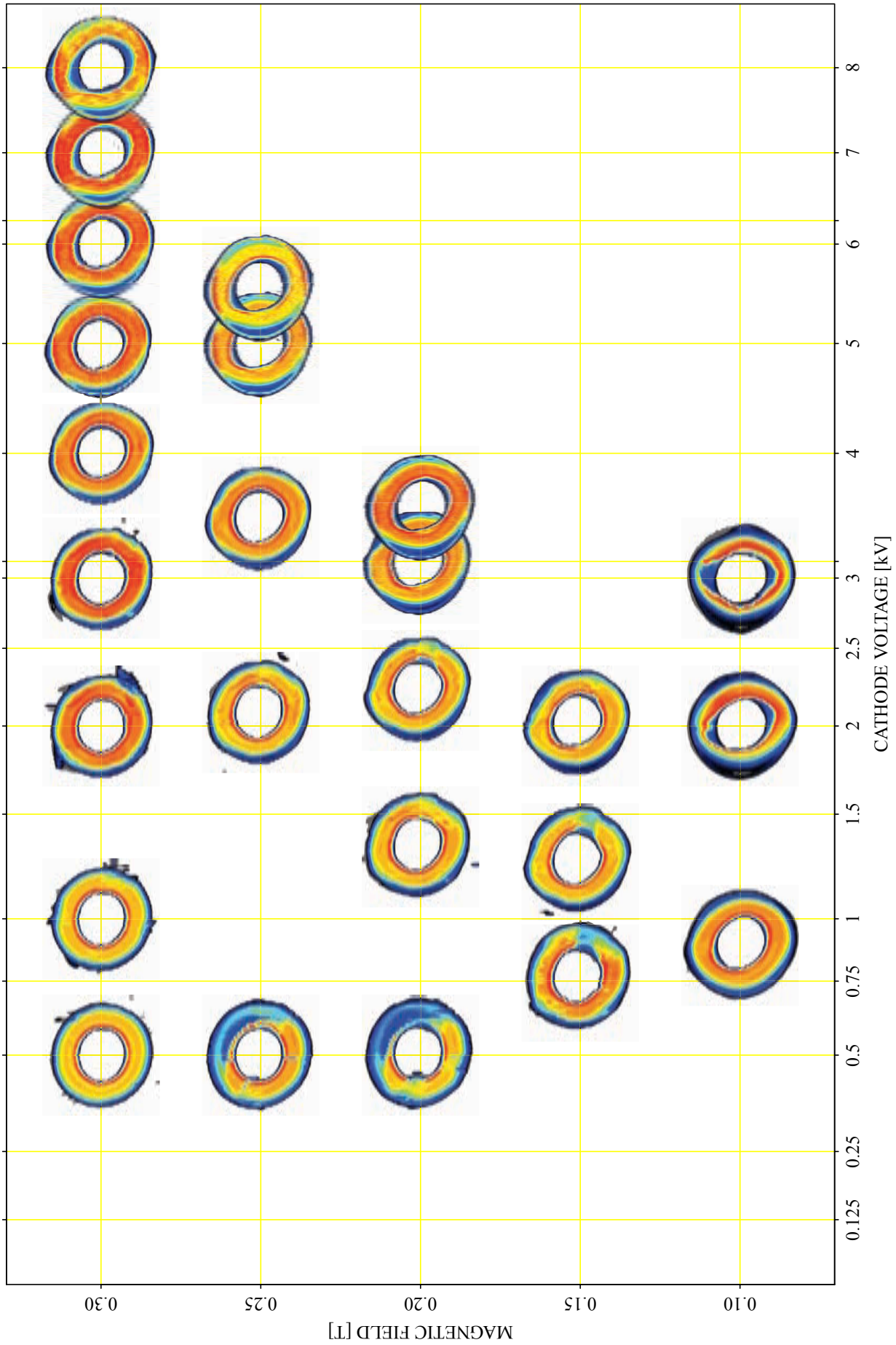


Figure 5.11: Profiles measured before the improvement of the transport (see section 5.2). They are ordered by the magnetic field of the solenoids and the cathode voltage. The same color coding was used for all profiles.

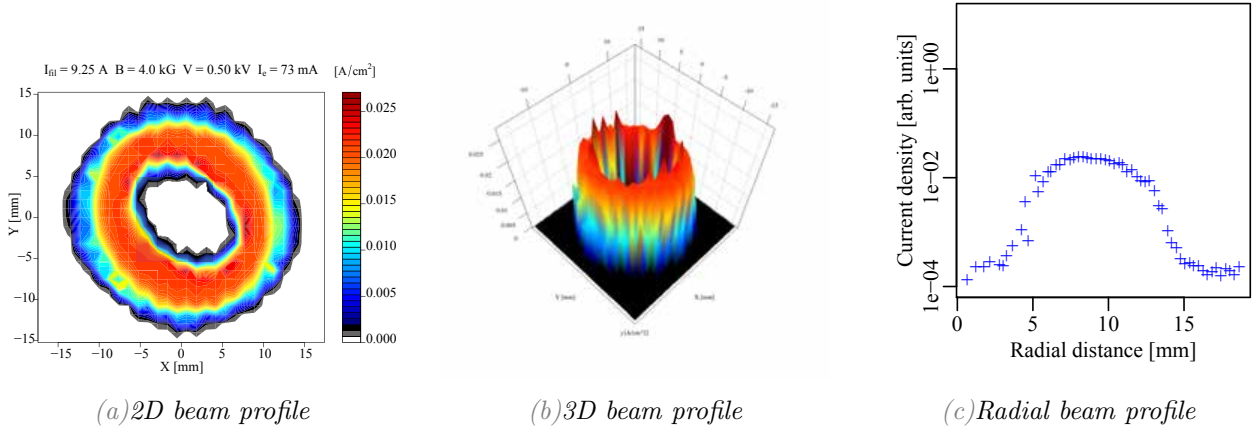


Figure 5.12: Beam profile at $B=1-4-1$ kG, $V=500$ V and $I_{peak}=73$ mA. The beam shows a good symmetry, being squeezed a little in the horizontal direction. fig. (b) shows slight slippage through two radially opposing centers. The radial profile in fig. (c) shows a smooth distribution, indicating that the beam is radially similarly distributed for all azimuthal angles.

operated around 4-5 kV. Fig. 5.12 shows the 2D, 3D and radial profile of an optimal measurement point at $B=1-4-1$ kG and $V=500$ V.

5.4.2 Beam Evolution

This section derives an equation for the angular rotation velocity of the transverse profiles. This is done as a sanity check for the evolutions observed in figures 5.10, 5.13 and 5.14.

The e-beam is essentially a non-neutral plasma that exhibits collective behavior. In order for plasmas to be in equilibrium, they always require a restoring (space charge) and a disturbing self-field force. The radial motion is given by (see: [25, p. 175])

$$\ddot{r} = \frac{\omega_p^2}{2} r \quad \omega_p^2 = \frac{q^2 n}{\epsilon_0 \gamma^3 m} (1 - \gamma^2 f_e) \quad (5.5)$$

Here r is the transverse position of the profile, ω_p is the plasma frequency, q is the elementary charge, n is the particle density, ϵ_0 is the permittivity of vacuum, γ is the relativistic factor and f_e is the neutralization factor. As discussed earlier, we can assume non-relativity and thus set $\gamma = 1$.

In the case of our electron beam, the restoring force is the $E \times B$ twist, where the magnetic field B is applied externally through the solenoids and the electric field E is radially outward, given by the self fields of the space charge in a 2D approximation. Equilibrium between these two forces is given when the beam is matched (beam envelope on straight line). The beam is matched for a oscillation frequency ω due to the applied focusing force and the space charge force of (see: [25, p. 191]):

$$\omega^2 = \omega_L^2 - \frac{\omega_p^2}{2} = \left(\frac{eB}{2m_e} \right)^2 - \frac{ne^2}{2\epsilon_0 m_e} \quad (5.6)$$

ω_L is the larmor frequency, $\frac{qB}{2m_e}$. Due to the radial oscillations, particles have a non-zero transverse velocity and thus exhibit larmor oscillations in the axial magnetic field, causing the beam to rotate. The angular rotation velocity ω_r is given by the diocron frequency ω_D [33, p. 298]:

$$\omega_r = \omega_D = \frac{\omega_p^2}{2\omega_c} = \frac{ne}{2\epsilon_0 B} \quad (5.7)$$

where ω_c is the cyclotron frequency which is 2 times the larmor frequency. For a full cylindrical electron beam the angular rotation velocity ω_r is independent of the radial position of the particle because the radial electric field rises linearly with the electric field. Considering a *Hollow Electron Beam (HEB)*

configuration and including neutralization f and a contribution due to a rotation of the beam induced by the axial electron current and the azimuthal self-magnetic field β_z^2 , we obtain the radially dependent azimuthal rotation velocity [33, p. 308]:

$$\omega_r = \omega_D(1 - f - \beta_z^2) \left[1 - \left(\frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \quad (5.8)$$

where R_i is the inner beam radius, R_o is the outer beam radius and r is the particle radius. We assume neutralization to be negligible [28, p. 15], $f = 0$, and neglect self-magnetic fields, $\beta_z^2 = 0$. It is thus possible to deduce the angle through which the radial profile layers evolve by multiplying with the time needed to transverse the electron beam tube. The distance between the cathode and the collector L is 2.86 m in the test stand. Assuming that the particle velocity v_z is constant throughout the beam tube, we can give the angle of rotation by:

$$\varphi_r = \frac{\omega_D L}{v_z} \left[1 - \left(\frac{R_i}{r} \right)^2 \right] = \frac{n_e e L}{2 \varepsilon_0 B v_z} \left[1 - \left(\frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \quad (5.9)$$

Given electrons, the number density of electrons n_e and the transverse charge density ρ of electrons are related by $n_e = 6.24 \times 10^{18} \rho L^{-1}$, where $\rho = \frac{I}{v_z \pi (R_o^2 - R_i^2)}$. Furthermore using equation 5.4, one obtains:

$$\varphi_r = \frac{IL}{2\pi\varepsilon_0 B (R_o^2 - R_i^2) v_z^2} \left[1 - \left(\frac{R_i}{r} \right)^2 \right] \quad (5.10)$$

$$= \frac{IL}{2\pi\varepsilon_0 B (R_o^2 - R_i^2) c^2 e V_a \left(\frac{2E_0 + eV_a}{(E_0 + eV_a)^2} \right)} \left[1 - \left(\frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \quad (5.11)$$

where c is the speed of light, e the electron charge and V_a the acceleration potential between the anode and the cathode. Given that $\frac{eV_a}{E_0} \ll 1$, we can approximate $\frac{2E_0 + eV_a}{(E_0 + eV_a)^2} \approx \frac{2}{E_0}$ and thus write:

$$\varphi = \frac{IE_0 L}{2\pi\varepsilon_0 B (R_o^2 - R_i^2) 2c^2 e V_a} \left[1 - \left(\frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \quad (5.12)$$

Having a dependency upon B , V_a , I and r at this point, one can eliminate the dependency on I through the Child-Langmuir law. As perveance, the measured perveance of the test stand in fig. 5.2 of 5.33 $\times 10^{-6}$ perv was used. Furthermore $E_0 = 8.19 \times 10^{-14}$ J, $\varepsilon_0 = 8.85 \times 10^{-12}$ A² s⁴ m⁻³ kg⁻¹, $c = 3.00 \times 10^8$ m s⁻¹ and $e = 1.60 \times 10^{-19}$ C. The inner and outer radius must be taken as an average of the beam radii before, during and after the magnetic compression. Given a magnetic compression of a factor 2, the average beam radii are 0.63 times the cathode beam radii. This gives an average outer beam radius of 8.0 mm and an inner radius of 4.3 mm. Using these values we can thus write:

$$\varphi = \frac{PE_0 L}{4\pi\varepsilon_0 c^2 (R_o^2 - R_i^2) e} \times \frac{\sqrt{V_a}}{B} \left[1 - \left(\frac{R_i}{r} \right)^2 \right] \quad (5.13)$$

$$= 2.7 \times 10^{-2} \frac{\sqrt{V_a}}{B} \left[1 - \left(\frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \quad (5.14)$$

If we consider particles halfway between the average inner and outer cathode radius, $r = 6.15$ mm, the angular rotation velocity is given by:

$$\varphi = 1.4 \times 10^{-2} \frac{\sqrt{V_a}}{B}, \quad \forall R_i \leq r \leq R_o \quad (5.15)$$

Table 5.6 gives a list of all angles of rotation in radians due to the diocron profile evolution for profiles with an acceleration potential of $V_a = 1$ kV to 8 kV and $B_{\text{main}} = 0.16$ T to 0.4 T. We can use this equation as a sanity check for the beam evolution and beam profiles we have measured. It is important that B in eq. 5.15 is the average magnetic field throughout the beam tube, which is 0.87 times the magnetic field in the main solenoid.

Angle of rotation [°]	Acceleration Potential [kV]							
Magnetic Field [T]	1	2	3	4	5	6	7	8
0.40	72	101	124	143	160	175	189	202
0.32	89	127	155	179	200	219	237	253
0.24	120	169	207	239	267	292	316	337
0.16	179	253	310	358	400	438	473	506

Table 5.6: Transverse rotation angles for particles halfway between outer and inner cathode amplitude as a dependence of acceleration potential V_a and magnetic field strength in the main solenoid B_{main}

Evolution as a function of V

The beam evolution is portrayed in fig. 5.13 for a constant magnetic field of $B = 0.32$ T. With increasing cathode potential, the beam diverges from a uniform distribution ($V = 500$ V) to a two-island shape ($V = 3$ kV) and eventually into one major peak ($V = 8$ kV). The radial profiles portray an average over all azimuthal angles of the beam profile. At 125 V and 250 V a clear beam edge can be seen at a radius of about 3 mm. As the cathode potential increases, this blurs out. At low voltages, the beam seems to be very stable and axis-symmetrical. As expected, the area underneath the radial profile increases, signaling a higher beam current. The beam profiles rotate in fig. 5.13 with a radially dependent frequency, indicated by the change in beam profile with changing V. Given that $\omega_0 \propto \sqrt{V_a}$, doubling the cathode potential should make the profiles evolve 1.4 times as fast. According to table 5.6, going from 2 kV to 3 kV causes a rotation of 28° . This can be qualitatively confirmed.

Evolution as a function B

Fig. 5.14 shows the scaling of the transverse profiles with constant cathode potential. Given that $\omega_0 \propto B^{-1}$, a change of the magnetic field from 3.2 kG to 4 kG means that the evolution should be slower by 20%. According to table 5.6, transitioning from $B_{main}=3.2$ kG to 2.4 kG should make the profile turn by 42° . This seems to be the case.

5.4.3 Beam Scaling

Considering tab. 5.6 and fig. 5.10, we can assume that profiles will be frozen at magnetic fields of a few Tesla. Still we attempt a first quantitative analysis of dynamical similarity between the profiles, by finding an approximate scaling law for equal profiles with respect to B and V .

In 1914, Mr. E. Buckingham published a paper on dimensional analysis that is still cited regularly today (see [34]). He discussed several techniques that allow one to draw fundamental, but necessary conclusions just by considering the dimensional units of equations.

Assuming the necessity to describe a system solely based on n physically different quantities, a physically complete relation can be formulated as

$$f(Q_1, Q_2, \dots, Q_n, r^1, r^2, \dots) = 0 \quad (5.16)$$

where r^1, r^2, \dots signify a number of ratios between dimensionally equal quantities. Assuming that these remain constant, one can reduce the above to

$$f(Q_1, Q_2, \dots, Q_n) = 0 \quad (5.17)$$

which describes the complete system and is called a physical equation. Each such equation can be expressed in the more specific form

$$\sum MQ_1^{b_1} Q_2^{b_2} \dots Q_n^{b_n} = 0 \quad (5.18)$$

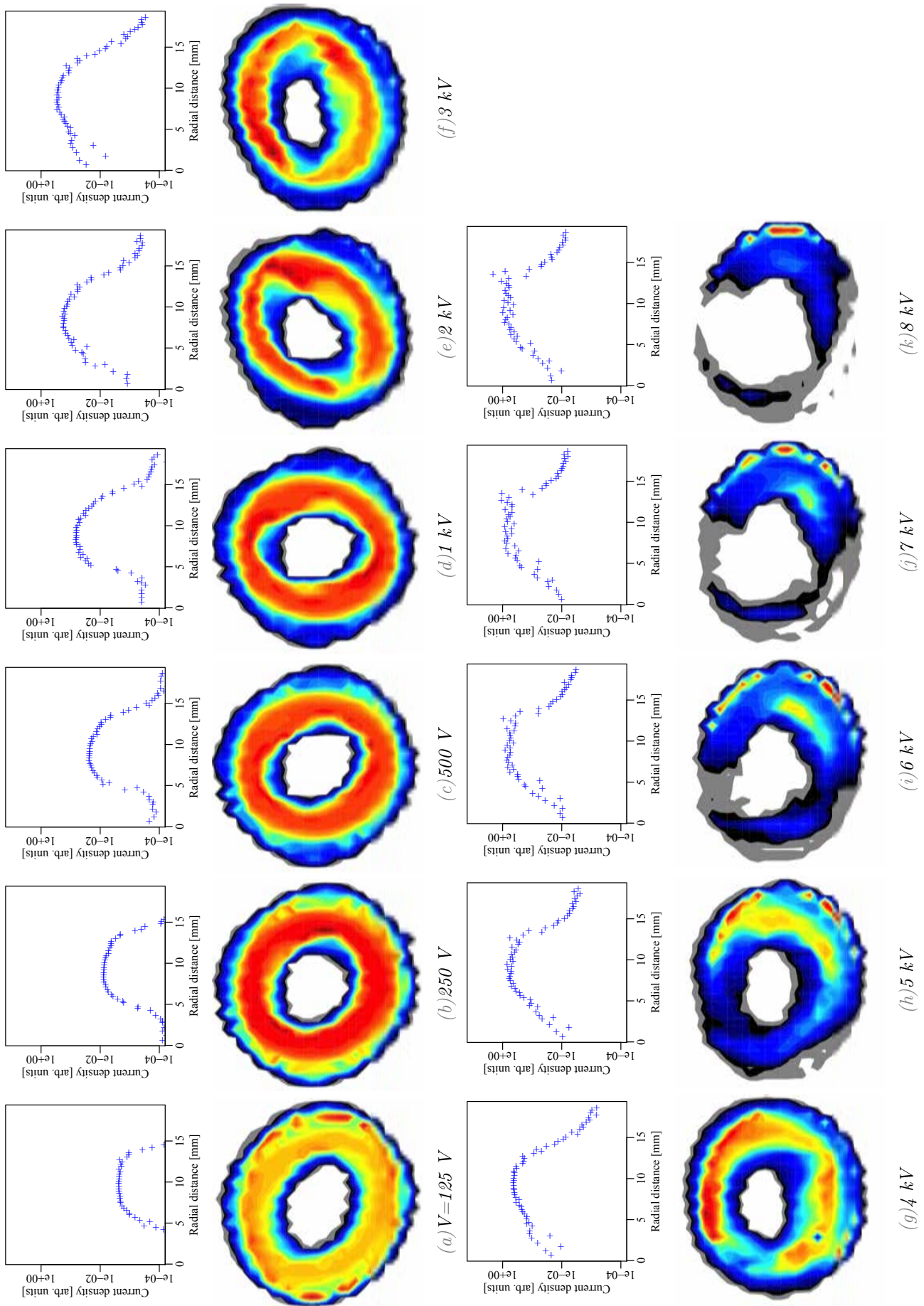


Figure 5.13: Series of the profiles at $B=0.8-3.2-0.8\text{ kG}$ with gradually increasing cathode potential.

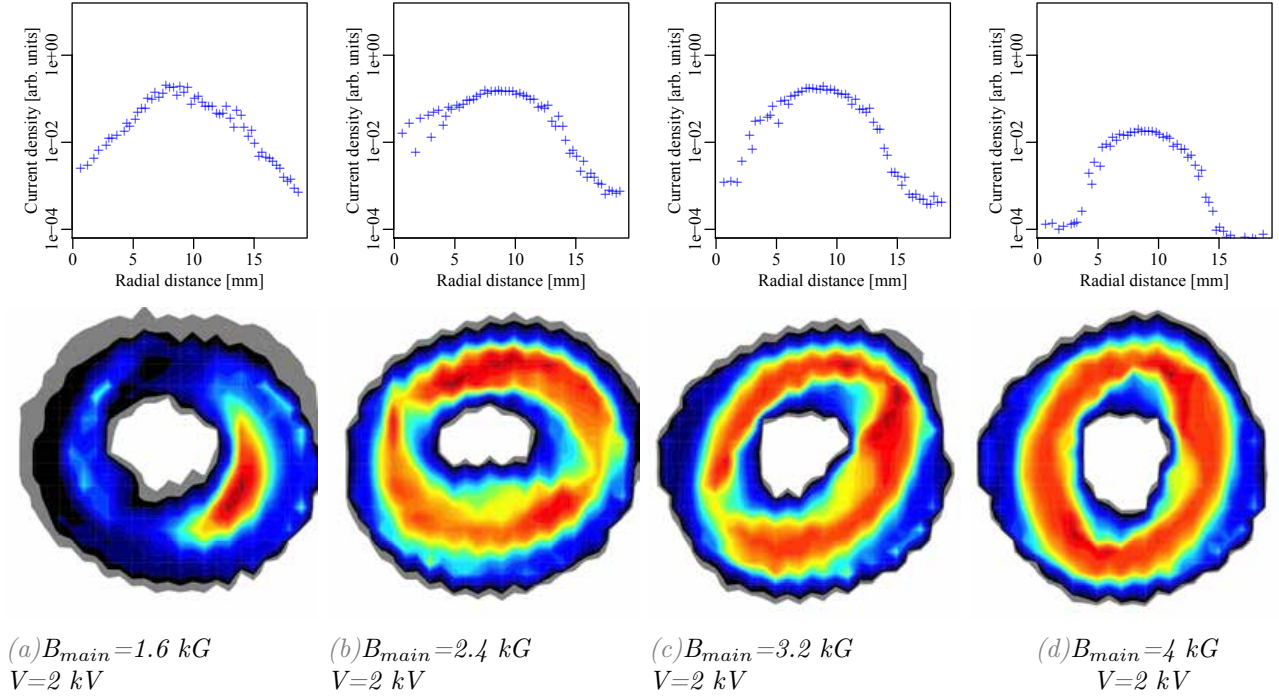


Figure 5.14: Transverse profile series at $V = 2 \text{ kV}$.

where terms such as logarithms and sin functions have been replaced by their respective expansions. If we now divide through by any one term, this becomes

$$\sum MQ_1^{a_1} Q_2^{a_2} \dots Q_n^{a_n} + 1 = 0. \quad (5.19)$$

Each term in this equation must have the same dimension and therefore, one can write the dimensional equations

$$[Q_1^{a_1} Q_2^{a_2} \dots Q_n^{a_n}] = [1]. \quad (5.20)$$

By defining the dimensionless products $\Pi = Q_1^{a_1}, Q_2^{a_2}, \dots, Q_n^{a_n}$ we can rewrite eq. 5.19 as

$$\sum \Pi + 1 = 0. \quad (5.21)$$

Considering that Π is dimensionless, we can rewrite eq. 5.21 as

$$\sum \Pi_1^{x_1} \dots \Pi_i^{x_{n-k}} + 1 = 0 \quad (5.22)$$

and thus for every complete physical equation of the form 5.16 we can write a relation in terms of the $n - k$ dimensionless quantities Π , combined from the n physical quantities Q_1, Q_2, \dots, Q_n and the k fundamental units entailed in these physical quantities, as

$$\Psi(\Pi_1, \Pi_2, \dots, \Pi_{n-k}) = 0 \quad (5.23)$$

$$[\Pi_1] = \dots = [\Pi_{n-k}] = [1] \quad (5.24)$$

Eq. 5.23 describes the system in terms of the $n - k$ dimensionless quantities. From this one can then formulate a scaling law.

In order to obtain a perception for the profiles at higher magnetic fields, as used at the LHC, a scaling law for a constant profile evolution was derived using a reduced dimensional analysis, where the permittivity of free space ϵ_0 was omitted. Constant profile evolution requires that the ratio of $I_{pinhole} I_{total}$ remains constant. Given the assumption that we operate in the space charge limited regime, we assume Child-Langmuir's law, eq. 4.6, and thus consider the following 5 independent variables

Given 5 independent physical quantities and 4 SI units, one can define 1 dimensionless parameter that describes the system through the equation

$$\Psi(\Pi) = R, \quad (5.25)$$

where $R = I_{pinhole}/I_{total}$.

We chose the 4 fundamental units not to be the SI units, but the magnetic field B , the cathode potential V , the system length L and the electron mass e_m allowing us to write the following according to equation 5.20:

Quantity	Symbol	Units	SI Units
Electron charge	e^-	[C]	$[A \times s]$
Electron mass	e_m	[amu]	[kg]
Magnetic field in solenoids	B	[T]	$\left[\frac{kg}{A \times s^2}\right]$
Cathode potential	V	[V]	$\left[\frac{kg \times m^2}{A \times s^3}\right]$
System length	L	[m]	[m]

Table 5.7: Physical quantities used for the dimensional analysis of the constant beam profile. Neutralization, which would be in the form of a cross-section, and boundary conditions due to the conductors were neglected.

$$\left[B^\alpha \times V^\beta \times L^\gamma \times e_m^\zeta \times e^- \right] = [1] \quad (5.26)$$

$$\left[\left(\frac{kg}{A \times s^2} \right)^{\alpha_1} \left(\frac{kg \times m^2}{A \times s^3} \right)^{\beta_1} (m)^{\gamma_1} (kg)^{\zeta_1} (A \times s) \right] = [1] \quad (5.27)$$

The solution of the above equation is:

Equation	α	β	γ	ζ	Dimensionless quantity
1	2	-1	2	-1	$\frac{B^2 \times L^2 \times e^-}{V \times e_m}$

We can thus rewrite eq. 5.25 as

$$\Psi \left(\frac{B^2 \times L^2 \times e^-}{V \times e_m} \right) = R \quad (5.28)$$

$$\frac{B^2 \times L^2 \times e^-}{V \times e_m} = \Psi^{-1}(R) \quad (5.29)$$

$$B = \sqrt{V} \times \frac{\sqrt{e_m}}{L \times \sqrt{e^-}} \Psi^{-1}(R) \quad (5.30)$$

Considering that e_m and e^- are constant and we do not change the system length, the scaling law thus states that:

$$B \propto \sqrt{V} \quad (5.31)$$

This scaling law coincides with the formula for the angle of rotation in eq. 5.13, obtained from the diocron frequency ω_D . If we wish to determine the scaling for equal profiles, the angle of rotation of the different profiles must be equal. Keeping φ constant in eq. 5.13, we obtain the same scaling law of $B \propto \sqrt{V}$.

Having discussed a possible scaling law, fig. 5.15 sorts measured profiles by their magnetic field B in the main solenoid and the scaling factor. The scaling can not be replicated perfectly, but is observable to a given degree. Especially at the lowest scaling factor of $4.47 \times 10^{-3} \text{ T V}^{-\frac{1}{2}}$. Here the only profile diverging from the scaling is that at $B=0.4-1.6-0.4 \text{ kG}$ and $V=500 \text{ V}$. Qualitatively the scaling laws holds, but profiles break down at high cathode potentials, making it difficult to confirm the scaling law.

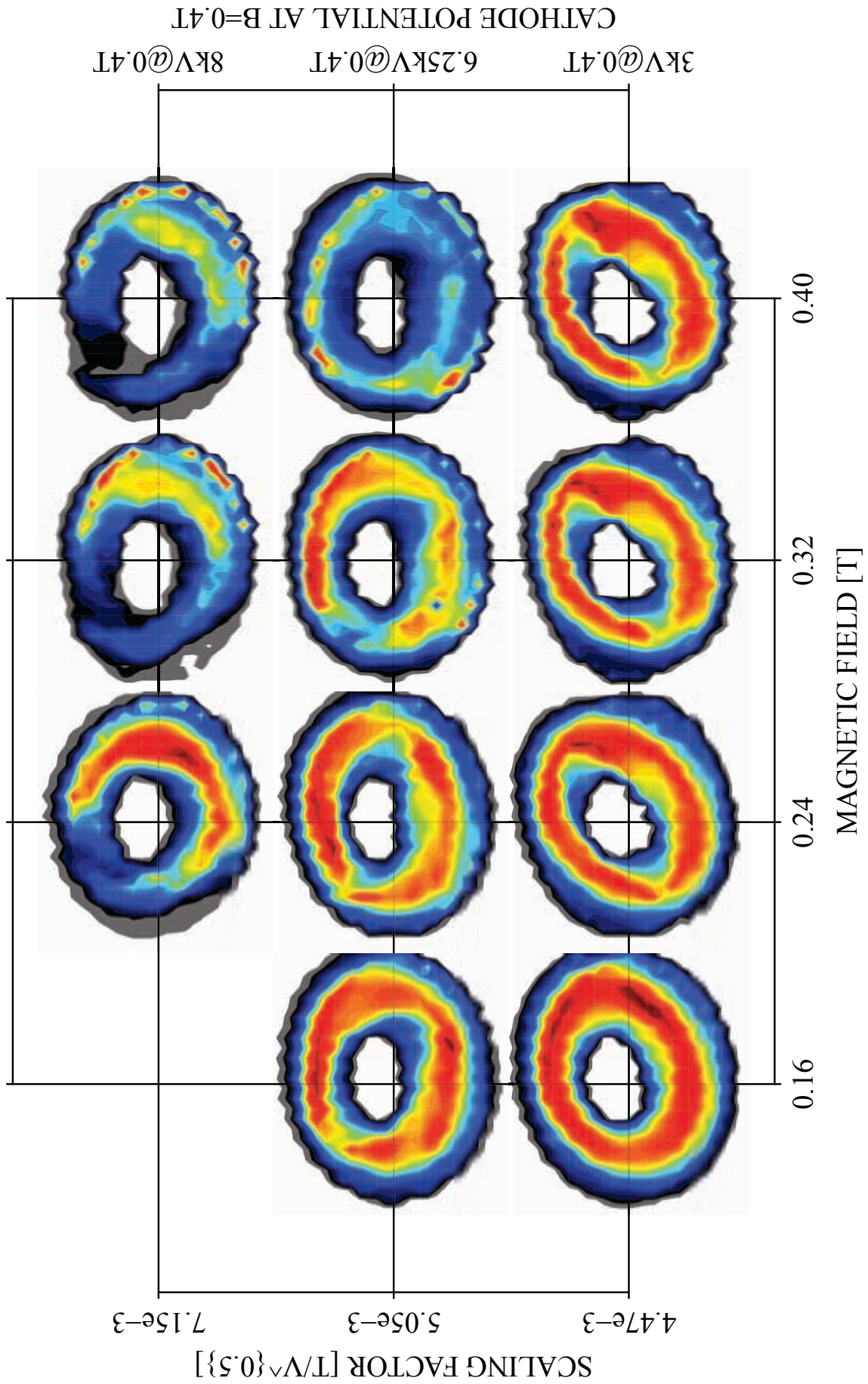


Figure 5.15: $B\sqrt{V}$ scaling for Beam Profiles. Profiles are ordered by their scaling factor and the magnetic field.

Chapter 6

Transverse Fields of Measured Profiles

This chapter discusses the transverse electric fields of the electron beam and an upper limit for the emittance growth due to the electric field of the *Hollow Electron Beam (HEB)*.

Using WARP¹ the charge density, electric potential and electric field of the measured profiles are calculated. It is important to note that WARP is only being used as a tool for the calculations. It is used in a 2D setup and no 3D simulations are done. Therefore the detailed discussion of WARP is left to chap. 7, where full 3D simulations are conducted. The transverse fields will be used in tracking studies to examine the effect on the proton beam core and halo. As a preliminary check, the upper limits of the emittance growth due to the transverse electric fields is calculated by assuming the E-field fluctuations in the hole act like random kicks.

WARP was developed in the pursuit of heavy-ion driven inertial confinement fusion. It has been greatly enhanced since and is suited for the simulation of a *HEB*. It contains three coordinate systems: a 3D model (WARP3d) we use in chap. 7; an axis-symmetrical model (WARP_{Prz}) and a transverse slice model (WARP_{xy}), which is used here. For further information refer to [35, p. 9]

6.1 Transverse Field of Hollow Electron Beams

The field of a *HEB*, can be described using the first Maxwell equation, Gauss' Law in integral and microscopic form.

$$\oiint_{\partial\Omega} E \cdot dS = \frac{Q_{encl,\Omega}}{\epsilon_0} \quad (6.1)$$

The left hand side is an integral over the electric field E of the surface of a cylinder $\partial\Omega$. The electric field is assumed to be constant everywhere on the surface $\partial\Omega$. $Q_{encl,\Omega}$ is the charge enclosed by $\partial\Omega$ and ϵ_0 is the vacuum permittivity. In a 2D approximation, where the cylinder is assumed to be infinitely long, the front and back parts of the cylinder can be neglected. The right hand side, assuming a uniform line charge distribution, is written as an integral over the charge density ρ .

$$E \cdot 2\pi r L = \frac{\int_0^R \rho(r') 2\pi r' L dr'}{\epsilon_0} \quad (6.2)$$

$r = r(\partial\Omega)$ is defined as the radius at the transverse surface of the cylinder and L as the length of the beam. The electric field E is singled out and some constants are eliminated.

$$E = \frac{\int_0^R \rho(r') r' dr'}{\epsilon_0 r} \quad (6.3)$$

¹A particle in cell code developed at Lawrence Berkley National Laboratory.

The inner beam radius is R_i and the outer R_o . Assuming a uniform charge distribution $\rho(r') = \rho$ in the hollow beam, 3 cases are considered.

$$r \leq R_o \quad E = 0 \quad (6.4)$$

$$R_i \geq r \leq R_o \quad E(r) = \frac{\rho(r^2 - R_i^2)}{2\varepsilon_0 r} = \frac{IL(r^2 - R_i^2)}{2\pi v_z \varepsilon_0 r (R_o^2 - R_i^2)} \quad (6.5)$$

$$R_o \geq r \quad E(r) = \frac{\rho(R_o^2 - R_i^2)}{2\pi \varepsilon_0 r} = \frac{IL}{2\pi v_z \varepsilon_0 r} \quad (6.6)$$

These 3 equations fully qualify the electric field of a hollow uniform cylindrical charge distribution. Fig. 2.5 shows the transverse electric field distributions for the profiles corresponding to $V=500$ V and $V=8$ kV at $B=1-4-1$ kG ($B_{gun} - B_{main} - B_{coll}$).

6.2 Emittance Growth

From the radial electric field of the beam, the energy of the protons and the length during which the protons are exposed to the electric field, an upper boundary for the additional emittance growth of the proton beam can be estimated. The purpose hereof is to obtain a rough estimate of the emittance growth of the proton beam in the *Large Hadron Collider (LHC)* due to the *Hollow Electron Beam Lens (HEBL)*.

Assuming the transverse electric field to be the only source of a transverse force on the proton particles, the following equation holds:

$$\frac{d}{dt} p_r = F_y = q \vec{E}_r \quad (6.7)$$

Here the subscript r indicates the radial direction in the transverse plane, p is the momentum q the elementary charge and \vec{E} the radial electric field. Assuming that the particles are on a perfect design orbit ($p_r = 0$), and that the electric field is constant in time, the above equation can be integrated.

$$p_r = q \vec{E}_r t \quad (6.8)$$

We define θ to be the inscribed angle between the total momentum and the axial momentum along z . Expressing p_r in terms of the total momentum and the momentum along z , $p_r = p \sin(\theta) = p_z \tan(\theta)$ gives:

$$p_z \tan(\theta) = q \vec{E}_r \quad (6.9)$$

$$\rightarrow \tan(\theta) = \frac{q \vec{E}_r t}{p_z} \quad (6.10)$$

$$\rightarrow \tan(\theta) = \frac{q \vec{E}_r L}{p_z v_z} \quad (6.11)$$

$$\rightarrow \tan(\theta) = \frac{\gamma E_0 q \vec{E}_r L}{c^2 p_z^2} \quad (6.12)$$

$$\rightarrow \tan(\theta) = \frac{E_{tot} q \vec{E}_r L}{E_{tot}^2 - E_0^2} \quad (6.13)$$

Given that the kick in the transverse direction is $x' = dx/dz$, it follows that $x' = \tan \theta \stackrel{!}{=} \vartheta$. Here γ is the relativistic factor, E_0 is the rest energy of the proton, v_{0z} is the velocity along z , q is the elementary charge, L is the length of the *Hollow Electron Gun (HEG)* and E_{tot} is the total energy of the proton beam. The transverse kick on a particle due to a transverse electric field is thus:

$$\vartheta = \frac{E_{tot} q E_r L}{E_{tot}^2 - E_0^2} \quad (6.14)$$

A normal transfer equation for a particle in an accelerator is given by [36]:

$$\begin{pmatrix} x_{n+1} \\ x'_{n+1} \end{pmatrix} = M \begin{pmatrix} x_n \\ x'_n \end{pmatrix} \quad (6.15)$$

where M is the transfer matrix. If the particles are not disturbed by the electron lens, the Courant Snyder invariant (see: [36, p. 105])

$$\varepsilon = \gamma x_{n+1}^2 + 2\alpha x_{n+1} x'_{n+1} + \beta x_{n+1}'^2 = \gamma x_n^2 + 2\alpha x_n x'_n + \beta x_n'^2 \quad (6.16)$$

is conserved. Considering the kick that is introduced by the electron lens, eq. 6.15 changes to:

$$\begin{pmatrix} \tilde{x}_{n+1} \\ \tilde{x}'_{n+1} \end{pmatrix} = M \begin{pmatrix} x_n \\ x'_n \end{pmatrix} + \begin{pmatrix} 0 \\ \vartheta \end{pmatrix} \quad (6.17)$$

Assuming that the electron lens is turned on after n turns of the beam, the change of emittance per turn can be found. The emittance after turn $n + 1$ is:

$$\varepsilon = \gamma \tilde{x}_{n+1}^2 + 2\alpha \tilde{x}_{n+1} \tilde{x}'_{n+1} + \beta \tilde{x}_{n+1}'^2 = \gamma x_{n+1}^2 + 2\alpha x_{n+1} (x'_{n+1} + \vartheta) + \beta (x'_{n+1} + \vartheta)^2 \quad (6.18)$$

The difference is given by

$$\Delta\varepsilon = 2\vartheta(\alpha x_{n+1} + \beta x'_{n+1}) + \beta\vartheta^2 \quad (6.19)$$

Given Floquet Transformations (see [37, p.37]), the emittance is retained, but projected onto a circle in a transformed phase space with the axis x and $\alpha x + \beta x'$. In this system, the contribution made to the emittance growth by the first term in eq. 6.19 is always orthogonal to the growth and therefore the first term can be neglected. The emittance growth can thus be given as:

$$\Delta\varepsilon = \beta\vartheta^2 = \beta \left(\frac{E_{tot} q E_r L}{(E_{tot}^2 - E_0^2)} \right)^2 \left[\frac{m}{turn} \right] \quad (6.20)$$

6.3 Method and Script

WARP is a Python package that includes Fortran² in order to facilitate the simulation of particle beams³. Scripts are written in Python, using WARP specific syntax. The script used to calculate the transverse fields and the emittance growths (`Fieldsolver_single.py`) is included in appendix C.2.

After loading the appropriate Python packages and setting options, the code defines a list of all the text files containing the particle positions, produced by `profile_analysis.R` (see sec. 5.4.1) as well as lists containing the parameters of those profiles, such as the magnetic fields, the cathode potentials and the beam currents. The script has to be executed individually for each profile, setting the profile to be executed through the variable `n` (Code Line: 104). It is not recommended to execute several simulations in one run. Upon starting a new run, the charge distribution is not correctly deleted by WARP. One should thus quit Python and restart it between simulations or run Python in a non-interactive mode.

Having defined author information and titles for WARP, it defines the species that is to be loaded; electrons (Code Line: 123). The code then defines the lattice which consists of a drift pipe with a transverse number of mesh cells defined by `nx` and `ny` and a longitudinal mesh size of 1 cell (Code Line: 138-146). The drift pipe is installed as a conductor to enforce the boundary conditions of $\vec{E}_r = 0$. Consecutively, beam parameters such as the current and the beam energy are set. With all preliminary settings completed, the script now calls the 2D WARP package and generates. The conductor is installed, the particles are loaded and the charge is deposited onto them by `loadrho()` (Code Line: 202). Particle coordinates are loaded into transverse coordinate vectors `xinit` and `yinit`. The particle positions are

²A programming language specifically suited for numerical computing.

³WARP is available at warp.lbl.gov. For a Willson-Cluster specific WARP, I have compiled a zip-file with installation instructions that can be found here [.Tevatron Electron Lens Test Stand \(TELTS\) wiki page](#)

scaled to the correct positions, in order to accommodate magnetic (de)compression. This scaling is done using $\sqrt{B_{coll}/B_{main}}$.

At this point seven types of plots are made: particle plot, charge density plot, electric potential plot, 3 transverse electric field plots and an electric field line plot along the x and y-axis. Furthermore the script writes the electric fields to a file which has the name `_fields.txt` appended (Code Line: 262). The transverse fields have thus been completely characterized and the script starts with the determination of the upper limit for the emittance growth.

In order to discuss the emittance growth under expected operating conditions of the *HEBL* at the LHC, the emittance growth has to be calculated with the inner radius of the electron beam set at 4σ and 6σ of the LHC beam. σ is the standard deviation of the Gaussian distribution of the proton beam in the LHC.

To calculate the σ of the LHC, we use the two relations (see [10, p. 66])

$$\varepsilon_{RMS} = \frac{\sigma_x^2}{\beta} \quad \varepsilon_N = \varepsilon_{RMS} \times \gamma\beta_c \quad (6.21)$$

where ε_N is the normalized emittance, ε_{RMS} is the *Root Mean Square (RMS)* emittance as defined by [38], γ and β_c are the relativistic parameters, σ_x is the standard deviation from the beam in the x direction and β is the beta-function of the beam at the point of insertion of the *HEBL*. We set β to 250 m [39]. The normalized emittance is $3.75 \mu m$ as specified in [7, p. 243]. σ is thus given by

$$\sigma_x = \sqrt{\varepsilon_{RMS}\beta} = \sqrt{\frac{\varepsilon_N\beta}{\gamma\beta_c}} = 4.69 \times 10^{-4} m \quad (6.22)$$

at $\beta = 250$ m, $\varepsilon_N = 3.75 \mu m$ and $\gamma = 4264.39$.

Given σ and the cathode radius, the script applies a Gaussian weighting with a standard deviation of σ to the measured electric field. This factors in the probability of a particle from the LHC proton beam interacting with a given point of the electric field produced by the *HEBL*. Considering that the transverse profile has been compressed by the magnetic field, $\sqrt{B_{gun}/B_{main}}$, the script now selects all points in the 80%ile of the cathode radius. It then takes the *RMS* value of all those points and uses them as the transverse field in eq. 6.20. This can be done, because we assume that the electric field in the center acts like random kicks on the core protons and thus only the *RMS* value of the electric field is significant.

At this stage the transverse field is given at the magnetically compressed cathode radius, $6.75 \times 10^{-3} \sqrt{B_{coll}/B_{main}}$ and stored in the variable `Er_center` (Code Line 326). The scaling for the radius goes as R^{-1} as shown in equation 6.3. The emittance is thus scaled further down to 4σ and 6σ and stored in the variables `Er_center_4` and `Er_center_6` (Code Line: 327-328).

Using eq. 6.20, we can thus calculate the emittance growth per turn. In order to obtain the emittance growth in units of s^{-1} , we divide $\Delta\varepsilon$ by the normalized emittance and the revolution time. This quantity is denoted *Emittance Growth Rate (EGR)* (Code Line: 337). The transverse electric field, emittance growth per turn and *EGR* are then saved in a table for the cathode radius, and a scaled radius of 4σ and 6σ . It is important to note that this estimate of the emittance growth is only a rough upper limit, because in reality multipole components will be present in the electric field that do not cause an emittance growth.

6.4 Results

Here the general shape of the electric field and the upper limit for the emittance growth are discussed.

6.4.1 Field Measurements

Fig. 6.1 shows the plots obtained from WARP for the transverse electric fields of the profile shown in fig. 5.12 at $V=500$ V and $B=1-4-1$ kG. Since the charge density in fig. 6.1a is symmetric with a slight

TABLE VI. Initial emittances (wire scan, synch-light, average), emittance growth rates (EGR) γ , and diffusion slopes D' .

Plane	Emittance [μm]				EGR [1/s]				Diffusion [$\mu\text{m/s}$]	
	ϵ_{ws}	$\delta\epsilon_{ws}$	ϵ_{sl}	$\delta\epsilon_{ws}$	ϵ	$\delta\epsilon$	γ	$\delta\gamma$	D'	$\delta D'$
B1 H	1.92	1.3×10^{-2}	2.15	9.6×10^{-3}	2.03	0.07	5.23×10^{-5}	1.50×10^{-5}	2.49×10^{-8}	7.4×10^{-9}
B1 V	1.36	2.0×10^{-3}	1.29	4.7×10^{-3}	1.33	0.02	1.70×10^{-5}	1.00×10^{-5}	5.27×10^{-9}	3.2×10^{-9}
B2 H	1.69	6.6×10^{-3}	2.43	1.3×10^{-2}	2.06	0.21	5.37×10^{-5}	1.90×10^{-5}	2.60×10^{-8}	9.6×10^{-9}
B2 V	1.73	4.6×10^{-2}	1.98	1.2×10^{-2}	1.85	0.09	1.10×10^{-5}	1.70×10^{-5}	4.79×10^{-9}	7.2×10^{-9}

Table 6.1: Current EGR at the LHC. Source: [39, p. 8]

EGR [$\times 10^{-5} \frac{1}{s}$]		Cathode Voltage [kV]									
Radius [mm]	B_{max} [kG]	500	1000	2000	3000	4000	5000	6000	7000	8000	
3.325	4	0.028	0.076	0.344	30.2 (3125 V)	26.6	25.6	24.5 (6250 V)	-	691	
	3.2	0.008	0.029	9.05	15.1	22.9	276	617	978	1050	
	2.4	0.003	1.42	5.85	70.3	192	318	-	-	-	
	2.4	0.414	1.40	44.7	-	-	-	-	-	-	
6σ	4	0.039	0.109	0.495	43.4 (3125 V)	38.3	36.8	35.2 (6250 V)	-	994	
	3.2	0.011	0.041	13.0	21.7	33.0	397	887	1410	1510	
	2.4	0.005	2.04	8.41	101	276	-	-	-	-	
	2.4	0.595	2.02	64.4	-	-	-	-	-	-	
4σ	4	0.089	0.246	1.11	97.8 (3125 V)	86.2	82.8	79.3 (6250 V)	-	2240	
	3.2	0.025	0.093	29.3	48.7	74.3	893	2000	3170	3390	
	2.4	0.010	4.59	18.9	227	621	-	-	-	-	
	2.4	1.34	4.54	144	-	-	-	-	-	-	

Table 6.2: The EGR due to the transverse fields caused by the HEB at the given inner beam radius, magnetic field strength and cathode potential. Green cells give acceptable EGR.

elongation in the y-direction, the resulting electric potential and electric fields are symmetric around the z-axis. The electric field in the center is $\approx 1 \text{ kV m}^{-1}$, as shown in fig. 6.1b. Comparing this plot to fig. 2.5a, shows that the measured and theoretical electric fields coincide very well. This furthermore indicates that our assumptions in the theoretical deduction in section 6.1 are correct and thus the charge density is near uniform.

In order to contrast these results at a low cathode potential with higher cathode potentials, the plots for $V=8 \text{ kV}$ and $B=1\text{-}4\text{-}1 \text{ kG}$ are shown in fig. 6.2. The charge distribution in fig. 6.2a is clearly asymmetric. The charge is concentrated in the lower right corner, causing the electric field in the center to be of the order of $\approx 300 \text{ kV m}^{-1}$. A small area of significantly lower electric field, $\leq 100 \text{ kV m}^{-1}$, is apparent in the lower right corner in fig. 6.2f. One would thus expect the proton beam to be much more perturbed at a cathode potential of -8 kV instead of -500 V .

6.4.2 Upper Limit for Emittance growth

As a reference for the EGR values published on 19 February 2013 in Physical Review Special Topics Accelerators and Beams are used [39, p. 8]. They are presented in tab. 6.1. One should note that the nominal emittance of the LHC of $3.75 \mu\text{m}$ has not yet been reached.

Table 6.2 presents the EGR in units of 10^{-5} s^{-1} . The quantity of $1 \times 10^{-5} \text{ s}^{-1}$ was chosen as an upper limit below which the EGR is acceptable, on the basis that EGR values in table 6.1 are just above that threshold.

When one compares table 6.2 with fig. 5.10, we can see that the EGR tends to rise above $1 \times 10^{-5} \text{ s}^{-1}$ only when the charge distribution deviates strongly from an azimuthally uniform distribution. Values then tend to rise significantly.

Given that the scaling law $B \propto \sqrt{V}$ in section 5.4.3 holds to a certain degree, we are interested in profiles with low cathode potential and high magnetic field. Because the EGR values are only upper boundaries, due to the presence of multipole components, no error calculation was done.

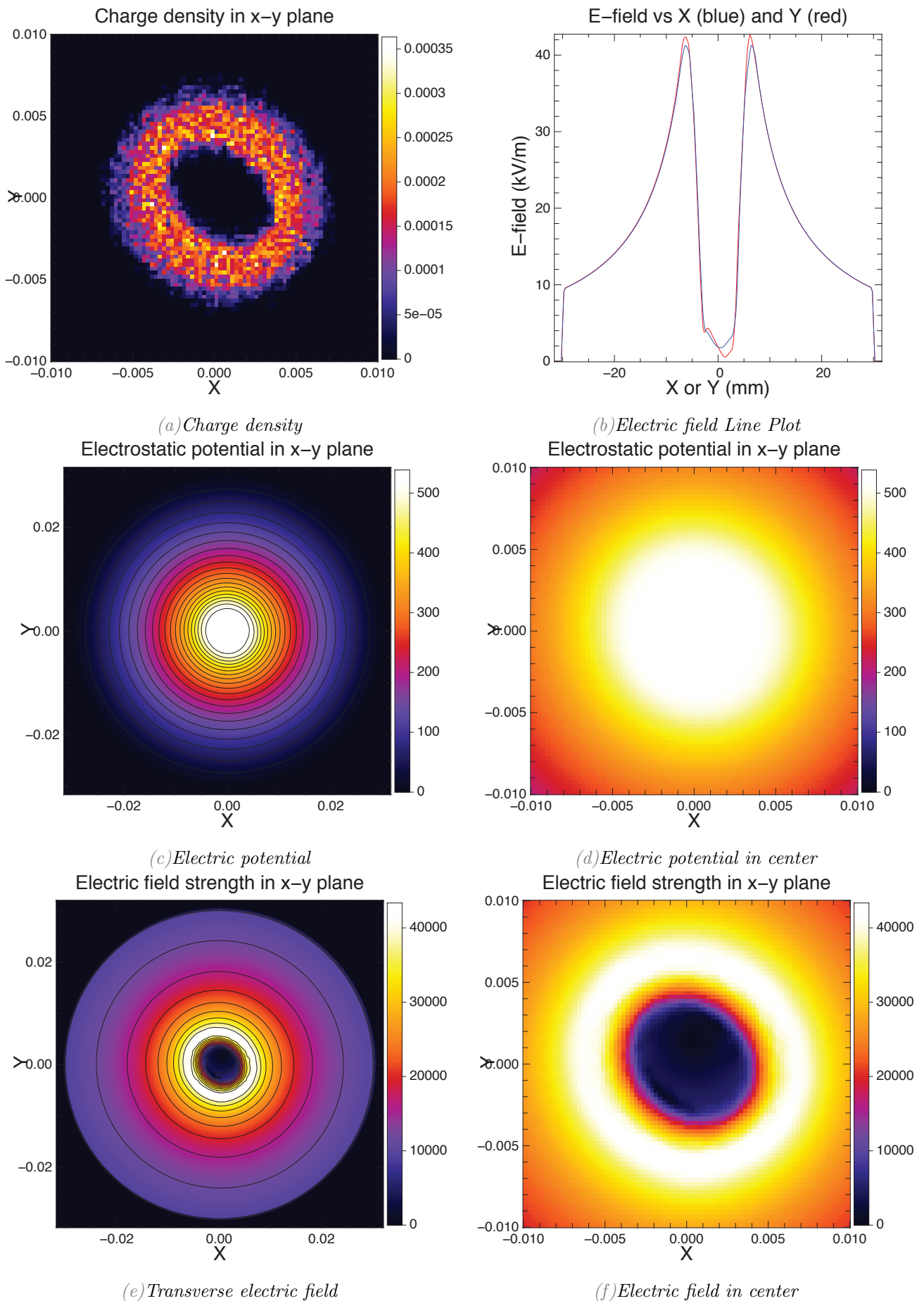
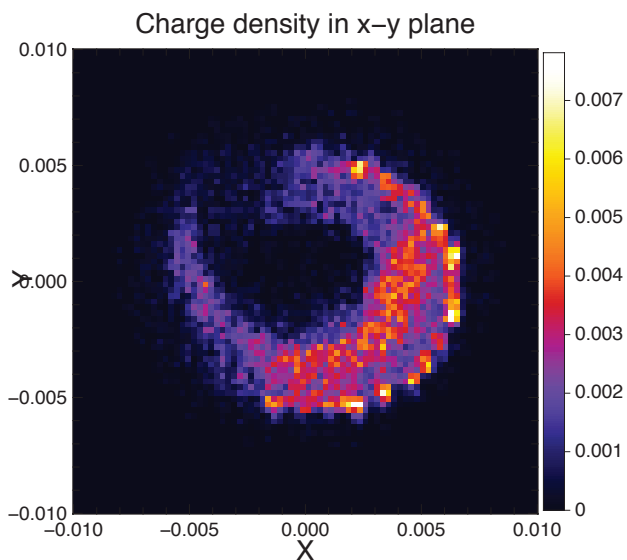
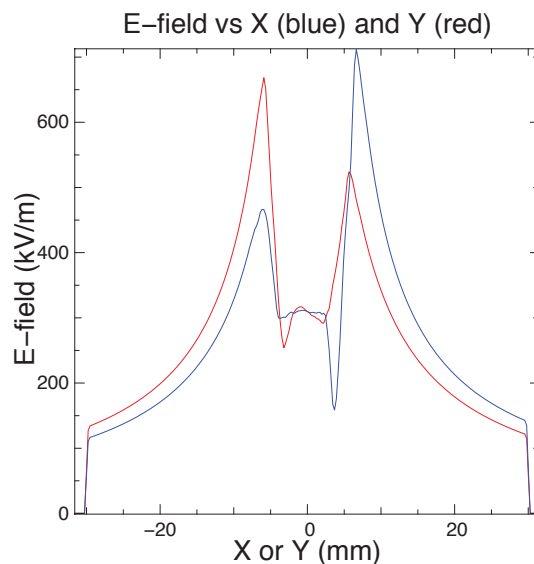


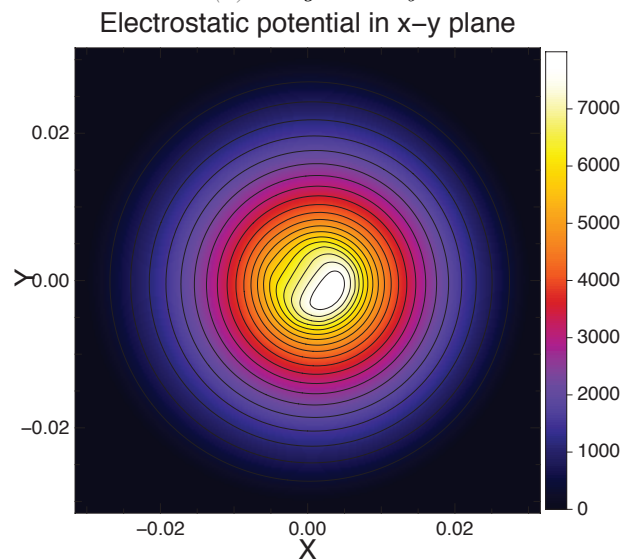
Figure 6.1: Charge density, electric potential and electric field at $B=1-4-1kG$ and $V=500V$.



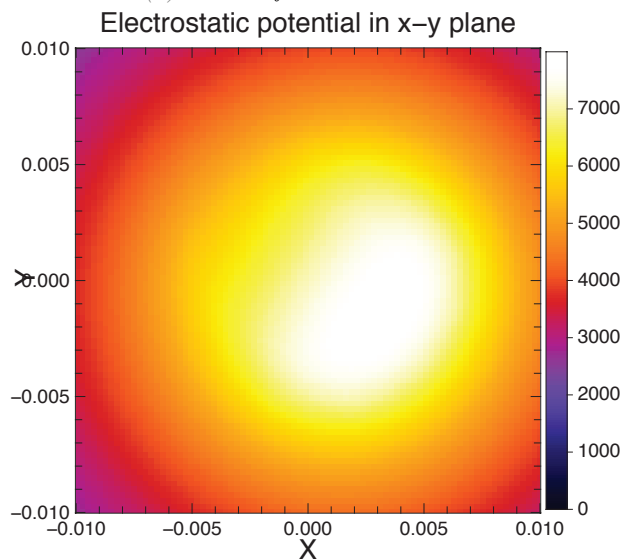
(a) Charge density



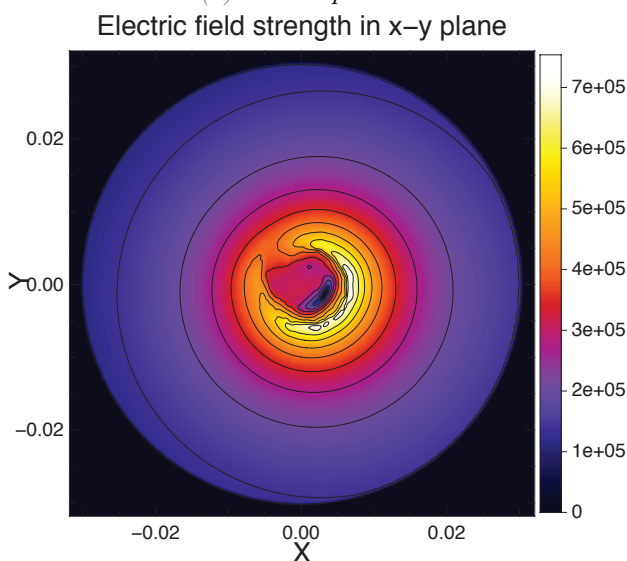
(b) Electric field in x direction



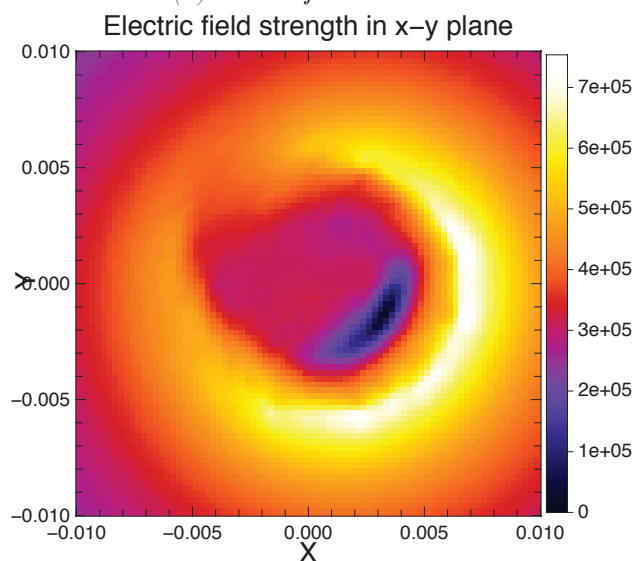
(c) Electric potential



(d) Electric field Line Plot



(e) Electric field in y direction



(f) Transverse electric field

Figure 6.2: Charge density, electric potential and electric field at $B=4$ kG and $V=8$ kV.

Chapter 7

Numerical Simulations of Electron Beam Dynamics

Having discussed all experimental measurements, the first attempt of 3D numerical simulations of the *Hollow Electron Beam Lens (HEBL)* through a *Particle-In-Cell (PIC)* code called WARP¹ will be discussed. This serves as a basis for future 3D beam simulations in order to implement a non-linear map for core and halo tracking studies in SixTrack or Lifetrack. Additionally such simulations are promising for calculating the 3D magnetic and electric fields for the electron lens and for examining the effect of the bends in *Tevatron Electron Lens 2 (TEL2)* on the beam core. During this thesis, WARP was installed on the *Accelerator Simulations Cluster (TEV)*² and the first full simulations were completed.

WARP was developed at Lawrence Berkeley National Laboratory in California, USA, by Dave Grote³, Jean-Luc Vay⁴ and Alex Friedman⁵. WARP is a *PIC* code that was designed in order to simulate high current particle beams. It runs in the highly interactive Python interpreter, using precompiled packages. The interpreter allows one to control the simulations interactively.

7.1 Introduction to WARP

WARP was installed on the *TEV* at *Fermi National Accelerator Lab (Fermilab)*. Version-compatibility issues with Python installed on the cluster prevented the installation of WARP. Therefore Python was installed in the home directory with the necessary packages. This new installation was used to compile WARP. Installation instructions and files can be found on the Electron Lens Wiki⁶. Future users of WARP on the *TEV* may choose to link to my local installation of WARP instead of reinstalling. For this the \$PATHs must be adapted as explained in the instructions on the Wiki.

During this thesis, WARP codes were developed on local machines using a low number of iterations. Normal laptops were mostly sufficient for this. Full simulations were run on the *TEV* at Fermilab. The *TEV* cluster has 32 AMD nodes and 12 Intel nodes. Each AMD node has 32 processors and 64 GB of RAM. The WARP simulations are highly memory intensive. In order to run a full simulation, 12 nodes were used with 2 processes per node. This allowed us to use 24 parallel processors and 768 GB of memory. At lower amounts of memory, the code crashed due to heavy disk swapping. This is an issue that will have to be investigated but could not be done in the scope of this thesis.

As mentioned in chapter 6, WARP contains several basic models, including a transverse slice model (WARPxy) and an axis symmetric model (WARPz). Models exist in 2D and 3D. Additionally, three coordinate frames are available. The lab frame in which all transverse positions are given. In this frame,

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³DPGrote@lbl.gov

⁴JLVay@lbl.gov

⁵AFriedman@lbl.gov

⁶<https://cdcv.s.fnal.gov/redmine/documents/619>

the user sets a 0-point and the axial-coordinate increases continually along the axial position. The lab frame follows bends when they are used. In closed accelerators, the lab frame axial coordinate will increase lap by lap. The beam frame and grid frame move along with the beam. The location of the beam frame is given by `zbeam`.

PIC codes are well known from plasma physics and are used to simulate neutral and non-neutral plasmas. In a *PIC* code, macromolecules are assigned to cells on a discrete mesh and advanced using the Lorentz equation of motion. Often such codes are also called "Nearest-Grid-Point Particle Mesh models". From the distribution of the macromolecules on the mesh, the charge density is calculated, using a linear interpolation of the particles on the mesh. By solving Poisson's equation, the electrostatic potential and ultimately the electric field are calculated. These calculations are done for each time step, after which the velocities and positions are updated. As explained in [40, p. 28], while positions are usually updated during each full time step, the velocities of the particles are updated every half time step. This can cause errors in diagnostics. Whenever a diagnostic is made in WARP, the isochronous leap frog scheme is used, which additionally updates the velocity at the full time step. Else, the usual leap-frog system is used, for which velocities are only updated at half time steps. For a detailed explanation of the time-step layout, refer to [35, Chap. 3].

WARP combines the power of *PIC* codes with the easy implementation of accelerator lattices. An extensive set of lattice elements are precompiled and included in WARP. These include dipole, quadrupole and sextupole magnets, accelerator cavities and solenoids. Additional elements can easily be implemented through surfaces of revolution. Furthermore WARP includes several diagnostics packages and allows one to either use a set of precompiled plotting methods or develop individual plotting methods. These can then be executed at predefined time points during the simulation and interactively after the simulation.

7.2 General Structure of the WARP Script

The code used for the WARP simulations is listed in appendix C.3. This section discusses the general layout of a WARP code. We have used two injection methods throughout the simulations. First a direct injection from a replica of the *1 inch Hollow Electron Gun (HG1b)* and second an injection of the measured profiles from the test bench at the z-coordinate of the cathode. The injection mechanisms will be discussed more closely in sec. 7.3 and 7.4.

The WARP code initially calls the WARP package. The code is separated into a few sections: **file loading**, **options**, **headers**, **variables** and the actual scripting, which is divided into further sections. The **file loading** sets the profile that is to be injected or simulated. In **options** (Code Line: 115) the injection type is defined in the variable `machine_injtype` and the cathode emittance method is set in `machine_emitttype`. For gun injection, the cathode emits according to the Child-Langmuir law. For profile injection, it emits at a constant current. WARP requires the user to define a variable called `runid`, which sets the name of the current run. Additionally one can set some variables that are used as descriptors in the plots and the variable `runmaker` which defines the author of the run. In the section **variables** (Code Line: 144), the parameters of all lattice elements and some beam parameters are defined, in order to prevent the user from having to deal with the more complicated WARP codes in the section **Script** (Code Line: 267).

Having defined the `runid` and the `runmaker`, the `setup` (Code Line: 271) command must be called in order to initialize the graphic output file. The output is saved as *Computer Graphics Metafile (CGM)*. A software called `gist`⁷ is used to view and manipulate the plots from the *CGM* files. If profile injection is chosen, the selected measured profile from the test bench⁸ is loaded and saved in an array with the first column being the x-coordinates and the second column the y-coordinates. The number of particles that were loaded is printed to the standard output.

⁷Available at warp.lbl.gov

⁸Profile measurements in the test bench are explained in section 5.4

At this stage the code defines the particle species, in our case electrons are designated `elec` (Code Line: 303). It also defines the number of particles per macro-particles as `sw`. It then defines beam parameters such as the beam current, the kinetic energy and the time step used in the simulation. The time step is significant, because it needs to be small enough in order to consider all physical effects, such as the plasma frequency ω_p ⁹ and the cyclotron frequency ω_c ¹⁰. For the *HEBL* simulations, the cyclotron frequency exceeds the plasma frequency by a few orders of magnitude. In the case of a 500 V beam with a magnetic configuration of 1-4-1 kG, $\omega_c=7.0 \times 10^{11} \text{ s}^{-1}$ and $\omega_p=4.6 \times 10^8 \text{ s}^{-1}$. The time step is thus determined by the cyclotron frequency. In order to be certain that we use a small enough time step, it was chosen that

$$\frac{\omega_c \Delta t}{2\pi} = 0.25 \quad \Rightarrow \quad \Delta t = \frac{\pi}{2\omega_c} \approx 1 \times 10^{-12} \quad (7.1)$$

The electron velocity is set to 0 by the code and deduced from the electron energy through the command `derivqty()` (Code Line: 315). Next the code sets whether calculations should be done in a relativistic manner. The thermal velocity of the particles is set to 0. This should be changed in future versions of this code. Having set all the beam parameters, the number of steps necessary to complete the simulation are calculated via:

$$n_{steps} = 1.1 \times \frac{L}{v_e \Delta t} \quad (7.2)$$

Here L is the distance the beam travels from gun to collector, v_e is the electron velocity and Δt is the time step in eq. 7.1. The factor of 1.1 is used in order to increase the number of steps by 10% to accommodate for the fact that particles move slower than v_e while they are in the gun. Next the code defines the size of the electron beam and where it is to be injected (323-357). Amongst others it defines what type of injection is to be used.

Having set up the particle injection, the code now defines the solenoids. It is important to note that these solenoids do not manifest themselves as conductors in the code, but only provide the necessary magnetic fields. It is not necessary to include the solenoids as conductors, since they are positioned outside the drift tube and thus do not affect the electric field inside of the beam tube and are not involved in scraping. Next the script defines the lab frame mesh. When running the code in parallel mode, it is important that the number of grid cells in each direction exceeds the number of processors used to run the script.

In WARP it is possible to set up diagnostic windows, limiting the number of particles that will be involved in the diagnostics. For example it is possible to set up a window so that only the particles in the first 2 time steps after the cathode are plotted. For further information on diagnostic windows please refer to [35, Chap. 7]. Once diagnostic windows are set, it is important to define how often simulation data should be saved (`nhist`) and plots are made (`itplps`, `itplfreq` and `itplalways`) (Code Lines: 417-433). One can then choose a couple of precompiled plots. These plots are generally less useful and it is recommended to create ones own plots. For more information on plotting refer to [35, Chap. 7].

Having set up the diagnostics and the mesh, the field solver needs to be chosen. First of all the conductor boundary walls are set to absorb particles. Several field solvers are available with WARP. For more information on the individual field solvers, refer to [35, p. 61]. The field solver used is set by the variable `top.fstype` (Code Line: 442) which is set to 7, 3D multi-grid solver. The multi-grid solver is an extension of the Successive Over-Relaxation Field Solver (SOR). It uses the finite difference form of Poisson's equation in combination with a relaxation parameter that is given by:

$$\varphi_{ijk} = \omega \Delta^2 \left(\frac{\rho_{ijk}}{\epsilon_0} + \frac{\varphi_{i+1jk} + \varphi_{i-1jk}}{\Delta x^2} + \frac{\varphi_{ij+1k} + \varphi_{ij-1k}}{\Delta y^2} + \frac{\varphi_{ijk+1} + \varphi_{ijk-1}}{\Delta z^2} \right) + (1 - \omega) \varphi_{ijk} \quad (7.3)$$

⁹ $\omega_p = \frac{nq^2}{\epsilon_0 m}$

¹⁰ $\omega_c = \frac{qB}{\gamma m}$

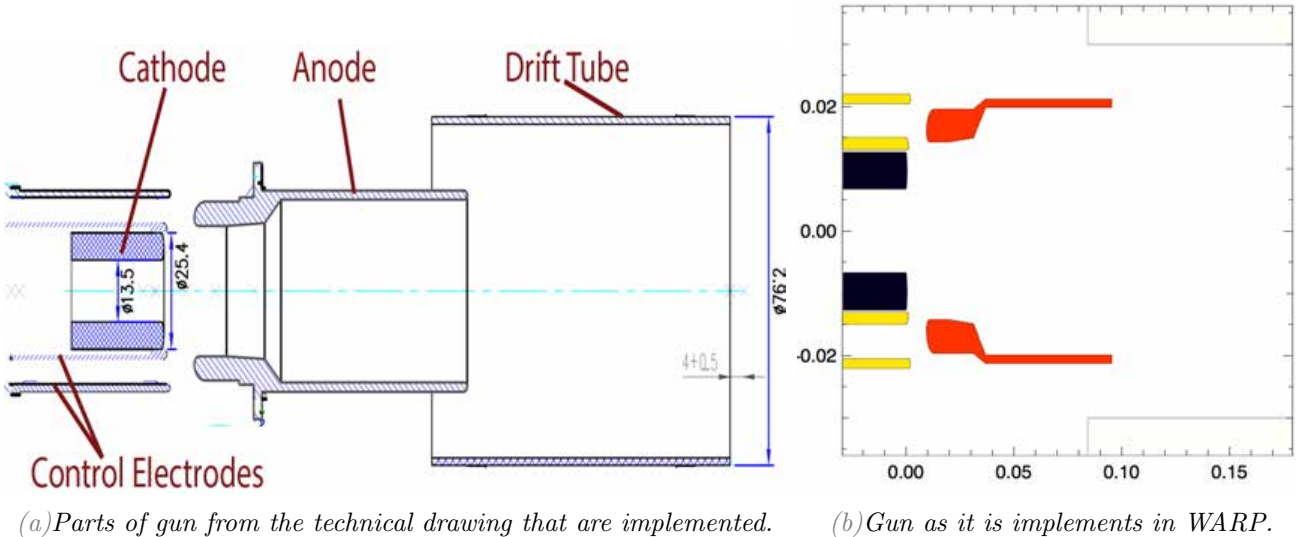


Figure 7.1: Technical drawing and plot of the gun that was implemented into WARP.

here φ is the potential of the respective cell designated by ijk , ω is the relaxation parameter, ρ is the charge density and $\frac{1}{\Delta^2} = \frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}$ where $\Delta(x, y, z)$ are the respective grid cell sizes [35, p. 69]. At this point the code is ready to initialize. A package is initialized using the command `generate` and a time step is made using the command `step`. The 3D model is initialized (allocating storage, load particles, etc...) using `package("w3d");generate()` (Code Line: 464). It is time to implement all the conductors. Both injection methods require the implementation of the drift tube which has a radius of 3 cm. On top of that, the gun injection requires the implementation of all necessary conductors in the gun. The drift tube can be implemented using a precompiled version of a solenoid `ZCylinderOut`, which defines the outside of a cylinder as a conductor. All conductors that are defined must be installed using `installconductors`. Lastly self made plots are defined for the diagnostics. Plots that are to be repeated at the time steps given by `itplalways` and `itplseldom` must be defined as a function and installed using `installplalways` and `installplseldom` (Code Line: 567).

Having completed all the preparatory work, the simulation can now be executed. With the command `step` one can define how many time steps are to be made. By writing `steps(nsteps)` (Code Line: 570) the full simulation is done. In order to test new settings, it might be useful to just run a few iteration steps. Lastly a dump of the simulation can be made. This has not yet been implemented, since when running the code on 32 processors in parallel mode, 32 dump files are created, which is counterproductive.

7.3 Gun Injection

Gun injection refers to the injection of particles directly of the cathode of the gun. It is thus necessary to implement the gun in the code according to the specifications given in the technical drawings of the gun, fig. 3.7. Fig. 7.1a shows the parts that were implemented and fig. 7.1b shows a plot of the conductors in the WARP code. The most important dimensions of these conductors are listed in appendix D. All 4 conductors were installed using the function `ZSrfrv` which creates surfaces of revolution. The function takes 3 vectors containing the radial coordinates, the axial coordinates and the radii of curvature for the sections between the specified points. The surface spanned by the points in the vectors is then spun around the lab frame beam axis to produce the conductors in 3D space. The function immediately sets the voltage of the conductors. The conductors must be passed on as a list to the command `installconductor` in order to be implemented.

On top of installing the gun, the injection of the particles must be specified. This is done earlier in the code in the section labelled injection. First the cathode emission is set to Child-Langmuir law. This is set in the variable `top.inject`. Additionally the surface from which the particles are injected, their

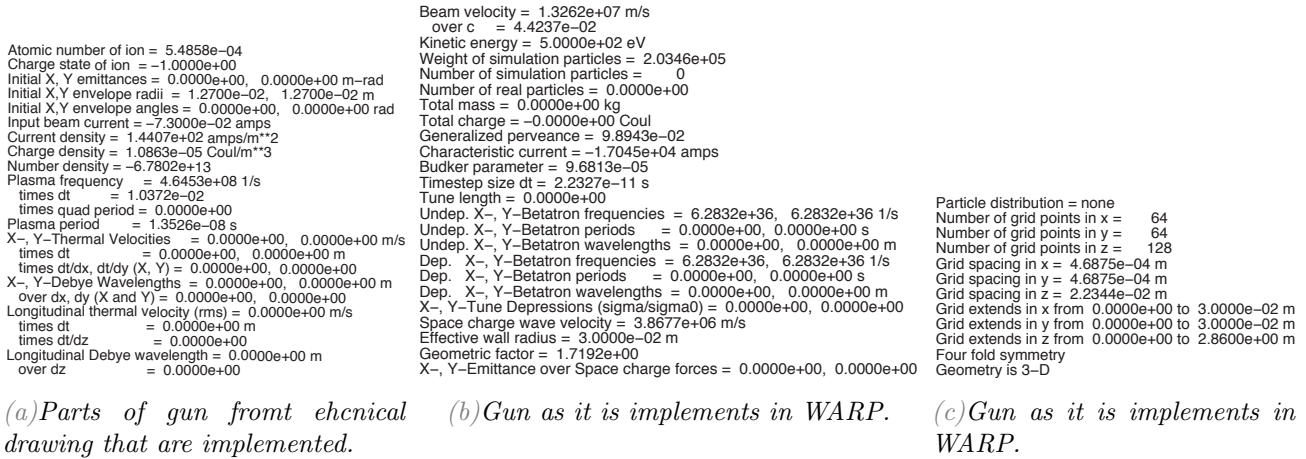


Figure 7.2: Technical drawing and plot of the gun that was implemented into WARP.

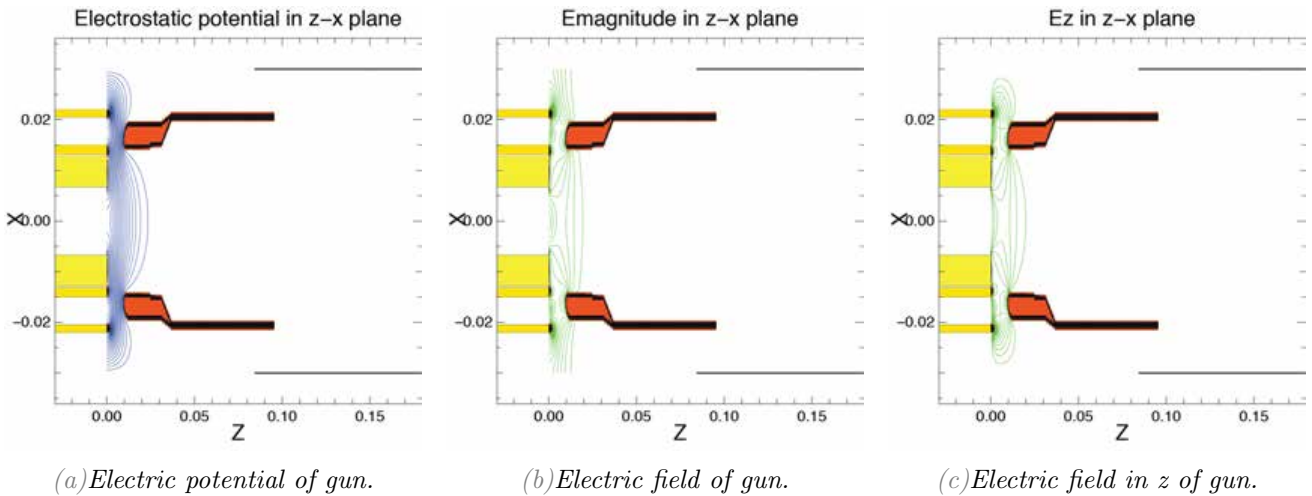


Figure 7.3: Plot of the electrostatic potential and electric field of the gun implemented in WARP.

angles and their velocities are defined. Lastly the voltage of the injector source is set with `vinject`. An additional variable called `elec.npinject` defines how many macro particles are injected during each time step. In the case of Child-Langmuir law injection, this value may be set to an approximate value, since the law will change the number of particles injected as necessary.

Fig. 7.2 shows the settings used for a normal run on the *TEV*. The generalized perveance in fig. 7.2b serves as a reference to our measured gun perveance. In section 5.3.5 we measured a generalized perveance of $7.93(7) \times 10^{-3}$. The WARP simulation gives us a generalized perveance of 9.89×10^{-2} . Our measured generalized perveance is $\approx 80\%$ of our simulated generalized perveance.

The electrostatic potential and electric field of the gun that was implemented in WARP is shown in fig. 7.3. It is important to notice that one needs to increase `w3d.nz` to a very high number in order to present the field correctly (2048). It is thus recommended to reduce the system length `machin_syslen` and only simulate the gun for these plots. The plots in fig. 7.3 were made with `w3d.nx=128`, `w3d.ny=128`, `w3d.nz=512`.

Lastly fig. 7.4 shows the full trajectory of the beam. Three main features can be recognized. First, we see the clear magnetic compression of the beam as it enters the main solenoid that has a 4-fold magnetic field, meaning a 2-fold compression. Additionally we see that the beam is nicely hollow, portrayed through the two yellow bars. And lastly we see some suspected micro-bunching as the beam reaches the end of the beam tube.

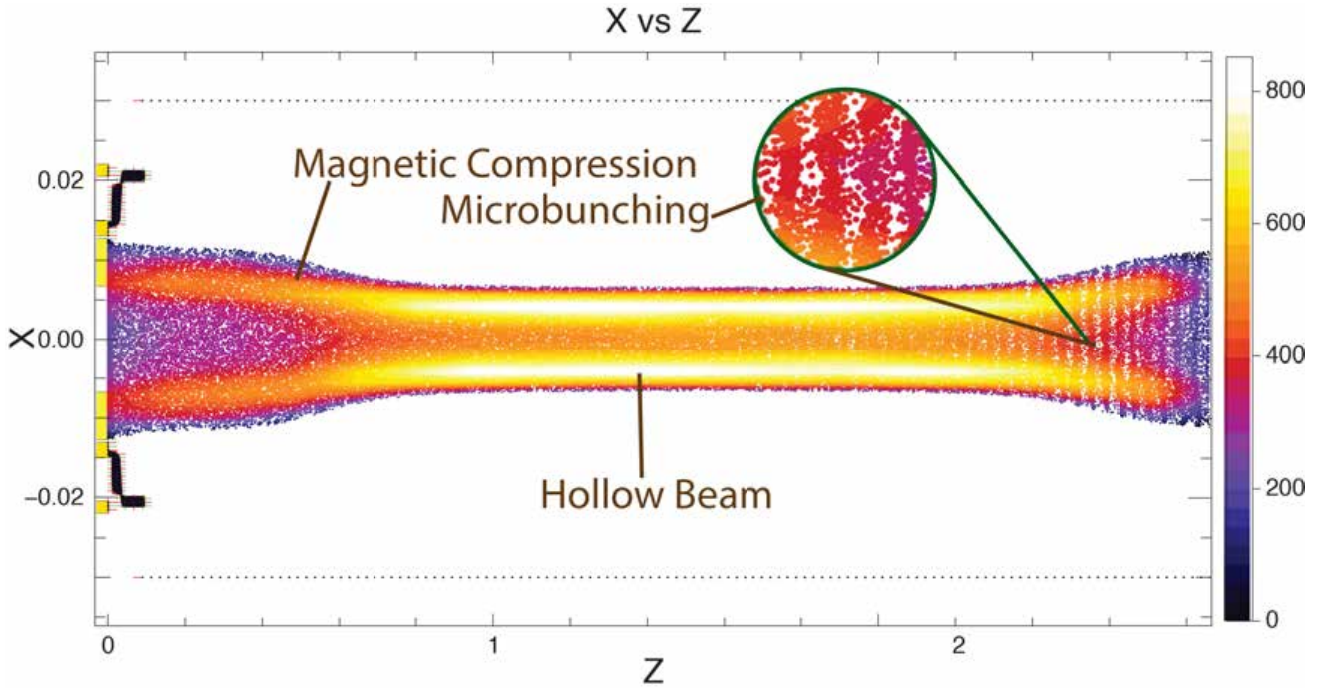


Figure 7.4: Full electron beam as implemented in WARP due to gun injection. Three important features are visible: the magnetic compression of the beam before and after the main solenoid, the hollow center of the beam and micro bunching towards the end of the beam.

7.4 Profile Injection

Profile injection refers to the injection of particle distributions measured in the test stand. The assumption is that the measured profile at high magnetic field and low cathode potential has not yet undergone significant space charge evolution (see sec. 5.4.2) and is thus very similar to profiles that are emitted directly from the gun. The measured profile that is used for profile injection is that at a magnetic field of $B=1\text{-}4\text{-}1$ kG and a cathode potential of -500 V. This measured profile distribution is shown in fig. 7.5.

The injection of this profile is a user defined injection method in which a vector `fns` passes the path of the profile to the code. The code then imports the particle positions through the command `fromfile` into a vector `posi`. The x and y coordinates are read into one long vector in sequence, requiring one to split the single vector into an array with a column of x coordinates and a column of y coordinates. This is done using `reshape`. During profile injection, a test is conducted to verify that the right particles are injected, which is given through the variable `w3d.inj_js`, and the number of particles to be injected each time step is defined. Next the coordinates are passed on to `w3d.xt`, `w3d.yt` and `w3d.zt` which define the particle positions in the 3D lab frame. Additionally the initial

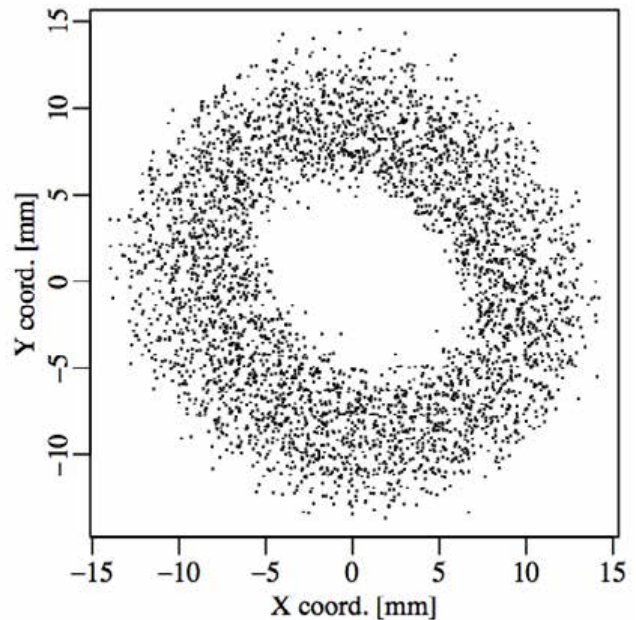


Figure 7.5: Particle distribution of measured profile at $B=1\text{-}4\text{-}1$ kG and $V=500$ V

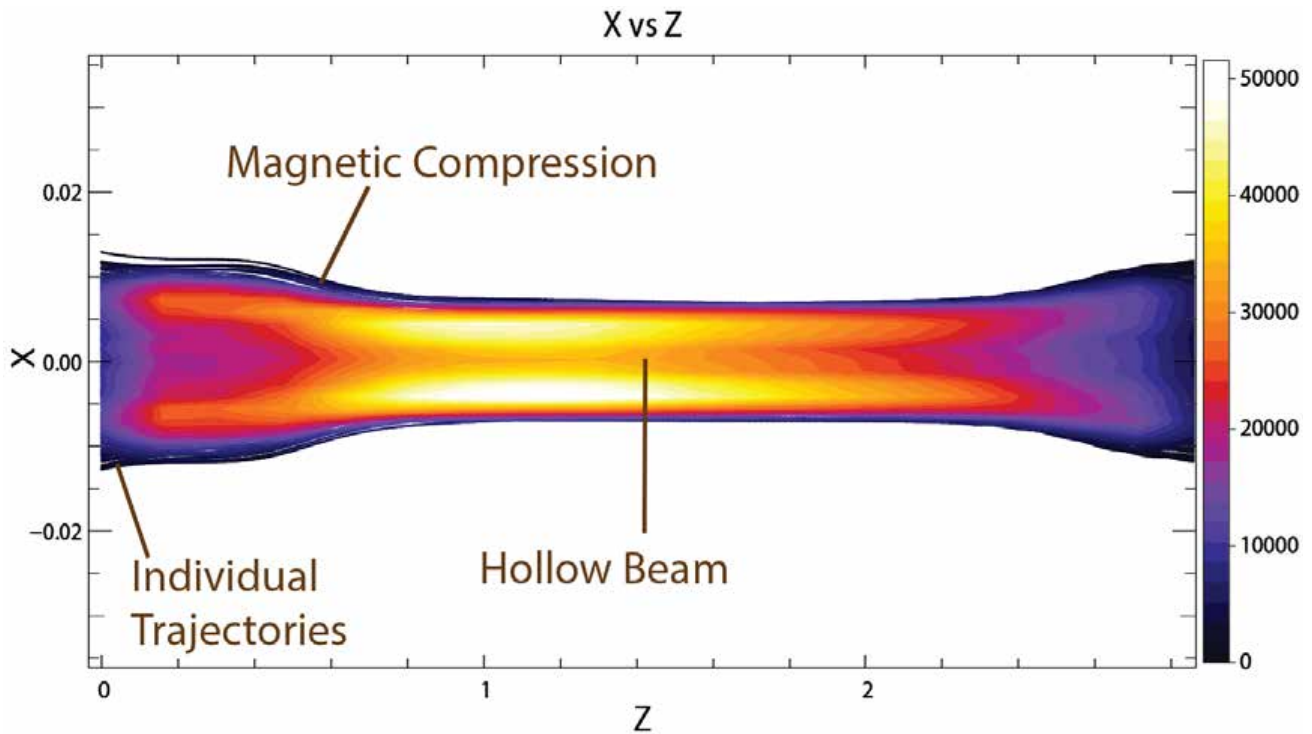


Figure 7.6: Full electron beam as implemented in WARP due to profile injection. The electron density is too high using this injection.

velocities are set to 0 for the transverse velocities and to the beam velocity for the axial velocity. To finalize injection, the source has to be installed using `installuserparticlesinjection`.

The injection method is not finalized at this stage, but initial runs have been conducted. The main issue with this injection type is that it injects too many particles. This is seen when comparing figure 7.6 with fig. 7.4, which has a ≈ 60 times lower particle count. The high particle count makes it nearly impossible to process these profiles. It is assumed that this is a consequence of the whole loaded profile being injected at each time step. Further development on this injection was not done, since gun injection was considered to be more important.

7.5 Directions for further studies on 3D WARP simulations

WARP has successfully been installed on *TEV* and the first few runs have been completed. Nonetheless, the simulations are far from complete and many things need to be improved. This section outlines some of the steps that need to be implemented in the current code:

- First of all the code needs to be optimized in order to use less computational resources.
- Additional diagnostics and plotting tools should be implemented. For example it would be interesting to implement a few diagnostic windows that allow us to compare the transverse profiles from the simulations with those from the measurements in *Tevatron Electron Lens Test Stand (TELTS)*.
- As discussed previously, the profile injection needs to be optimized in order to reduce the number of particles that are injected. Additionally to test whether the perveance and the beam current resemble measured values needs to be performed.
- The dumping of the simulations needs to be implemented, so that runs, which sometimes take a whole day, do not need to be repeated.

- Extraction of simulation data is possible through the package `ENV` and should be implemented.

Furthermore, the *TEL2* lattice or an optimal electron lens lattice for the *Large Hadron Collider (LHC)* should be implemented. Using this deductions can be made on the effect of the electron lens bends on the *Hollow Electron Beam (HEB)*. Furthermore it is possible to implement multiple species and sources in WARP, allowing the implementation of the accelerator proton beam and thus the direct simulation in WARP of the effect of the *HEB* on the proton beam in one single pass.

Chapter 8

Conclusion

The studies discussed in this thesis were completed in the context of supporting a conceptual design report on a *Hollow Electron Beam Lens (HEBL)* for proton beams at the *Large Hadron Collider (LHC)* at *European Organization for Nuclear Research (CERN)*. Experiments conducted at the Tevatron over recent years have provided a solid basis for this beam scraping and halo control technique. Nonetheless, several further issues need to be addressed in the extrapolation of the *HEBL* from the Tevatron to the *LHC*. In this thesis, we have discussed measurements and considerations that pertain to the design and feasibility of *Hollow Electron Gun (HEG)* hardware parameters, and to the effects of the *Hollow Electron Beam (HEB)* on the dynamics of the circulating proton beam.

For halo scraping, the inner radius of the *HEB* is envisioned to be placed between $\approx 3\sigma$ and 6σ of the *LHC* proton beam size. For the purpose of this thesis, σ was set to 4.7×10^{-4} m. For stability reasons, the field in the guiding solenoids should be as large as possible. Considering previous experience and technical feasibilities, we considered a magnetic configuration of $B=0.43\text{-}5\text{-}0.43$ T ($B_{gun} - B_{main} - B_{coll}$). This implies a magnetic compression of a factor 3.4, which sets the cathode inner radius to 4σ and the outer radius to $\approx 7.5\sigma$.

A *1 inch Hollow Electron Gun (HG1b)* based on a tungsten dispenser cathode was developed and tested. The perveance of this gun was determined to be $5.3(1) \times 10^{-6}$ perv, which is within 15% of numerical SAM simulations. This perveance implies a peak yield of over 5 A at 10 kV. Similar beam currents as were produced by the *0.6 inch Hollow Electron Gun (HG06)* of 1.2 A, were measured using the *HG1b* at cathode voltages of 3-4 kV. Based upon Tevatron experiments and numerical simulations for the *LHC*, this yield should be sufficient to smoothly scrape 7-TeV protons.

During *HEG* characterization studies at the *Tevatron Electron Lens Test Stand (TELTS)*, it was found that this larger *HG1b* required a compression in order to obtain a transmission of 100% in the beam tube. Previous cathodes did not require such compressions. The best achievable configuration in the *TELTS* was found to be $B_{gun} = B_{coll} = 0.25B_{main}$. This configuration results in a 2-fold compression of the *HEB*. Because the actual *HEBL* will have a larger inner aperture, we do not expect transmission degradation to be an issue. By examining the dependence of the cathode yield on filament current, it was found that the optimal filament current is about 8.5 A.

The transverse *HEB* profiles were measured to estimate the symmetry of the resulting electric fields and possible adverse effects on the proton beam core. Extensive profile measurements as a function of beam current and solenoidal magnetic field were completed. These allowed us to study the evolution of the magnetically confined *HEB* due to space charge. The profiles showed a scaling proportional to the accelerating voltage V_a and inversely proportional to the square of the axial magnetic field B , which is in qualitative agreement with the theory of the diocotron instability. Consequently, profiles measured at very low cathode voltages and at the highest possible magnetic fields in the conventional test stand solenoids will be similar to the profiles in the actual *HEBL* for the *LHC* using the parameters suggested above.

Effects on the beam dynamics were studied by calculating the transverse electric fields generated by the measured profiles, and by estimating the resulting emittance growth. For typical operational

parameters, the effect was much smaller than the natural emittance growth in the LHC. At higher *HEB* currents or very low magnetic fields, the *HEB* loses its azimuthal symmetry and electric fields in the center can no longer be considered negligible. This, together with the Tevatron experiments, provides a strong indication that it is possible to operate the *HEBL* without negatively affecting the *LHC* proton core. Nonetheless, this aspect will have to be further investigated by implementing the fields generated by the *HEB* in a numerical tracking code.

In view of a realistic representation of the *HEBL* in tracking simulations, the first full 3D calculation of the magnetized electron beam dynamics was completed using the WARP *Particle-In-Cell (PIC)* code. The *HEG* was implemented in WARP together with the geometry of the *TELTS*. Three main effects could be verified: the magnetic compression of the beam, the evolution of the hollow profile, and some longitudinal micro-bunching towards the end of the drift tube.

This thesis work advanced the understanding of the physics and technology of *Hollow Electron Beam Collimation (HEBC)* and provided the basis for further studies on the implementation of this technique at *CERN*.

Works Cited

- [1] X. Zhang, V. Shiltsev, A. Valishev, G. Stancari, G. Kuznetsov, G. Saewert, and V. Kamerzhiev, “Operations of the Tevatron Electron Lenses,” *arXiv preprint arXiv:1207.6413*, 2012.
- [2] S. Redaelli US-LARP - CM20 - LHC Collimation Project Status, April 2013.
- [3] V. Previtali, “Numerical simulations of a proposed hollow electron beam collimator for the LHC upgrade at CERN,” Technical Memo FERMILAB-TM-2560-APC, Fermilab, July 2013.
- [4] E. Rutherford, “Stability of atoms,” *Royal Society of London*, pp. 389–394, June 1931.
- [5] J. Cockcroft and E. Walton, “Experiments with high velocity positive ions,” *Proceedings of the Royal Society of London. Series A*, vol. 129, no. 811, pp. 477–489, 1930.
- [6] A. M. Sessler and E. J. Wilson, *Engines of discovery: A Century of particle accelerators*, vol. 17. World Scientific Hackensack, NJ, 2007.
- [7] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, “The LHC Design Report, Vol. 1,” *CERN, Geneva*, 2004.
- [8] G. Stancari, “New methods of particle collimation in colliders,” No. FERMILAB-CONF-11-506-AD-APC, (Providence, Rhode Island), American Physical Society, Brown University, 10 2011.
- [9] N. Mokhov, J. Annala, R. Carrigan, M. Church, A. Drozhdin, T. Johnson, R. Reilly, V. Shiltsev, G. Stancari, D. Still, *et al.*, “Tevatron beam halo collimation system: design, operational experience and new methods,” *Journal of Instrumentation*, vol. 6, no. 08, p. T08005, 2011.
- [10] A. Chao and M. Tigner, *Handbook of accelerator physics and engineering*. World scientific, 1999.
- [11] G. Stancari, A. Valishev, G. Annala, G. Kuznetsov, V. Shiltsev, D. Still, and L. Vorobiev, “Collimation with hollow electron beams,” *Physical Review Letters*, vol. 107, no. 8, p. 084802, 2011.
- [12] J. Jeanneret, “Optics of a two-stage collimation system,” *Physical Review Special Topics-Accelerators and Beams*, vol. 1, no. 8, p. 081001, 1998.
- [13] N. V. Mokhov, “Beam collimation at hadron colliders,” in *AIP Conference Proceedings*, vol. 693, p. 14, 2003.
- [14] J. Jeanneret, D. Leroy, L. Oberli, and R. Trenkler, “Quench Levels and Transient Beam Losses in LHC Magnets,” LHC Project Report 44, European Organization For Nuclear Research, LHC Division, CERN, CH-1211 Geneva 23, Switzerland, July 1996.
- [15] N. V. Mokhov, A. I. Drozhdin, and G. W. Foster, “Beam-induced energy deposition issues in the Very Large Hadron Collider,” in *Particle Accelerator Conference, 2001. PAC 2001. Proceedings of the 2001*, vol. 4, pp. 3171–3173, IEEE, 2001.

- [16] V. Shiltsev, “Tevatron electron lenses: Design and operation,” *Physical Review Special Topics - Accelerators and Beams*, vol. 11, no. 10, 2008.
- [17] V. Shiltsev, “Considerations on compensation of beam-beam effects in the Tevatron with electron beams,” *Physical Review Special Topics - Accelerators and Beams*, vol. 2, no. 7, 1999.
- [18] X.-l. Zhang, K. Bishofberger, V. Kamerdzhev, V. Lebedev, V. Shiltsev, R. Thurman-Keup, and A. Tollestrup, “Generation and diagnostics of uncaptured beam in the fermilab tevatron and its control by electron lenses,” *Physical Review Special Topics-Accelerators and Beams*, vol. 11, no. 5, p. 051002, 2008.
- [19] G. Stancari, “Beam-Beam Compensation Studies in the Tevatron with Electron Lenses,” February 2013.
- [20] W. Fischer, Z. Altinbas, M. Anerella, M. Blaskiewicz, D. Bruno, W. Dawson, D. Gassner, X. Gu, R. Gupta, K. Hamdi, *et al.*, “Commissioning progress of the RHIC electron lenses,” tech. rep., Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider, 2013.
- [21] V. Previtali, G. Stancari, A. Valishev, and S. Redaelli, “Numerical simulations of a hollow electron lens as a scraping device for the LHC,” *MOPWO044, IPAC13*.
- [22] G. Stancari, G. Annala, T. Johnson, D. Still, and A. Valishev, “Measurements of transverse beam diffusion rates in the Fermilab Tevatron collider,” *PAC11, San Sebastian, Spain*, p. 1882, 2011.
- [23] G. Stancari, G. Annala, V. Shiltsev, D. Still, A. Valishev, and L. Vorobiev, “Experimental study of magnetically confined hollow electron beams in the Tevatron as collimators for intense high-energy hadron beams,” in *Conf. Proc. C*, vol. 110328, p. 370, 2011.
- [24] C. Crawford, A. Sery, V. Shiltsev, A. Aleksandrov, B. Skarbo, and B. Sukhina, “Magnetic field alignment in the beam-beam compensation device,” in *Particle Accelerator Conference, 1999. Proceedings of the 1999*, vol. 5, pp. 3321–3323, IEEE, 1999.
- [25] M. Reiser, *Theory and design of charged particle beams*. Weinheim: Wiley-VCH, 2nd, updated and expanded ed. ed., 2008.
- [26] G. Stancari, A. Drozhdin, G. Kuznetsov, V. Shiltsev, D. Still, A. Valishev, L. Vorobiev, R. Assmann, and A. Kabantsev, “Development of hollow electron beams for proton and ion collimation,” in *Conf. Proc. C100523: tupeb076, 2010*, no. FERMILAB-CONF-10-182-AD-APC, Fermi National Accelerator Laboratory (FNAL), Batavia, IL, 2010.
- [27] A. Gilmour, *Principles of Klystrons, Traveling Wave Tubes, Magnetrons, Cross-Field Amplifiers, and Gyrotrons*. Artech House microwave library, Artech House, Incorporated, 2011.
- [28] S. Li, “Characterization of an Electron Gun for Hollow Electron Beam Collimation,” Tech. Rep. FERMILAB-TM-2542-APC, Fermilab, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA, August 2012.
- [29] A. Ivanov and M. Tiunov, “ULTRASAM-2D code for simulation of electron guns with ultra high precision,” *Proceeding of EPAC-2002, Paris*, pp. 1634–1636, 2002.
- [30] L. Vorobiev, “Private communications.” Fermilab, 2013.
- [31] W. Umrath *et al.*, “Fundamentals of vacuum technology,” *Leybold, Cologne*, 1998.
- [32] G. Stancari, “Private communications.” Fermilab, 2013.
- [33] R. C. Davidson, *Physics of nonneutral plasmas*, vol. 5. Addison-Wesley New York, 1990.

-
- [34] E. Buckingham, “On physically similar systems; illustrations of the use of dimensional equations,” *Physical Review*, vol. 4, no. 4, pp. 345–376, 1914.
- [35] D. P. Grote *et al.*, “WARP Manual,” *Lawrence Livermore National Laboratory*, vol. 7000, pp. 94550–9234, April 2000.
- [36] M. Conte and W. W. MacKay, *An introduction to the physics of particle accelerators*, vol. 160. World Scientific, 1991.
- [37] J. Rossbach and P. Schmüser, “Basic course on accelerator optics,” *CERN European Organization for Nuclear Research-Reports-CERN*, pp. 17–17, 1994.
- [38] D. Möhl, “Sources of emittance growth,” *Proceedings of the CAS. Specialised CAS Course on Small Accelerators, Zeegse, The Netherlands, May 24-June 2*, pp. 2006–012, 2005.
- [39] G. Valentino, R. Aßmann, R. Bruce, F. Burkart, V. Previtalli, S. Redaelli, B. Salvachua, G. Stancari, and A. Valishev, “Beam diffusion measurements using collimator scans in the LHC,” *Physical Review Special Topics-Accelerators and Beams*, vol. 16, no. 2, p. 021003, 2013.
- [40] R. W. Hockney and J. W. Eastwood, *Computer simulation using particles*. CRC Press, 2010.

Appendices

Appendix A

LHC and Tevatron Parameters

Quantity	Symbol	Unit	Tevatron [16, 9]	LHC [7]
Collider type			$p - \bar{p}$	$p - p$
Circumference	C	[m]	6.28 km	26.66 km
# Beam Pipes			1	2
# of IRs	N_{IR}		2	8
Injection Energy	E_{inj}	[GeV]	120/150	450
Nominal Energy	E_{nom}	[TeV]	0.98	7
Achieved Energy	E	[TeV]	0.980	4.5
# of bunches	N_b		36 (3 bunch trains)	2808
Protons per bunch	N_p		$2.7 \times 10^{11} / 1.35 \times 10^{11}$	1.15×10^{11}
Bunch spacing	T_b	[ns]	396	25
Nominal Beam Intensity	$N_p, N_{\bar{p}}$		$9.72 \times 10^{12}, 4.86 \times 10^{12}$	3.23×10^{14}
Peak Luminosity	L_0	[$\text{cm}^{-2}\text{s}^{-1}$]	3.15×10^{32}	2.3×10^{34}
Nominal Emittance (RMS)	ε	[μm]	2.8/1.4	3.75
Nominal Energy Density	U	[MJ/mm ²]	2	360
Cryogenic Temperature	T	[K]	4	1.9

Table A.1: Important parameters of Tevatron and LHC

It is important to notice that the proton and anti-proton beams in the Tevatron share the same beam pipe, in which they are transversely displaced. Beam-Beam effects are thus significantly more important at the Tevatron. In the LHC, both beams have their own channels, which intersect at 4 Interaction Regions (IRs), where the experiments ATLAS, CMS, ALICE, LHCb and others can be found.

Appendix B

Measured Profiles

B.1 List of measured profiles

Table B.1: Table showing all profile measurements made.

#	Date	Magnetic Field [T]	Cathode Potential [kV]	Cathode Current [mA]	Avg. Current [mA]	Collector Current [mA]	Rep. Rate [Hz]	Vacuum [V]	Pulse Length [μ s]
1	20.02.13 11:35	0.1-0.1-0.1	0.9	N/A	N/A	118	500	N/A	8
2	21.02.13 11:00	0.2-0.2-0.2	3.6	N/A	N/A	928	50	N/A	8
3	21.02.13 11:40	0.1-0.1-0.1	2.0	N/A	N/A	398	200	N/A	8
4	21.02.13 13:05	0.1-0.1-0.1	3.0	N/A	N/A	726	100	N/A	8
5	04.04.13 09:00	0.25-0.25-0.25	5.6	2322	1.21	1770	20	6.48	8
6	04.04.13	0.25-0.25-0.25	5.0	1980	1.25	1484	30	6.41	8
7	04.04.13 12:25	0.25-0.25-0.25	2.1	548	1.33	412	200	6.47	8
8	04.04.13 13:45	0.25-0.25-0.25	3.5	1156	1.35	865	80	6.41	8
9	04.04.13 15:08	0.3-0.3-0.3	5.0	1964	1.24	1460	30	6.41	8
10	05.04.13 08:30	0.2-0.2-0.2	1.3	282	1.33	212	400	6.57	8
11	05.04.13 10:00	0.2-0.2-0.2	2.2	592	1.335	448	180	6.57	8
12	05.04.13 11:20	0.2-0.2-0.2	3.1	972.6	1.35	744.4	100	6.52	8
13	05.04.13 12:45	0.15-0.15-0.15	0.75	120.8	1.26	90.4	800	6.52	8
14	05.04.13 14:15	0.15-0.15-0.15	2.0	506	1.25	390	200	6.51	8
15	05.04.13 15:47	0.15-0.15-0.15	1.3	254	1.21	192	400	6.52	8
16	02.05.13	0.25-0.25-0.25	0.50	69.6	0.96	51	1000	6.64	8
17	02.05.13	0.2-0.2-0.2	0.50	68.4	0.94	49	1000	6.60	8
18	02.05.13	0.3-0.3-0.3	0.50	68.4	0.94	56	1000	6.60	8
19	07.05.13	0.3-0.3-0.3	0.50	70.8	0.98	50.4	7000	6.58	8
20	13.05.13	0.3-0.3-0.3	0.50	74.4	1.05	50.2	1000	6.64	8
21	13.05.13	0.3-0.3-0.3	0.50	N/A	0.36	N/A	300	6.64	8
22	13.05.13	0.3-0.3-0.3	0.50	70.4	0.99	50.8	1000	6.60	8
23	13.05.13	0.3-0.3-0.3	0.50	N/A	0.34	N/A	300	6.60	8
24	13.05.13	0.1-0.3-0.1	0.50	72.4	1.02	69.8	1000	N/A	8
25	14.05.13 20:21	0.08-0.32-0.08	0.50	74.4	1.02	72.8	1000	N/A	8
26	14.05.13 20:22	0.08-0.32-0.08	1.0	198	0.98	195	400	N/A	8
27	14.05.13 20:24	0.08-0.32-0.08	2.0	528	1.07	526	150	N/A	8
28	14.05.13 20:31	0.08-0.32-0.08	4.0	1460	1.13	1450	40	N/A	8
29	15.05.13 11:49	0.08-0.32-0.08	8.0	3760	1.57	3700	10	N/A	8
30	15.05.13 12:31	0.08-0.32-0.08	7.0	3160	1.33	3100	10	N/A	8
31	15.05.13 13:22	0.08-0.32-0.08	0.25	27.0	1.09	25.8	2500	N/A	8
32	15.05.13	0.08-0.32-0.08	0.125	9.72	0.91	9.32	4000	N/A	8
33	15.05.13	0.08-0.32-0.08	3.0	956	1.32	944	100	N/A	8
34	15.05.13 15:39	0.08-0.32-0.08	5.0	7990	1.01	7990	15	N/A	8
35	15.05.13	0.08-0.32-0.08	6.0	2560	1.14	2530	10	N/A	8
36	15.05.13 17:53	0.1-0.4-0.1	1.0	197	0.97	196	400	N/A	8
37	15.05.13 18:51	0.1-0.4-0.1	3.125	1024	1.4	1022	100	N/A	8
38	15.05.13 19:20	0.1-0.4-0.1	6.250	2780	1.16	2754	10	N/A	8
39	16.05.13 10:45	0.06-0.24-0.06	1.0	798	0.99	796	400	N/A	8
40	16.05.13 11:02	0.04-0.16-0.04	1.0	797	0.99	795	400	N/A	8
41	16.05.13 11:46	0.04-0.16-0.04	0.50	74.4	1.02	72.4	7000	N/A	8
42	20.05.13 11:40	0.1-0.4-0.1	0.50	73.6	1.02	72.8	1000	N/A	8

43	20.05.13 11:42	0.1-0.4-0.1	2.0	530	1.06	534	750	N/A	8
44	20.05.13 12:19	0.1-0.4-0.1	4.0	1463	1.13	1440	40	N/A	8
45	20.05.13 12:59	0.1-0.4-0.1	5.0	1990	1.01	1980	15	N/A	8
46	20.05.13 13:40	0.1-0.4-0.1	8.0	3880	1.56	3880	10	N/A	8
47	20.05.13 14:33	0.04-0.16-0.04	2.0	498	1.03	488	150	N/A	8
48	20.05.13 15:21	0.04-0.16-0.04	0.75	127.2	0.83	125.5	500	N/A	8
49	21.05.13 10:57	0.04-0.16-0.04	1.5	338.5	0.92	332.5	200	N/A	8
50	21.05.13 14:10	0.04-0.16-0.04	2.5	682	1.04	658	100	N/A	8
51	21.05.13 14:50	0.06-0.24-0.06	0.50	74.0	0.98	73.2	7000	N/A	8
52	21.05.13	0.06-0.24-0.06	2.0	528	1.07	526	150	N/A	8
53	21.05.13 15:31	0.06-0.24-0.06	3.0	928	1.32	923.8	100	N/A	8
54	21.05.13 16:18	0.06-0.24-0.06	4.0	1384	1.11	1368	40	N/A	8

Appendix C

Codes

C.1 Profile Measurement

C.1.1 Data Acquisition - ACL script

```
1 #####
2 #+description
3 #
4 # Measurement of current-density electron beam
   profile
5 # in electron lens test stand (linac lab)
6 # Raster scan of magnetic correctors, recording
   pinhole current and vacuum
7 #
8 # v1 - Giulio Stancari, 18 Dec 2012
9 #
10 #-description
11 #####
12
13 # initialize
14 fst = newline + newline + "=== Electron lens
   test stand profile scan ===" + newline + "# " +
   dateToString()
15 print fst
16 print/output=file:scan.txt fst
17
18 # define list of horizontal and vertical
   correctors
19 # (only 6 --7th and 8th H and V correctors are
   not wired)
20 deviceList/create hcor devices='Z:HCOR02,Z:HCOR06
   ,Z:HCORB2,Z:HCOR10,Z:HCOR14,Z:HCORB6'
21 deviceList/create vcor devices='Z:VCOR01,Z:VCOR05
   ,Z:VCORB1,Z:VCOR09,Z:VCOR13,Z:VCORB5'
22
23 # define list of variables to read
24 # Z:BC1AD3 = probe current
25 # Z:BC1AD5 = tube current
26 # Z:BC2AD5 = diode pump vacuum
27 deviceList/create devin devices='Z:BC1AD3,Z:
   BC1AD5,Z:BC2AD5,Z:HCOR02,Z:HCOR06,Z:HCORB2,Z:
   HCOR10,Z:HCOR14,Z:HCORB6,Z:VCOR01,Z:VCOR05,Z:
   VCORB1,Z:VCOR09,Z:VCOR13,Z:VCORB5'
28 deviceList/size/output=variable:ndevin devin
29 declare rd float[15]
30
31 # define scan parameters
32 # mix = minimum value of horizontal correctors[A]
33 # max = maximum...
34 # miy = minimum value of vertical correctors[A]
35 # may = maximum...
36 # step = step size [A]
37 # dt = time spent at each point [s]
38 input/user/float/default=-1 inmix "Min. H value (
   mix) [A]"
39 mix = <inmix>
40 input/user/float/default=1 inmax "Max. H value (
   max) [A]"
41 max = <inmax>
42 input/user/float/default=-1 inmiy "Min. V value (
   miy) [A]"
43 miy = <inmiy>
44 input/user/float/default=1 inmay "Max. V value (
   may) [A]"
45 may = <inmay>
46 input/user/float/default=0.5 instep "Step size [A
   ]"
47 step = <instep>
48 input/user/float/default=1 indt "Time interval [s
   ]"
49 dt = <indt>
50 fst = "# Scan parameters:" + newline + "# mix = "
   + toString(mix,8) + " A" + newline + "# max = "
   + toString(max,8) + " A" + newline + "# miy = "
   + toString(miy,8) + " A" + newline + \
51 "# may = " + toString(may,8) + " A"+newline+"
   # step = "+toString(step,8)+" A"+newline+"# dt
   = "+toString(dt,8)+" s"
52 print fst
53 print/output=file:scan.txt fst
54
55 # validating scan parameters
56 if (mix < -5) or (max > 5) or
57 (miy < -5) or (may > 5) or \
58 (mix > max) or (miy > may) or \
59 (step <= 0) or (step > 5) or \
60 (dt <= 0) or (dt > 600)
```

```

61  exit "Invalid scan parameters."
62  endif
63
64  # calculating scan duration
65  nx = (max-mix)/step + 1
66  ny = (may-miy)/step + 1
67  dur = nx*ny*dt
68  print "Estimated scan duration: " dur " s"
69
70  # initialize direction of raster scan
71  # stepsign = +1 -> positive
72  # stepsign = -1 -> negative
73  stepsign = 1
74  enable settings
75  print "Ramping correctors to initial settings..."
76  x = mix
77  y = miy
78  ramp/duration=2 deviceList=hcor x
79  ramp/duration=2 deviceList=vcor y
80  print "Starting raster scan..." newline newline
81
82  # screen header
83  print pos(2) " x [A] " \
84        pos(10) " y [A] " \
85        pos(20) "probe [arb.]" \
86        pos(35) "tube [arb.]" \
87        pos(50) "vacuum [V]"
88
89  # file header
90  fst = newline + newline + "# xset [A] yset [A]"
91  loop ndevin
92    fst=fst+" "+name(Q:DEVIN)+" ["+units(Q:DEVIN)+"
93      "]"
94  deviceList/inc devin
95  endloop
96  fst = fst + " ctime [s]"
97  print/output=file:scan.txt fst
98  while x <= max
99    ramp deviceList=hcor x
100   if stepsign = 1
101     else
102       y = may
103     endif
104   while (y >= miy) and (y <= may)
105     ramp deviceList=vcor y
106     wait/sec dt
107     read_list/nodisplay/values=rd device_list=
108       devin
109     # format file output
110     fst = " "+toString(x,6)+" "+toString(y,6)
111     loop ndevin i
112       fst = fst + " " + toString(rd[i],12)
113     endloop
114     fst = fst + " " + toString(ctimeNow)
115     print/output=file:scan.txt fst
116   # format screen output
117   print pos(2) width(x,7) \
118         pos(10) width(y,7) \
119         pos(20) width(rd[0],12) \
120         pos(35) width(rd[1],11) \
121         pos(50) width(rd[2],10)
122   # increase or decrease vertical setting
123   y = y + stepsign*step
124   endwhile
125   # revert direction of vertical scan
126   stepsign = -1 * stepsign
127   x = x + step
128   endwhile
129   exit
130 # always clean up
131 always:
132   print "Ramping correctors back to zero..."
133   ramp/duration=2 deviceList=hcor 0
134   ramp/duration=2 deviceList=vcor 0
135   fst = newline + "# === End of profile scan ==="
136     + newline + \
137     "# " + dateToString()
138   print fst newline newline
139   print/output=file:scan.txt fst

```

C.1.2 Data Processing - R script

```

1  #####
2  # NAME: profile_amalysis.R
3  # AUTHOR: Vince Moens, Giulio Stancari
4  # LAST MODIFIED: 05.07.2013
5  # PURPOSE: Profile Calibration, Particle Export,
6  #           Transverse Profile Calculation, Radial Profile
7  #           Calculation, Polar Decomposition
8  #####
9  # Initialization
10 library(fields)
11 require(MASS); require(rgl); require(RSEIS)
12 T <- TRUE; F <- FALSE
13 par(ask=FALSE)
14 # Profile Loading
15 fns <- c(
16   "../Data/HG/HG_091023_775A_250V_303030kG_16mA.
17   dat", #1
18   ...
19   "../Data/HG1/HG1b_130521_9p25A_06-24-06kG_4kV_
20   1368mA.txt.gz" #136
21 )
22 ### CONTROL SWITCHES ###
23 profile.list <- 99:100 #length(fns)
24
25 CORRECT.SCALLOPS <- T
26 FIND.SCALLOP.CORRECTION.PAR <- F
27 SUBTRACT.BACKGROUND <- T
28 CORRECT.BOTTOM.LEFT <- T
29 NORMALIZE.PROFILE <- T
30 CALIBRATE.CORRECTORS <- F

```

```

164 MAKE.PLOTS <- T
165 EXPORT.CALIBRATED.PROFILE <- T
166 EXPORT.RADIAL <- T
167 EXPORT.PARTICLES <- T; Nmax <- 8192
168 POLAR.DECOMPOSITION <- T
169 RUBBER.STAMP <- T
170 BKGR.BLACK <- F
171 BKGR.TRANS <- T
172 COLOR.CHART <- T
173 D3.AXIS <- T
174
175 if(COLOR.CHART) {out.dir <- "../Results/Chart_
    Colors/"
176         polar.dir <- "../Polar/Results/
            Chart_Colors/"
177 } else {out.dir <- "../Results/Matlab_Colors/"
178         polar.dir <- "../Polar/Results/Matlab_
            Colors/"
179 }
180 radial.dir <- "../Radial/Results/"
181 fname.id <- "test"
182
183 # log file
184 logfile <- "log.txt"
185 unlink(logfile)
186 sink(logfile, split=TRUE)
187 cat("\nAnalysis of electron beam profiles\n")
188 cat("Start: ", date(), "\n")
189
190 # plot options
191 if(BKGR.BLACK) par(bg="black",fg="white",col="
    white",col.axis="white",col.lab="white", col.
    main="white",col.sub="white")
192 if(BKGR.BLACK) pbgr <- "black" else pbgr <- "
    white"
193 if(BKGR.TRANS) par(bg="transparent")
194 if(BKGR.TRANS) pbgr <- "transparent"
195 pwid <- 3.25; phei <- 3.25
196 reso <- 300; pwp <- pwid*reso; phpx <- phei*reso
197 resoRGL <- 300; pwpRGL <- pwid*resoRGL; phpxRGL
    <- phei*resoRGL
198 pfon <- "Times"; ptsz <- 10
199 quartz.options(width=pwid, height=phei, family=
    pfon,pointsize=ptsz,bg=pbgr,reset=TRUE)
200 pdf.options(width=pwid,height=phei,family=pfon,
    pointsize=ptsz,bg=pbgr,reset=TRUE)
201 setEPS(width=pwid,height=phei,family=pfon,
    pointsize=ptsz,bg=pbgr,reset=TRUE)
202 matlab.colors <- colorRampPalette( c("#00007F",
    "blue", "#007FFF", "cyan", "#7FFF7F", "yellow", "#
    FF7F00", "red", "#7F0000"))
203
204 # filled contour with no key
205 filled.contour.nokey <- function (x=seq(0,1,
    length.out=nrow(z)),y=seq(0,1,length.out=ncol(z)
    ),z,xlim=range(x,finite=TRUE),ylim = range(y,
    finite = TRUE), zlim = range(z, finite = TRUE),
    levels = pretty(zlim, nlevels), nlevels = 20,
    color.palette = cm.colors,col = color.palette(
    length(levels) -1), plot.title, plot.axes,key.
    title, key.axes, asp = NA, xaxs = "i", yaxs = "i
    ", las = 1,axes = FALSE, frame.plot = axes, ...)
206 {
207     if (missing(z)) {
208         if (!missing(x)) {
209             if (is.list(x)) {
210                 z <- x$z
211                 y <- x$y
212                 x <- x$x
213             }
214             else {
215                 z <- x
216                 x <- seq.int(0, 1, length.out =
                    nrow(z))
217             }
218         }
219         else stop("no 'z' matrix specified")
220     }
221     else if (is.list(x)) {
222         y <- x$y
223         x <- x$x
224     }
225     if (any(diff(x) <= 0) || any(diff(y) <= 0))
226         stop("increasing 'x' and 'y' values
            expected")
227     mar.orig <- (par.orig <- par(c("mar", "las", "
        mfrow")))$mar
228     on.exit(par(par.orig))
229     par(las = las, xaxs = "i", yaxs = "i")
230     plot.new()
231     plot.window(xlim, ylim, "", asp = asp)
232     if (!is.matrix(z) || nrow(z) <= 1L || ncol(z)
        <= 1L)
233         stop("no proper 'z' matrix specified")
234     if (!is.double(z))
235         storage.mode(z) <- "double"
236     .Internal(filledcontour(as.double(x), as.
        double(y), z, as.double(levels),
        col = col))
237     if (missing(plot.axes)) {
238         if (axes) {
239             title(main = "", xlab = "", ylab = "")
240             Axis(x, side = 1)
241             Axis(y, side = 2)
242         }
243     }
244     else plot.axes
245     if (frame.plot)
246         box()
247     if (missing(plot.title))
248         title(...)
249     else plot.title
250     invisible()
251 }
252
253
254 # Centering corrections
255 Seq <- c(1.6,2.4,3.2,4)
256 Xcorrl <- c( -1.210455, -2.381263, -3.072298, -
    3.208143)
257 Ycorrl <- c( -0.4880404, -0.6774335, -0.926263, -
    1.03759)
258
259 # experimental conditions
260 # filament heater current [A]
261 IH <- c(rep(7.75,20), rep(5.79,2), rep(7.75,6),
    rep(4,2), rep(8.75, 17),rep(6.25, 5), rep(8.75,

```

```

2) , rep(9.25, 10), rep(7.25, 2), rep(9.25, 30),
  rep(10.0,4), rep(9.25,36))
262 # cathode voltage [V]
263 V <- c(250, 500, 1000, 1500, 2000, 3000, 4000,
  5000, 6000, 7500,9000, 3e3, 3e3, 9e3, 9e3, 9e3,
  250, 250, 1e3, 6e3, 500, 7500, 500,2000, 7500,
  7500, 50, 2000, 100, 5000,500, 1e3, 2e3, 4e3, 8
  e3, 1e3, 2e3, 500, 4e3, 8e3, 500,500, 1e3, 2e3,
  4e3, 8e3, 3e3,8e3, 2e3, 500, 500, 500, 8e3, 500,
  1e3, 5e3,500, 8e3, 4e3, 2e3, 1e3, 6e3, 3e3, 7e3
  , rep(8e3,2), 889, 2e3, 3e3, 3556, 5556, 5000,
  2083, 3472, 5000, 1333, 2222, 3111, 750, 2000,
  1250, rep(500,23) ,1e3 ,2e3, 4e3, 8e3, 7e3, 250,
  125, 3e3, 5e3, 6e3, 1e3, 3125, 6250, rep(1e3,5)
  , 500, 500, 2000, 4000, 5000, 8000, 2000, 750,
  1500, 2500, 500, 2000, 3000, 4000)
264 # peak beam current at collector [A]
265 I <- c(0.016, 0.044, 0.121, 0.220, 0.325, 0.582,
  0.876, 1.180,1.490, 2.020, 2.490, 0.564, 0.600,
  2.330, 2.470, 2.550, 0.016,0.015, 0.118, 1.46,
  0.023, 0.074, 0.044, 0.330, 2.040, 1.984, 1460e-
  6,0.348, 0.00198, 1.670,0.050, 0.134, 0.386,
  1.030, 2.2850, 0.134, 0.394, 0.049, 1.064,2.860,
  0.050,0.050, 0.135, 0.376, 1.056, 2.940,
  0.692,0.140, 0.098, rep(0.048, 3), 2.860, 0.050,
  0.004, 0.013,0.051, 2.94, 1.1, .388, .14,
  1.924, .694, 2.394, .440, .027,0.118, .398,
  .726, .928, 1.770, 1.484, .412, .865, 1.460,
  .213, .448, 0.744, .090, .390, .192, rep(.051,3)
  , rep(.049,5), rep(.051,6), rep(0.050,5), rep
  (0.070,2), rep(0.073,2), 0.195, 0.526, 1.45,
  3.7, 3.1, 0.026, 0.009, 0.944, 1.99, 2.53,
  0.195, 1.022, 2.754, 0.196, rep(0.195,4), 0.072,
  0.073, 0.0534, 1.44, 1.98, 3.88, 0.488, 0.125,
  0.332, 0.658, 0.073, 0.526, 0.924, 1.368)
266 # solenoidal field [T]
267 B <- c(rep(.3,11), 0.1, 0.4, 0.1, 0.2, 0.4, 0.1,
  0.033, 0.133,0.223, rep(0.3,7), 0.4, rep(0.4,2),
  rep(0.3, 5), rep(0.1, 5), 0.4, rep(0.2, 5), 0.3,
  rep(0.3,7), rep(0.2,2), rep(0.3,10), rep(0.1,3)
  , 0.2, rep(0.25,4), 0.3, rep(0.2,3), rep(0.15,3)
  , rep(0.25,3), rep(0.2,5), rep(0.3,13), rep
  (0.32,12), rep(0.4,3), 0.24, rep(0.16,5), rep
  (0.4,5), rep(0.16,4), rep(0.24,4))
268 # number of correctors
269 NC <- c(rep(4,11), 3, 6, 3, 3, 6, 3, 3, 3, rep
  (6,7), 4, rep(4,2),rep(6, 106))
270 # raster-scan correction Parameters
271 besttp <- c(-0.6069, -0.5819, -0.7744, -0.8363, -
  0.5632, -0.5392,-0.3877, -1.017, -0.5627, -
  0.5051, -0.7392, 0.0392, -1.9296,-0.1264, -
  0.3909, -1.631, -0.2347, -0.2685, -0.1528, -
  0.0197,-1.7174, -0.7895, -1.2949, -1.5334, -
  1.6833, -1.2, -1.19, -4.02,-0.37, -0.44,-
  0.3901180, -0.4279687, -0.4502339, -0.3418769, -
  0.2973467,-0.3418769, -0.3203540, -0.3233227, -
  0.2928937, -0.3671107,-0.4932798,-0.4583977, -
  0.4895689, -0.4784364, -0.2832455, -0.2832455,-
  0.3878915, -0.350783, rep(-0.4, 6), rep(-0.62,
  2), rep(-0.62, 8),-.18,-.62, -0.3418769, -
  0.3203540, -0.3, rep(-0.2832455,67))
272 # calibration constants [mm*T/A/corr]
273 calx.v <- rep(0.13, length(fns))
274 caly.v <- rep(0.14, length(fns))
275 calx.v[which(NC==3)] <- 0.1285 # checked
276 calx.v[20] <- 0.1526 # NC=3 but different
  settings
277 calx.v[which(NC==4)] <- 0.1313 # checked
278 calx.v[which(NC==6)] <- 0.1706 # checked
279 calx.v[29:30] <- 0.199 # 3.5-4.0-1.5 kG, Gaussian
  gun
280 caly.v[which(NC==3)] <- 0.1389 # checked
281 caly.v[20] <- 0.1436 # NC=3 but different
  settings
282 caly.v[which(NC==4)] <- 0.1450 # checked
283 caly.v[which(NC==6)] <- 0.1793 # checked
284 caly.v[29:30] <- 0.216 # 3.5-4.0-1.5 kG, Gaussian
  gun
285
286 # offsets [A]
287 xoff.v <- rep(0, length(fns))
288 yoff.v <- rep(0, length(fns))
289 xoff.v[which(NC==4)] <- -0.4109
290 xoff.v[which(NC==3)] <- c(-0.0199, -0.0895, -
  0.3217, -0.0787, -0.0081, -0.1633, 0) # NC=3
291 xoff.v[20] <- 0.5942 # NC=3 special case
292 xoff.v[which(NC==6)] <- -0.3265 # NC=6
293 xoff.v[which(NC==8)] <- -0.1772 # NC=8
294 xoff.v[29:30] <- -1.2 # 3.5-4.0-1.5 kG
295 xoff.v[c(31:35,47:54,57:66)] <- -0.419 # 1-in
  hollow gun, 3 kG
296 xoff.v[c(36:40,67:69)] <- -0.114 # 1-in hollow
  gun, 1 kG
297 xoff.v[41] <- -0.58 # 1-in hollow gun, 4 kG, to
  be verified
298 xoff.v[c(42:46, 55:56,70)] <- -0.23 # 1-in hollow
  gun, 2 kG
299 yoff.v[which(NC==4)] <- -0.1157
300 yoff.v[which(NC==3)] <- c(-0.0533, -0.0872, -
  0.0786, -0.0469, -0.0330, -0.0582, 0) # NC=3
301 yoff.v[20] <- 0.1957 # NC=3 special case
302 yoff.v[which(NC==6)] <- -0.1000 # NC=6
303 yoff.v[which(NC==8)] <- -0.0510 # NC=8
304 yoff.v[29:30] <- -0.40 # 3.5-4.0-1.5 kG
305 yoff.v[c(31:35,47:54,57:66)] <- 0.081 # 1-in
  hollow gun, 3 kG
306 yoff.v[c(36:40, 67:69)] <- 0.033 # 1-in hollow
  gun, 1 kG
307 yoff.v[41] <- 0.067 # 1-in hollow gun, 4 kG, to
  be verified
308 yoff.v[c(42:46, 55:56,70)] <- 0.07 # 1-in hollow
  gun, 2 kG
309
310 # inner (r1) and outer (r2) gun radii [m]
311 r1 <- c( rep(0.00450, 28), rep(0.00000, 2), rep
  (0.00675, 106) )
312 r2 <- c( rep(0.00762, 28), rep(0.00508, 2), rep
  (0.01270, 106) )
313 xylim.fudge <- 1.2 # fudge factor for xy limits =
  r2 * xylim.fudge
314
315 # constants
316 c <- 299792458
317 eps0 <- 8.854187817e-12
318 me <- 9.1093826e-31
319 q <- 1.60217653e-19

```



```

320 L <- rep(2.86, length(fns)) # anode-collector
    distance [m]
321 # electron velocities
322 gamma <- 1 + q*V/(me*c^2)
323 beta <- sqrt(gamma*gamma-1)/gamma
324 v <- beta*c
325 # flight times
326 t <- L/v
327 # average densities
328 lambda <- I/(q*v) # linear
329 n <- lambda/(pi*(r2*r2-r1*r1)) # volume
330 # plasma frequencies
331 wp <- sqrt(n*q*q/(eps0*me))
332 # cyclotron frequencies
333 wc <- q*B/me
334 # diocotron frequencies
335 wD <- wp*wp/(2*wc)
336 # evolution numbers
337 nev <- wD*t/(2*pi)
338 # assemble data frame
339 DSET <- data.frame(fns, IH, B, V, I, NC, besttp,
    calx.v, caly.v, xoff.v, yoff.v, r1, r2, L, beta,
    t, lambda, n, wc, wp, wD, nev)
340 write.table(DSET, file=paste(out.dir, fname.id, "
    _data_set.txt", sep=""))
341
342 # loop over profiles
343 for(l in profile.list) {
344   if(B[l]==0.16){
345     Xcorr=Xcorrl[1]
346     Ycorr=Ycorrl[1]
347   }
348   else if(B[l]==0.24){
349     Xcorr=Xcorrl[2]
350     Ycorr=Ycorrl[2]
351   }
352   else if(B[l]==0.32){
353     Xcorr=Xcorrl[3]
354     Ycorr=Ycorrl[3]
355   }
356   else if(B[l]==0.4){
357     Xcorr=Xcorrl[4]
358     Ycorr=Ycorrl[4]
359   }
360   else {
361     Xcorr=0
362     Ycorr=0
363   }
364   fname.id <- substr(fns[l],13,nchar(fns[l])-7) #
    filename prefix
365   message("fname = ", fname.id)
366   graphics.off()
367   if(rgl.cur()>0) rgl.close()
368
369   # read scan data
370   message("\n\n\n==== Reading file", fns[l], "
    ...====")
371   cat("Hollow gun inner radius:", format(r1[l]*1
    e3, di=3), "mm\n")
372   cat("Hollow gun outer radius:", format(r2[l]*1
    e3, di=3), "mm\n")
373   cat("Anode-collector distance:", format(L[l],
    di=3), "m\n")
374   cat("Filament heater current:", format(IH[l],di
    =3), "A\n")
375   cat("Solenoidal field:", format(B[l]*10,di=4),
    "kG\n")
376   cat("Cathode voltage:", format(V[l]/1e3,di=4),
    "kV\n")
377   cat("Peak collector current:", format(I[l]*1e3,
    di=4), "mA\n")
378   cat("Number of correctors:", format(NC[l]), "\n
    ")
379   cat("Electron velocity:", format(v[l],di=3), "m
    /s (beta =",format(beta[l],di=3), ")\n")
380   cat("Flight time:", format(t[l],di=3), "s\n")
381   cat("Linear number density:", format(lambda[l],
    di=3), "/m\n")
382   cat("Volume number density:", format(n[l],di=3)
    , "/m3\n")
383   cat("Cyclotron frequency:", format(wc[l]/(2*pi)
    ,di=3), "Hz\n")
384   cat("Plasma frequency:", format(wp[l]/(2*pi),di
    =3), "Hz\n")
385   cat("Diocotron frequency:", format(wD[l]/(2*pi)
    ,di=3), "Hz\n")
386   cat("Evolution number:", format(nev[l],di=3), "
    rev/flight\n")
387
388   # Finding the number of data points to plot.
389   message("Obtaining scan parameters...")
390   xraw <- round(D$V1, digits=3) # horz. deflector
    , rounded
391   Xmin <- min(xraw); Xmax <- max(xraw)
392   Nx <- nlevels(as.factor(xraw)); Xstep <- (Xmax-
    Xmin)/(Nx-1)
393   yraw <- round(D$V2, digits=3) # vert. deflector
    , rounded
394   Ymin <- min(yraw); Ymax <- max(yraw)
395   Ny <- nlevels(as.factor(yraw)); Ystep <- (Ymax-
    Ymin)/(Ny-1)
396
397   # define grid
398   X <- seq(Xmin, Xmax, length.out=Nx)
399   Y <- seq(Ymin, Ymax, length.out=Ny)
400   cat("X scan: from", Xmin, "to", Xmax, "(", Nx,
    "points)\n")
401   cat("Y scan: from", Ymin, "to", Ymax, "(", Ny,
    "points)\n")
402
403   # new profiles have vacuum data in 5th column (
    ACL scripts)
404   VACUUM <- FALSE
405   if(l>=57) VACUUM <- TRUE
406   # calibration of 20-l/s Tevatron diode pump
    gauge
407   Vga <- c(9,8.4,8,7,6.9,6,5.4,5,4,3.85,3) # V
408   logPtorr <- log10(c(4e-10, 1e-9, 2e-9, 8.5e-9,
    1e-8, 4e-8, 1e-7, 1.8e-7, 8e-7, 1e-6, 5.5e-6)
    ) # [torr], log scale
409   logPvsVsm <- smooth.spline(Vga, logPtorr)
410   PvsV <- function(V=6){
411     Vmin <- 2.8; Vmax <- 9.9
412     P <- 1e-4 + 0*V
413     P[V>=Vmax] <- 1e-10
414     P[V<=Vmin] <- 1e-4

```

```

415   good <- Vmin<V & V<Vmax
416   P[good] <- predict(logPvsVsm, x=V[good])$y
417   P[good] <- 10^P[good] * 1.333 # [mbar]
418   return(P)
419 }
420 message("Defining profile matrices...")
421 Zprobe <- matrix(0, nrow=Nx, ncol=Ny)
422 Ztube <- matrix(0, nrow=Nx, ncol=Ny)
423 Zvac <- matrix(NA, nrow=Nx, ncol=Ny)
424 # assign value according to position in grid
425 for(k in 1:length(D$V3)) {
426   i <- round((xraw[k]-Xmin)/Xstep) + 1
427   j <- round((yraw[k]-Ymin)/Ystep) + 1
428   Zprobe[i,j] <- D$V3[k]
429   Ztube[i,j] <- D$V4[k]
430   # new profiles have vacuum data
431   if(VACUUM) Zvac[i,j] <- PvsV( D$V5[k] )
432 }
433
434 # choose which variable to analyze and plot
435 Z <- Zprobe
436
437 # correct for scallops due to raster scan?
438 if(CORRECT.SCALLOPS){
439   message("Correcting for scallops due to raster
440     scan...")
441   # find best correction parameter?
442   if(FIND.SCALLOP.CORRECTION.PAR){
443     message("Looking for best correction parameter
444       ...")
445     # tpval <- seq(-2, 0, by=0.05)
446     tpval <- seq(besttp[1]-0.2,besttp[1]+0.2,by
447       =0.05)
448     hfc <- 0*tpval
449     for(t in 1:length(tpval)) {
450       tp <- tpval[t]
451       Ztmp <- Z
452       for(i in seq(1,Nx)) {
453         if(floor(i/2)==(i/2)) { # odd rows
454           for(j in 2:(Ny)) {
455             Ztmp[i,j] <- Z[i,j-1] + (Z[i,j] -Z[i,j-1])
456               / (1-tp) }}
457         else{ # even rows
458           for(j in 1:(Ny-1)) {
459             Ztmp[i,j] <- Z[i,j+1] + (Z[i,j] -Z[i,j+1])
460               / (1-tp) }}}
461         # evaluate scallop frequency component
462         # by looking at FFT of aligned rows
463         if(F){
464           if(floor(Nx/2) != (Nx/2)) {
465             Zv <- Ztmp[1:(Nx-1),1]
466             for(j in 2:Ny){Zv <- c(Zv,Ztmp[1:(Nx-1),j
467               ])}
468           }
469           else{
470             Zv <- Ztmp[1:Nx,1]
471             for(j in 2:Ny){Zv <- c(Zv,Ztmp[1:Nx,j])} }
472         LFZv <- length(Zv)
473         win <- get.slepians(LFZv, 1, 3)[,1]
474         FZv <- abs(fft(Zv*win))^2
475         centr <- LFZv/2
476         hwdth <- 3
477         hfc[t] <- sum(FZv[floor(centr-hwdth):ceiling(
478           centr+hwdth)])
479       }
480     }
481     # by looking at spatial FFT
482     if(T){
483       icmtmp <- sum(t(1:Nx) * Ztmp) / sum(Ztmp)
484       jcmtmp <- sum(Ztmp * 1:Ny) / sum(Ztmp)
485       scallop.filter <- abs((1:Nx-icmtmp) %%(1:
486         Ny-jcmtmp))
487       scallop.filter <- scallop.filter / max(
488         scallop.filter)
489       scallop.filter <- 1 -scallop.filter
490       scallop.filter <- (scallop.filter>0.8)
491       win <- get.slepians(Nx, 1, 3)[,1] %>% get.
492         slepians(Ny, 1, 3)[,1]
493       FZ <- Mod(fft(Ztmp*win))
494       hfc[t] <- sum( FZ[scallop.filter] ) / sum(
495         FZ[!scallop.filter] )
496     }
497     # "maximum entropy"
498     if(F){
499       Zprb <- Ztmp / sum(Ztmp)
500       hfc[t] <- sum(Zprb)*log(sum(Zprb))
501       for(i in 1:Nx){ for(j in 1:Ny){hfc[t] <- hfc
502         [t] -Zprb[i, j]*log(Zprb[i, j]) }}
503       hfc[t] <- -hfc[t]
504     }
505   }
506   cat("Please select minimum of figure of merit
507     (1 click)\n")
508   par(mar=c(5,4,4,2)+0.1)
509   plot(tpval, hfc, type="p", pch=16)
510   spf <- splinefun(tpval, hfc)
511   curve(spf(x), min(tpval), max(tpval), add=TRUE
512     )
513   tp <- locator(1)$x
514   besttp[1] <- tp
515 }
516 else {
517   tp <- besttp[1]
518 }
519 cat("Raster-scan correction parameter:", tp, "\
520 n")
521
522 # correct profile
523 Zc <- Z
524 for(i in seq(1,Nx)) {
525   if(floor(i/2)==(i/2)) { # odd rows
526     for(j in 2:(Ny)) {
527       Zc[i,j] <- Z[i,j-1] + (Z[i,j] -Z[i,j-1]) / (1
528         -tp) }}
529   else{ # even rows
530     for(j in 1:(Ny-1)) {
531       Zc[i,j] <- Z[i,j+1] + (Z[i,j] -Z[i,j+1]) / (1
532         -tp) }}}
533 Z <- Zc
534 }
535
536 # fix 250-V profile (power supply trip)?
537 if(T & fns[1]=="../Data/HG/HG_091023_775A_250V_
538   303030kG_16mA.dat") {
539   message("Correcting profile with HVPS trip...")
540 }
541 itrip <- 63; ic <- 54; ioff <- 1; imag <- 1
542 jc <- 52.8; joff <- 3; jmag <- 1

```

```

522   Zc <- Z
523   for(riga in itrip:min(Nx,(Nx-ioff))) {
524     for(colo in 1:min(Ny,(Ny-joff))) {
525       ixcor <- ic+(riga-ic)*imag+ioff
526       jycor <- jc+(colo-jc)*jmag+joff
527       icor <- round(ixcor)
528       if(icolor < itrip) icor <- 1
529       if(icolor > Nx) icor <- Nx
530       jcor <- round(jycor)
531       if(jcor < 1) jcor <- 1
532       if(jcor > Ny) jcor <- Ny
533       Zc[riga,colo] <- Z[icolor,jcor]
534     }
535   }
536   Z <- Zc
537 }
538
539 # subtract background?
540 if(COLOR.CHART & SUBTRACT.BACKGROUND) {message(
541   "Subtracting background..."); Z <- Z -mean(Z[Z
542   <=as.numeric(quantile(Z,probs=0.25))]);Z[Z<0]<
543   -0}
544 else if(!COLOR.CHART & SUBTRACT.BACKGROUND){
545   message("Subtracting background..."); Z <- Z -
546   mean(Z[Z<=as.numeric(quantile(Z,probs=0.25))])
547 } #Should we average over the few minimum
548   places?
549
550 # eliminate fake signals at bottom LEFT
551 if(CORRECT.BOTTOM.LEFT){Z[1:2,1:2] <- min(Z)}
552
553 # normalize?
554 Zu <- Z # save unnormalized profile
555 if(NORMALIZE.PROFILE){message("Normalizing...")
556   ; Z <- Z/(sum(Z))}
557
558 # find "center of mass" in terms of coordinates
559   and array indices for plotting slices
560 message("Finding center of mass...")
561 xcm <- sum(t(X) * Z) / sum(Z)
562 icm <- sum(t(seq(1,Nx)) * Z) / sum(Z)
563 ycm <- sum(Z * Y) / sum(Z)
564 jcm <- sum(Z * seq(1,Ny)) / sum(Z)
565 cat("xcm =", xcm, "(row", icm, ")\n")
566 cat("ycm =", ycm, "(column", jcm, ")\n")
567
568 # horizontal and vertical scales in mm
569 # corrector calibration: mm*T/A/ncorr
570 message("Axis calibration...")
571 calx <- calx.v[1]; caly <- caly.v[1]
572 Xoff <- xoff.v[1]; Yoff <- yoff.v[1]
573 if(CALIBRATE.CORRECTORS){
574   message("Calibration by fitting ellipse...")
575   rp <- c(r1[1], r2[1], 0)*1e3 # mm
576   rx <- rep(0,3); ry <- rep(0,3)
577   xcent <- rep(0,2); ycent <- rep(0,2)
578   message <- c("inner", "outer")
579   for(k in 1:2){
580     image(X, Y, Z, col=matlab.colors(64))
581     np <- 8
582     cat("Please choose", np, "points on",
583       message[k], "edge\n")
584     po <- locator(np)
585     x <- po$x; y <- po$y
586     e <- rep(0.01, length(x)) # errors
587     rguess <- mean(sqrt((x-xcm)^2+(y-ycm)^2))
588     ipar <- c(rguess, rguess, 0, xcm, ycm)
589     # parameter scales
590     pscl <- c(rguess, rguess, pi, 3*Xstep, 3*
591       Ystep)
592     # initial step sizes
593     dpar <- rep(0.01, 5)
594     # define function to be optimized
595     fopt <- function(p) {
596       a2 <- p[1]*p[1]; b2 <- p[2]*p[2]
597       st <- sin(p[3]); ct <- cos(p[3])
598       x0 <- p[4]; y0 <- p[5]
599       A <- ct*ct/a2 + st*st/b2
600       B <- 2*st*ct*(1/a2-1/b2)
601       C <- st*st/a2 + ct*ct/b2
602       D <- -2*x0*A -B*y0
603       E <- -B*x0 -2*C*y0
604       F <- -1+A*x0*x0+B*x0*y0+C*y0*y0
605       fopt <- sum((((A*x*x + B*x*y + C*y*y + D*x
606         + E*y)/F + 1)/e)^2)
607       return(fopt)
608     }
609     # minimize function
610     fit <- optim(ipar, fopt, hessian=TRUE,
611       method="BFGS",
612       control=list(trace=6, parscale=pscl, ndeps=
613         dpar,reltol=1e-5, REPORT=1))
614     # fitted parameters
615     fpar <- fit$par
616     # covariance matrix
617     emat <- solve(fit$hessian)
618     # parameter uncertainties
619     epar <- sqrt(diag(emat))
620     # matrix of correlation coefficients
621     cmat <- emat
622     for (i in 1:length(fpar)) {
623       for (j in 1:length(fpar)) {
624         cmat[i,j] <- emat[i,j]/epar[i]/epar[j]
625       }
626     }
627     cat("\n", "Parameters:\n")
628     pars <- data.frame(fitted=fpar, errors=epar,
629       initial=ipar)
630     print(round(pars,6))
631     cat("\n", "Covariance matrix:\n")
632     write.matrix(emat)
633     cat("\n", "Correlation matrix:\n")
634     write.matrix(round(cmat,3))
635     # Results
636     a <- fpar[1]; b <- fpar[2]
637     th <- fpar[3]
638     xc <- fpar[4]; yc <- fpar[5]
639     if(a>=b) {c <- sqrt(a*a-b*b)} else {c <-
640       sqrt(b*b-a*a)}
641     ecc <- c/a
642     cat("\n\nRotation =", th*180/pi, "deg\n")
643     cat("Axes =", a, "and", b, "\n")
644     cat("Center-foci distance =", c, "\n")
645     cat("Eccentricity =", ecc, "\n")
646     cat("Center = (", xc, ",", yc, ")\n")
647     # draw fitted ellipse

```

```

632     plot(x, y, pch=16)
633     phi <- seq(0, 2*pi, length.out=300)
634     rho <- sqrt(a*a*b*b/(a*a*sin(phi)*sin(phi) +
635               b*b*cos(phi)*cos(phi)))
636     xx <- rho*cos(phi+th) + xc
637     yy <- rho*sin(phi+th) + yc
638     points(xx, yy, type="l")
639     points(xc, yc, pch="+")
640     # save results for linear interpolation
641     rx[k] <- abs(a); ry[k] <- abs(b)
642     xcent[k] <- xc; ycent[k] <- yc
643     }
644     CALx <- lm(rp ~ rx); CALy <- lm(rp ~ ry)
645     plot(range(c(rx,ry)), range(rp), type="n")
646     points(rx, rp); points(ry, rp)
647     curve(CALx$coef[1] + CALx$coef[2]*x, min(rx),
648           max(rx), add=TRUE)
649     curve(CALy$coef[1] + CALy$coef[2]*x, min(ry),
650           max(ry), add=TRUE)
651     calx <- CALx$coef[2] * B[1] / NC[1]
652     caly <- CALy$coef[2] * B[1] / NC[1]
653     Xoff <- mean(xcent); Yoff <- mean(ycent)
654     }
655     cat("Axis calibration coefficients:\n", "\tcalx
656       = ", calx, "mm*T/A/corr\n", "\tcaly = ", caly,
657       "mm*T/A/corr\n")
658     calx.v[1] <- calx
659     caly.v[1] <- caly
660     cat("Offsets:\n", "\tXoff = ", Xoff, "A\n", "\t
661       Yoff = ", Yoff, "A\n")
662     xoff.v[1] <- Xoff
663     yoff.v[1] <- Yoff
664     # calibrated coordinates and step sizes [mm]
665     Xc <- (X-Xoff) * calx / B[1] * NC[1]
666     Yc <- (Y-Yoff) * caly / B[1] * NC[1]
667     Xcstep <- median(abs(diff(Xc)))
668     Ycstep <- median(abs(diff(Yc)))
669     # calibrated centers of mass [mm]
670     Xcm <- (xcm-Xoff) * calx / B[1] * NC[1]
671     Ycm <- (ycm-Yoff) * caly / B[1] * NC[1]
672     cat("Calibrated center of mass (should be zero)
673       :\n", "\tXcm = ", Xcm, "mm\n", "\tYcm = ", Ycm,
674       "mm\n")
675     # physical units [A/cm^2]
676     Zphys <- Z*I[1] / (Xcstep/10) / (Ycstep/10) #Z/
677       (Xcstep*Ycstep)
678     ### profile plots ###
679     # plot settings
680     if(COLOR.CHART) {;Zlim <- range(Zphys);Nc <-
681       100 # of colors;palette <- matlab.colors(Nc);
682       palette <- c(rgb(0,0,0),rgb(0,0,0.5),rgb
683       (0,0,0.1),palette[c(seq(1,29,by=3),seq(30,40,
684       by=3),seq(44,56,by=4),seq(60,80,by=2),seq
685       (80,100,by=2))]);Nc <-length(palette)}
686     else {Zlim <- range(Zphys)
687     Nc <- 64 # of colors
688     palette <- matlab.colors(64)}
689     icol <- round((Zphys-Zlim[1])/(Zlim[2]-Zlim[1])
690       *(Nc-1)) + 1
691     if(COLOR.CHART) icol[icol<=0]=1
692     }
693     mcol <- matrix(palette[icol], nrow=Nx, ncol=Ny)
694     # color matrix
695     # plot 1D slices
696     if(MAKE.PLOTS){
697     dev.new()
698     par(oma=rep(0, 4), mar=c(3.5, 3.5, 0.5, 0.5),
699     mgp=c(2, 0.5, 0), tcl=-0.2)
700     if(BKGR.BLACK) par(fg="white", col="white",
701     col.axis="white",col.lab="white", col.main="
702     white",col.sub="white")
703     xx <- Xc; yy <- Zphys[,jcm] # horz. along c.m.
704     slice
705     plot(xx, yy, type="n", axes=FALSE,xlab="
706     Horizontal position [mm]",ylab=expression(
707     paste("Current density [", A/cm^2, "]"))
708     axis(1); axis(2, las=1)
709     grid(lty="solid")
710     box()
711     points(xx, yy, pch=16)
712     f <- splinefun(xx, yy)
713     curve(f(x), min(xx), max(xx), n=301, add=TRUE)
714     file.prefix <- paste(out.dir, fname.id, "1Dx_"
715     , sep="")
716     fout <- paste(file.prefix,formatC(1, width=2,
717     flag="0"), ".pdf", sep="")
718     dev.print(pdf, file=fout)
719     fout <- paste(file.prefix,formatC(1, width=2,
720     flag="0"), ".eps", sep="")
721     dev.print(postscript, file=fout)
722     }
723     # --- 2D PLOTS ---#
724     if(MAKE.PLOTS){
725     # raw 2D measurement
726     dev.new()
727     par(oma=rep(0,4), mar=c(4.2, 4.2, 0.5, 0.5))
728     if(BKGR.BLACK) par(fg="white", col="white",
729     col.axis="white",col.lab="white", col.main="
730     white",col.sub="white")
731     image(X, Y, Zprobe, col=matlab.colors(64), asp
732     =1,xlab="H. corrector setting [A]",ylab="V.
733     corrector setting [A]")
734     # save to file
735     file.prefix <- paste(out.dir, fname.id, "_
736     raw2D_", sep="")
737     fout <- paste(file.prefix,formatC(1, width=2,
738     flag="0"), ".png", sep="")
739     dev2bitmap(file=fout, width=pwid, height=peih,
740     res=reso)
741     fout <- paste(file.prefix,formatC(1, width=2,
742     flag="0"), ".pdf", sep="")
743     dev.print(pdf, file=fout)
744     fout <- paste(file.prefix,formatC(1,width=2,
745     flag="0"), ".eps", sep="")
746     dev.print(postscript,file=fout)
747     }
748     # 2D contours
749     xylim <- c(-1,1) * xylim.fudge * (r2[1]*1e3) #
750     plot limits [mm]
751     # --- 2D CONTOUR PLOTS ---#
752     if(MAKE.PLOTS){

```

```

722 # plot 2D contour, bare
723 dev.new()
724 par(oma=rep(0,4), mar=rep(0,4))
725 if(BKGR.BLACK) par(fg="white", col="white",
726   col.axis="white",col.lab="white", col.main="
727   white",col.sub="white")
728 filled.contour.nokey(Xc, Yc, Zphys, xlim=xylim
729   , ylim=xylim, asp=1,levels=seq(Zlim[1], Zlim
730   [2], length.out=Nc), col=palette,frame.plot=
731   FALSE)
732 # save to file
733 file.prefix <- paste(out.dir, fname.id, "2
734   Dbare_", sep="")
735 fout <- paste(file.prefix,formatC(1, width=2,
736   flag="0"), ".png", sep="")
737 dev.print(png, file=fout, width=pwpx, height=
738   phpx)
739 #dev2bitmap(file=fout, width=pwid, height=phei
740   , res=reso)
741 fout <- paste(file.prefix,formatC(1, width=2,
742   flag="0"), ".pdf", sep="")
743 dev.print(pdf, file=fout)
744 fout <- paste(file.prefix,formatC(1,width=2,
745   flag="0"), ".eps", sep="")
746 dev.print(postscript,file=fout)
747 }
748 if(MAKE.PLOTS){
749   # plot 2D contour, legend,
750   wiland <- 7; heland <- 6
751   dev.new(width=wiland, height=heland)
752   par(oma=rep(0,4), mar=c(4.2,3.2,4.2,0.5), mgp=
753   c(1.5, 0.5, 0))
754   if(BKGR.BLACK) par(fg="white", col="white",
755   col.axis="white",col.lab="white", col.main="
756   white",col.sub="white")
757   tick <- diff(range(Xc)) * 0.015; tcol <- "
758   white"
759   plot.ticks <- function() {axis(1); axis(2);
760   lines(c(Xcm,Xcm), c(min(Yc), min(Yc)+tick),
761   col=tcol);lines(c(Xcm,Xcm), c(Ycm-tick, Ycm+
762   tick), col=tcol);lines(c(Xcm,Xcm), c(max(Yc)-
763   tick,max(Yc)), col=tcol);lines(c(min(Xc),min(
764   Xc)+tick), c(Ycm,Ycm), col=tcol);lines(c(Xcm-
765   tick,Xcm+tick), c(Ycm,Ycm), col=tcol);lines(c
766   (max(Xc)-tick,max(Xc)), c(Ycm,Ycm), col=tcol)
767   }
768   plot.title <- function() {title(main=bquote(
769   paste(I[fil], " = ", .(format(IH[1], nsmall
770   =2)), " A ", "B = ", .(format(B[l]*10, nsmall
771   =1)), " kG ", "V = ", .(format(V[l]/1e3,
772   nsmall=2)), " kV ", I[e], " = ", .(format(I[l]
773   *1e3, nsmall=0)), " mA")),xlab="X [mm]",ylab=
774   "Y [mm]")}
775   filled.contour(Xc, Yc, Zphys, xlim=xylim, ylim
776   =xylim, asp=1,levels=seq(Zlim[1], Zlim[2],
777   length.out=Nc), col=palette,plot.title=plot.
778   title(),plot.axes=plot.ticks(),key.title=
779   title(main=expression(paste(j, " [" , A/cm^2,
780   "]" )),key.axes=axis(4))
781   if(RUBBER.STAMP){mtext(paste(fns[l], "\n", "
782   Analyzed on", date(), " ",R.version.string),
783   side = 1, line = 3, adj = 1,font = 3, cex =
784   .7)}
785   # save to file
786   file.prefix <- paste(out.dir, fname.id, "2D_",
787   sep="")
788   fout <- paste(file.prefix,formatC(1, width=2,
789   flag="0"), ".png", sep="")
790   #dev.print(png, file=fout, width=wiland*reso,
791   height=heland*reso)
792   dev2bitmap(file=fout, width=wiland, height=
793   heland, res=reso)
794   fout <- paste(file.prefix,formatC(1, width=2,
795   flag="0"), ".pdf", sep="")
796   dev.print(pdf, file=fout)
797   fout <- paste(file.prefix,formatC(1,width=2,
798   flag="0"), ".eps", sep="")
799   dev.print(postscript,file=fout)
800 }
801 # --- 2D CENTERED CONTOUR PLOTS ---#
802 if(MAKE.PLOTS){
803   # plot 2D contour, bare, centered
804   dev.new()
805   par(oma=rep(0,4), mar=rep(0,4))
806   if(BKGR.BLACK) par(fg="white", col="white",
807   col.axis="white",col.lab="white", col.main="
808   white",col.sub="white")
809   filled.contour.nokey(Xc-Xcorr, Yc-Ycorr, Zphys
810   , asp=1,levels=seq(Zlim[1], Zlim[2], length.
811   out=Nc), col=palette,frame.plot=FALSE)
812   # save to file
813   file.prefix <- paste(out.dir, fname.id, "2
814   Dcentbare_", sep="")
815   fout <- paste(file.prefix,formatC(1, width=2,
816   flag="0"), ".png", sep="")
817   dev.print(png, file=fout, width=pwpx, height=
818   phpx)
819   #dev2bitmap(file=fout, width=pwid, height=phei
820   , res=reso)
821   fout <- paste(file.prefix,formatC(1, width=2,
822   flag="0"), ".pdf", sep="")
823   dev.print(pdf, file=fout)
824   fout <- paste(file.prefix,formatC(1,width=2,
825   flag="0"), ".eps", sep="")
826   dev.print(postscript,file=fout)
827 }
828 if(MAKE.PLOTS){
829   # plot 2D contour, legend, centered
830   wiland <- 7; heland <- 6
831   dev.new(width=wiland, height=heland)
832   par(oma=rep(0,4), mar=c(4.2,3.2,4.2,0.5), mgp=
833   c(1.5, 0.5, 0))
834   if(BKGR.BLACK) par(fg="white", col="white",
835   col.axis="white",col.lab="white", col.main="
836   white",col.sub="white")
837   tick <- diff(range(Xc)) * 0.015; tcol <- "
838   white"
839   plot.ticks <- function() {axis(1); axis(2);
840   lines(c(Xcm,Xcm), c(min(Yc), min(Yc)+tick),
841   col=tcol);lines(c(Xcm,Xcm), c(Ycm-tick, Ycm+
842   tick), col=tcol);lines(c(Xcm,Xcm), c(max(Yc)-
843   tick,max(Yc)), col=tcol);lines(c(min(Xc),min(
844   Xc)+tick), c(Ycm,Ycm), col=tcol);lines(c(Xcm-
845   tick,Xcm+tick), c(Ycm,Ycm), col=tcol);lines(c
846   (max(Xc)-tick,max(Xc)), c(Ycm,Ycm), col=tcol)
847   }
848   plot.title <- function() {title(main=bquote(
849   paste(I[fil], " = ", .(format(IH[1], nsmall
850   =2)), " A ", "B = ", .(format(B[l]*10, nsmall
851   =1)), " kG ", "V = ", .(format(V[l]/1e3,
852   nsmall=2)), " kV ", I[e], " = ", .(format(I[l]
853   *1e3, nsmall=0)), " mA")),xlab="X [mm]",ylab=
854   "Y [mm]")}
855   filled.contour(Xc, Yc, Zphys, xlim=xylim, ylim
856   =xylim, asp=1,levels=seq(Zlim[1], Zlim[2],
857   length.out=Nc), col=palette,plot.title=plot.
858   title(),plot.axes=plot.ticks(),key.title=
859   title(main=expression(paste(j, " [" , A/cm^2,
860   "]" )),key.axes=axis(4))
861   if(RUBBER.STAMP){mtext(paste(fns[l], "\n", "
862   Analyzed on", date(), " ",R.version.string),
863   side = 1, line = 3, adj = 1,font = 3, cex =
864   .7)}
865   # save to file
866   file.prefix <- paste(out.dir, fname.id, "2D_",
867   sep="")
868   fout <- paste(file.prefix,formatC(1, width=2,
869   flag="0"), ".png", sep="")
870   #dev.print(png, file=fout, width=wiland*reso,
871   height=heland*reso)
872   dev2bitmap(file=fout, width=wiland, height=
873   heland, res=reso)
874   fout <- paste(file.prefix,formatC(1, width=2,
875   flag="0"), ".pdf", sep="")
876   dev.print(pdf, file=fout)
877   fout <- paste(file.prefix,formatC(1,width=2,
878   flag="0"), ".eps", sep="")
879   dev.print(postscript,file=fout)
880 }

```



```

    }
784 plot.title <- function() {title(main=bquote(
      paste(I[fil], " = ", .(format(IH[1], nsmall
785 =2)), " A ", "B = ", .(format(B[1]*10, nsmall
      =1)), " kG ", "V = ", .(format(V[1]/1e3,
786 nsmall=2)), " kV ", I[e], " = ", .(format(I[1]
      *1e3, nsmall=0)), " mA")),xlab="X [mm]",ylab=
787 "Y [mm]")}
788
789 # save to file
790 file.prefix <- paste(out.dir, fname.id, "2
      Dcent_", sep="")
791 fout <- paste(file.prefix,formatC(1, width=2,
      flag="0"), ".png", sep="")
792 #dev.print(png, file=fout, width=wiland*reso,
      height=heland*reso)
793 dev2bitmap(file=fout, width=wiland, height=
      heland, res=reso)
794 fout <- paste(file.prefix,formatC(1, width=2,
      flag="0"), ".pdf", sep="")
795 dev.print(pdf, file=fout)
796 fout <- paste(file.prefix,formatC(1,width=2,
      flag="0"), ".eps", sep="")
797 dev.print(postscript,file=fout)
798 }
799
800 # --- 3D PLOTS ---#
801 if(MAKE.PLOTS){
802   # plot 3D
803   rgl.open()
804   #par3d(windowRect=c(0, 0, pwpRGL, phpRGL),
      family="serif", cex=2.5)
805   par3d(windowRect=c(0, 0, pwpRGL, phpRGL),
      family="serif")
806   bg3d(pbgr)
807   view3d(fov=45, userMatrix=matrix(c(0.7,-
      0.7,0,0,0.54,0.54,0.57,0,-0.4,-
808 0.4,0.86,0,0,0,1), nrow=4, ncol=4, byrow=
      TRUE))
809   if(D3.AXIS){persp3d(Xc, Yc, Zphys, col=mcol,
      lit=FALSE,xlab="X [mm]", ylab="Y [mm]", zlab=
      "j [A/cm^2]",axes=TRUE,box=FALSE)}
810   else{persp3d(Xc, Yc, Zphys, col=mcol, lit=
      FALSE, xlab="", ylab="", zlab="", axes=TRUE)}
811   grid3d(c("x+", "y+"), at = NULL,, lwd = 1, lty
      = 1, n = 5)
812   #bbox3d(color=c("#333377","black"), emission
      ="#333377", specular="#3333FF", shininess=5,
      alpha=0.8,xlab="X [mm]", ylab="Y[mm]", zlab="
      j[A/cm^2]")
813   #axes3d(edges="bbox", labels = TRUE, tick =
      TRUE, nticks = 5, main="Profile", xlab="X [mm]
      ", ylab="Y[mm]", zlab="j[A/cm^2]")
      #box3d()
814   #title3d(main = "Profile", sub = NULL, xlab =
      "X", ylab = "Y", zlab = "Z", line = NA)
815   file.prefix <- paste(out.dir, fname.id, "3D_",
      sep="")
816   fout <- paste(file.prefix,formatC(1, width=2,
      flag="0"), ".png", sep="")
817   rgl.snapshot(fout)
818 }
819 if(MAKE.PLOTS){
820   # 2D vacuum measurement
821   if(VACUUM){
822     #Plim <- c(1e-8, 1.5e-7)
823     Plim <- range(Zvac, na.rm=TRUE)
824     dev.new(width=wiland, height=heland)
825     par(oma=c(0, 0, 0, 1), mar=c
      (4.2,3.2,4.2,0.5), mgp=c(1.5, 0.5, 0))
826     if(BKGR.BLACK) par(fg="white", col="white",
      col.axis="white",col.lab="white", col.main=
      "white",col.sub="white")
827     plot.title <- function() {title(main=bquote(
      paste(I[fil], " = ", .(format(IH[1], nsmall
      =2)), " A ", "B = ", .(format(B[1]*10,
      nsmall=1)), " kG ", "V = ", .(format(V[1]/1
      e3, nsmall=2)), " kV ", I[e], " = ", .(
      format(I[1]*1e3, nsmall=0)), " mA")),xlab="
      H corrector setting [A]",ylab="V corrector
      setting [A]")}
828     filled.contour(X, Y, Zvac, asp=1,levels=seq(
      Plim[1], Plim[2], length.out=Nc), col=
      palette,plot.title=plot.title(),key.title=
      title(main=expression(paste(P, " [mbar]")))
      )
829     if(RUBBER.STAMP){mtext(paste(fns[1], "\n", "
      Analyzed on", date(), " ",R.version.string)
      ,side = 1, line = 3, adj = 1,font = 3, cex
      = .7)}
830     # save to file
831     file.prefix <- paste(out.dir, fname.id, "_
      vac2D_", sep="")
832     fout <- paste(file.prefix,formatC(1, width
      =2, flag="0"), ".png", sep="")
833     #dev.print(png, file=fout, width=wiland*reso
      , height=heland*reso)
834     dev2bitmap(file=fout, width=wiland, height=
      heland, res=reso)
835     fout <- paste(file.prefix,formatC(1, width
      =2, flag="0"), ".pdf", sep="")
836     dev.print(pdf, file=fout)
837     fout <- paste(file.prefix,formatC(1, width
      =2, flag="0"), ".eps", sep="")
838     dev.print(postscript, file=fout)
839   }
840 }
841 if(EXPORT.CALIBRATED.PROFILE){
842   message("Exporting calibrated profile...")
843   Xmat <- Xc %>% rep(1, Ny)
844   Ymat <- rep(1, Nx) %>% Yc
845   Zmat <- Zphys
846   CalProf <- data.frame(x.mm = as.vector(Xmat),y
      .mm = as.vector(Ymat),j.Acm2 = as.vector(
      Zphys))
847   fout <- paste(out.dir, fname.id, "_",formatC(1
      , width=2, flag="0"), "_calprof.txt", sep="")

```

```

848 write.table(CalProf, file=fout, row.names=      894 ypart[k] <- Yc[j] + runif(1, -0.5*Ycstep,
      FALSE, col.names=TRUE)                    895 0.5*Ycstep)
849 system(paste("gzip", fout))                896 k <- k+1
850 }                                             897 }}
851 if(EXPORT.RADIAL){                            898 }}
852 message("Calculating average radial profile... 899 cut <- (is.na(xpart)==FALSE) & (is.na(ypart)==
      ")                                         900 FALSE)
853 Xmat <- (Xc-Xcorr) %o% rep(1, Ny)            901 xpart <- xpart[cut]; ypart <- ypart[cut]
854 Ymat <- rep(1, Nx) %o% (Yc-Ycorr)           902 part_coord <- data.frame(xpart, ypart)
855 r <- as.vector(sqrt(Xmat^2 + Ymat^2))        903 dev.new()
856 rstep <- max(Xcstep, Ycstep)/4              904 par(oma=rep(0,4), mar=c(3.2, 3.2, 0.5, 0.5),
857 rf <- cut(r, breaks=seq(min(r), min(r2[1]*   905 mgp=c(1.5, 0.5, 0))
      1500, max(r)), by=rstep),ordered=TRUE)    906 N.plot.max <- 4096
858 j <- as.vector(Zphys)                       907 if(length(xpart) > N.plot.max) ii <- idwnsmpl(
859 rm <- tapply(r, rf, mean)                   908 x=xpart, n=N.plot.max)
860 jm <- tapply(j, rf, mean)                   909 else ii <- 1:length(xpart)
861 rpro <- data.frame(r.mm=rm, j.au=jm)         910 plot(xpart[ii], ypart[ii], pch=".", asp=1,xlab
862 message("Plotting radial profile...")        911 ="X coord. [mm]", ylab="Y coord. [mm]")
863 dev.new()                                    912 message("Saving Particle Plot")
864 par(oma=rep(0,4), mar=c(3.2, 3.2, 0.5, 0.5), 913 file.prefix <- paste(out.dir, fname.id, "_",
      mgp=c(1.5, 0.5, 0))                      914 sep="")
865 plot(rm, jm, xlab="Radial distance [mm]", ylab 915 fout <- paste(file.prefix,formatC(1, width=2,
      ="Current density [arb. units]",pch="+",col=" 916 flag="0"), "_particles.eps", sep="")
      blue")                                     dev.print(postscript, file=fout)
866 file.prefix <- paste(radial.dir, fname.id, "_" 917 message("Writing coordinates of ", length(
      , formatC(1, width=2, flag="0"), "_radial", 918 xpart), " particles...")
      sep="")                                     fnpart <- paste(file.prefix,formatC(1, width
867 fout <- paste(file.prefix, ".pdf", sep="")    919 =2, flag="0"), "_", length(xpart), "_
868 dev.print(pdf, file=fout)                   920 particles.txt", sep="")
869 message("Exporting radial profile to text file 921 write.table(part_coord, file=fnpart, row.names
      ...")                                     =FALSE, col.names=FALSE)
870 fout <- paste(file.prefix, ".txt", sep="")    922 system(paste("gzip", fnpart))
871 write.table(rpro, file=fout, row.names=FALSE, 923 }
      col.names=TRUE)                            924
872 }                                             925 # polar decomposition
873 }                                             926 if(POLAR.DECOMPOSITION){
874 # downsample a large array for plotting      927 dev.new(width=9, height=7)
      purposes                                   928 source("../Polar/polar_decomposition.R")
875 # function returns ordered vector of indices 929 nn <- 1:32 #Was 128
876 idwnsmpl <- function(x=runif(100), n=10){i <- 930 mm <- 0:32 #Was 48
      sort(sample(x=1:length(x), size=n));return(i)} 931
877 }                                             932 PD <- pol_dec(Xc=Xc-Xcorr,Yc=Yc-Ycorr,Z=Z,nn=
878 # export particle coordinates                933 nn,mm=mm,a=30,BOUNDARY=0)
879 if(EXPORT.PARTICLES){                       934 P_mat <- PD$P
880 message("Exporting particle coordinates for   935 #rownames(P_mat)<-1:32
      Warp field solver...")                   936 #colnames(P_mat)<-0:32
881 Znorm <- Z/sum(Z)                            937 nModes <- rowSums(Mod(P_mat))
882 Np <- round(Nmax*Znorm)                     938 mModes <- colSums(Mod(P_mat))
883 cat("Max # of particles per bin:", max(Np), "\ 939 I_mat <- PD$I
      n")                                       940
884 cat("Empty bins:", length(Np[Np==0]), "\n") 941
885 xpart <- numeric(Nmax); xpart <- NA          942 # plots
886 ypart <- numeric(Nmax); ypart <- NA          943 par(oma=c(0,0,3,0))
887 k <- 1                                       944 a <- layout(matrix(c(1,4,2,5,3,6),2,3),widths=
888 for(i in 1:Nx){                              945 c(0.9,0.9,0.9))
889 for(j in 1:Ny){                              946 layout.show(a)
890 if(Np[i,j]>=1 & k <= Nmax){                 947 image(Xc-Xcorr,Yc-Ycorr,Z,asp=1,col=palette,
891 for(m in 1:Np[i,j]){                         948 main="Measurement")
892 # generate coordinates uniformly within      949 image(Xc-Xcorr,Yc-Ycorr,Mod(I_mat),asp=1,col=
      each bin                                950 palette,main="Reconstruction")
893 xpart[k] <- Xc[i] + runif(1, -0.5*Xcstep,   951 image(Xc-Xcorr,Yc-Ycorr,abs(Mod(I_mat)-Z),asp
      0.5*Xcstep)                               952 =1,col=gray(0:64/64), main="Errors")

```



```

939 image.plot(nn,mm,log10(Mod(P_mat)), col=heat. 949
    colors(64),main="Mode amplitudes", xlab=" 950
    Radial mode n",ylab="Azimuthal mode m",nlevel951
    =64, axis.args=list( at=log10(ticks), labels=
    ticks)) 952
940 plot(nn,nModes,type="o",log="y",pch=16, main="953
    Radial modes",xlab="Radial mode n", ylab=" 954
    Amplitude") 955
941 plot(mm,mModes,type="o",log="y",pch=16, main="
    Azimuthal modes",xlab="Azimuthal mode m", 956
    ylab="Amplitude") 957
942 mtext(fname.id, outer=TRUE) 958 }
943 dev.print(pdf,file="polar.pdf",width=9,height 959 }
    =7,pointsize=10,family="Times")
944 layout(1) 960 if(MAKE.PLOTS) dev.off()
945 file.prefix <- paste(polar.dir, fname.id, "_", 961 quartz.options(reset=TRUE)
    sep="") 962 pdf.options(reset=TRUE)
946 # save coefficients 963 ps.options(reset=TRUE)
947 fncoe <- paste(file.prefix, 964
    formatC(1,width=2, flag="0"), ".RData", sep=" 965
    ") 966 cat("\nStop: ", date(),"\n")
    sink()

```

C.2 Transverse Field Measurement

```

1 #####
2 # NAME: Fieldsolver_single.py
3 # AUTHOR: Vince Moens, Giulio Stancari
4 # LAST MODIFIED: 29.07.2013
5 # PURPOSE: Calculation of charge density,
6 #           electric potential and electric fields of the
7 #           measured electron beam profiles
8 #####
9 from warp import *
10 from numpy.linalg import *
11 import matplotlib.mlab as mlab
12 import matplotlib.pyplot as plt
13 import math as math
14 # Options
15 printfields = true
16 particleplot = true
17 chargedensityplot = true
18 potentialplot = true
19 electricfieldplot = true
20 electricfieldlineplot = true
21 zoomedplots = true
22 makepsfile = false
23 findmaxcenter = true
24 security_check = true
25 LHC = true
26
27 # Loading Files
28 fns = [
29 # new profiles acquired with ACL script
30 "../Profile/Results/Chart_Colors/
    HG1b_121218_9p25A_3-3-3
    kG_500V_51mA_b_57_8102_particles.txt", #0
    ...
    95 "../Profile/Results/Chart_Colors/
    HG1b_130521_9p25A_06-24-06
    kG_4kV_1368mA_136_8192_particles.txt" #63
    ]
96 ]
97
98 Bgun=[3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 1, 1, 1, 2.5,
    2, 2.5, 2.5, 2.5, 2.5, 2, 2, 2, 1.5, 1.5, 1.5,
    3, 2.5, 3, 3, 3, 3, 3, 1, 1, 0.8, 0.8, 0.8, 0.8,
    0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 1, 1, 1,
    0.6, 0.4, 0.4, 1, 1, 1, 0.6, 1, 0.4, 1, 0.4,
    0.4, 0.4, 0.6, 0.6, 0.6]
99 Bmain=[3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 1, 1, 1,
    2.5, 2, 2.5, 2.5, 2.5, 2.5, 2, 2, 2, 1.5, 1.5,
    1.5, 3, 2.5, 3, 3, 3, 3, 3, 3, 3.2, 3.2, 3.2,
    3.2, 3.2, 3.2, 3.2, 3.2, 3.2, 3.2, 3.2, 4, 4,
    4, 2.4, 1.6, 1.6, 4, 4, 4, 2.4, 4, 1.6, 4, 1.6,
    1.6, 1.6, 2.4, 2.4, 2.4]
100 Bcoll=[3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 1, 1, 1,
    2.5, 2, 2.5, 2.5, 2.5, 2.5, 2, 2, 2, 1.5, 1.5,
    1.5, 3, 2.5, 3, 3, 3, 3, 3, 3, 2, 0.8, 0.8, 0.8,
    0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 1, 1,
    1, 0.6, 0.4, 0.4, 1, 1, 1, 0.6, 1, 0.4, 1, 0.4,
    0.4, 0.4, 0.6, 0.6, 0.6]
101
102 Voltage=[500, 8000, 4000, 2000, 1000, 6000, 3000,
    7000, 8000, 8000, 889, 2000, 3000, 5556, 3556,
    5000, 2083, 3472, 5000, 1333, 2222, 3111, 750,
    2000, 1250, 3000, 500, 500, 500, 500, 500, 500,
    500, 500, 500, 2000, 4000, 1000, 8000, 7000,
    250, 125, 3000, 5000, 6000, 3125, 1000, 6250,
    500, 1000, 500, 500, 2000, 4000, 1000, 5000,
    2000, 8000, 750, 1500, 2500, 2000, 3000, 4000]
103 Current=[0.051, 2.940, 1.100, 0.388, 0.140,
    1.924, 0.694, 2.394, 0.440, 0.027, 0.118, 0.398,
    0.726, 1.770, 0.928, 1.484, 0.412, 0.865,
    1.460, 0.213, 0.448, 0.744, 0.090, 0.390, 0.192,
    0.582, 0.051, 0.050, 0.050, 0.050, 0.050,

```

```

0.050, 0.070, 0.070, 0.073, 0.526, 1.450, 0.195, 157 # --- beam
3.7, 3.1, 0.026, 0.009, 0.944, 1.99, 2.53, 158 top.ekin = Voltage[n]
1.022, 0.196, 2.754, 0.073, 0.195, 0.072, 0.073, 159 if security_check:
0.534, 1.44, 0.196, 1.98, 0.488, 3.88, 0.125, 160     if not ((str(int(top.ekin))[0]+"kV" in item) or
0.332, 0.658, 0.526, 0.924, 1.368]           (str(int(top.ekin)) in item)):
104 n=63                                         161         print("Voltage is wrong!")
105 if(n in [24]):LHC = false                    162         sys.exit()
106 item=fns[n]                                  163 top.vbeam = 0
107 print("Plotting results...")                 164 top.ibeam = -Current[n]
108 palette("ImageJ.Fire.gp")                   165 if security_check:
109 Bgun=Bgun[n]*0.1                             166     if str(int(top.ibeam*-1e3)) not in item:
110 Bmain=Bmain[n]*0.1                           167         print("Current is wrong!")
111 Bcoll=Bcoll[n]*0.1                           168         sys.exit()
112 print("Bgun = "+str(Bgun)+" T; Bmain = "+str( 169 top.lrelativ = true
    Bmain)+" T; Bcoll = "+str(Bcoll)+"_T")      170 top.relativity = true
113                                               171 top.derivqty()
114 # --- Set comment lines, user's name.        172 totalweight = top.ibeam * dz / abs(elec.zion) /
115 if item.startswith("../Profile/Results/      top.echarge / top.vbeam
    Chart_Colors/"): top.runid="Results/H1"+ item 173
    [38:]                                         174 # --- initialize
116 top.pline2 = "Hollow electron beam -1-in cathode" 175 print("Initializing...")
117 top.pline1 = "Field calculation from measured 176 package("wxy")
    current density profile"                   177 generate()
118 top.runmaker = "V. Moens"                   178 installconductor(driftpipe)
119 setup(makepsfile)                            179
120 winon()                                       180 # --- read particle positions
121                                               181 print("Reading particle positions...")
122 # --- Define the electron speices            182 posi = fromfile(item, sep=' ')
123 elec = Species(type=Electron)                183 npart = len(posi)/2
124                                               184 posi = reshape(posi, (npart,2))
125 # --- lattice                                185
126 print("Defining lattice...")                 186 # --- Set particle weight for the beam
127 rpipe = 0.03 # test stand: 3 cm; TEL2: 3.5 cm 187 elec.sw = totalweight/npart
128 syslen = 2.86                                188 elec.nps = 0
129 top.drftzs[0] = 0                             189
130 top.drftze[0] = syslen                       190 # --- add particles according to measured current
131 top.drftap[0] = rpipe                         density
132 print("Beam pipe radius = "+str(rpipe)+" m") 191 print("Calculating charge density according to
133 particle distribution...")
134 # --- field solver                           192 print("Macroparticle weight = %f" % elec.sw)
135 print("Setting up field solver...")           193 xinit = posi[:,0]*math.sqrt(float(Bcoll)/float(
136 w3d.solvegeom = w3d.XYgeom) * mm
137 fudge = 1.05                                  194 yinit = posi[:,1]*math.sqrt(float(Bcoll)/float(
138 w3d.xmmax = rpipe*fudge                       Bmain)) * mm
139 w3d.xmmin = -rpipe*fudge                      195 zinit = zeros(npart)
140 w3d.ymmax = rpipe*fudge                      196 vxinit = zeros(npart)
141 w3d.ymmin = -rpipe*fudge                    197 vyinit = zeros(npart)
142 w3d.zmmax = syslen                           198 vzinit = zeros(npart) + top.vbeam
143 w3d.zmmin = 0                                199 elec.addpart(xinit,yinit,zinit,vxinit,vyinit,
144 w3d.nx = 256                                  vzinit)
145 w3d.ny = 256                                  200
146 w3d.nz = 1                                    201 # --- deposit particle charge density
147 dx = (w3d.xmmax - w3d.xmmin) / w3d.nx        202 loadrho()
148 dy = (w3d.ymmax - w3d.ymmin) / w3d.ny        203
149 dz = (w3d.zmmax - w3d.zmmin) / w3d.nz        204 # --- find corresponding potentials and fields
150 w3d.l2symtry = false                          205 print("Solving for fields...")
151 w3d.l4symtry = false                          206 fieldsolxy(-1)
152                                               207
153 # --- Conductors                             208 # X vs. Y
154 driftpipe = ZCylinderOut(condid = 1, radius=0.03, 209 if particleplot:
    zlower=0, zupper=syslen, voltage=0)        210     ppxy()
155 scraper=ParticleScraper(driftpipe)           211     fma()
156                                               212 # charge density in x-y plane

```

```

213 if chargedensityplot:
214     pcrhoxy(lframe=1, cellarray=1, contours=None)
215     fma()
216 # potential
217 if potentialplot:
218     pcphixy(lframe=1, cellarray=1)
219     fma()
220 # electric field components and strength
221 if electricfieldplot:
222     pcselfexy(lframe=1, comp='x', cellarray=1)
223     fma()
224     pcselfexy(lframe=1, comp='y', cellarray=1)
225     fma()
226
227 Ef = sqrt(w3d.selfe[0,:,:]**2 + w3d.selfe
    [1,:,:]**2 + w3d.selfe[2,:,:]**2)
228 ppgeneric(grid=Ef,x=w3d.xmesh,y=w3d.ymesh,
    contours=10,cellarray=1,titles=0)
229 ptitles("Electric field strength in x-y plane",
    "X","Y")
230 fma()
231
232 if electricfieldlineplot:
233     plg(Ef[w3d.nx/2,:]/1e3, w3d.ymesh*1e3, color="
    red")
234     plg(Ef[:,w3d.ny/2]/1e3, w3d.xmesh*1e3, color="
    blue")
235     ptitles("E-field vs X (blue) and Y (red)", "X or
    Y (mm)", "E-field (kV/m)")
236     fma()
237
238 # zoomed-in plots
239 if zoomedplots:
240     if particleplot:
241         pcrhoxy(lframe=1, cellarray=1, contours=None)
242         limits(-0.01, 0.01, -0.01, 0.01)
243         fma()
244     if potentialplot:
245         pcphixy(lframe=1, cellarray=1, contours=None)
246         limits(-0.01, 0.01, -0.01, 0.01)
247         fma()
248     if electricfieldplot:
249         ppgeneric(grid=Ef,x=w3d.xmesh,y=w3d.ymesh,
            contours=None,cellarray=1,titles=0)
250         limits(-0.01, 0.01, -0.01, 0.01)
251         ptitles("Electric field strength in x-y plane"
            , "X", "Y")
252         fma()
253
254 # --- write results
255 if printfields:
256     print("Writing results to file...")
257     roi = 0.01 # region of interest in m, +/-
258     ispan = int(round(roi/dx))
259     print("Half span in grid points = "+repr(ispan)
        )
260     i1 = w3d.nx/2 - ispan
261     i2 = w3d.nx/2 + ispan
262     name = "Results/H1"+item[38:-4]+"_fields.txt"
263     out = open(name, 'wb')
264     line = "Xmesh_mm\tYmesh_mm\tRho_Cm3\tPhi_V\
        \tEx_Vm\tEy_Vm\n"
265     out.write(line)
266     for i in range(i1, i2):
267         for j in range(i1, i2):
268             xx = repr(w3d.xmesh[i]*1e3)
269             yy = repr(w3d.ymesh[j]*1e3)
270             rho = repr(w3d.rho[i,j,0])
271             pot = repr(w3d.phi[i,j,0])
272             ex = repr(w3d.selfe[0,i,j,0])
273             ey = repr(w3d.selfe[1,i,j,0])
274             line = xx+"\t"+yy+"\t"+rho+"\t"+pot+"\t"
                +ex+"\t"+ey+"\n"
275             out.write(line)
276     out.close()
277
278 ## -- Calculating the emittance Groth in the
    center --##
279 print "\n Calculating Emittance Growth in the
    center \n"
280 intervall = 0.8
281 mean=0
282 sigma=4.69e-4
283 print "Sigma = "+ str(sigma)
284 Cath_radius=6.75e-3
285 print "Cathode Radius = "+ str(Cath_radius)
286 R = array([[sqrt(w3d.ymesh[i]**2+w3d.xmesh[j]**2)
            for i in range(w3d.ymesh.size)] for j in range(
            w3d.xmesh.size)])
287 Gauss=mlab.normpdf(R,mean,sigma)
288 Gauss=Gauss/sum(Gauss)
289 Efw=array([[Ef[i,j]*Gauss[i,j] for i in range(w3d
            .ymesh.size)] for j in range(w3d.xmesh.size)])
290 Efcw=Efw[R <= 0.00675*intervall*math.sqrt(float(
            Bcoll)/float(Bmain))]
291 Efc=Ef[R <= 0.00675*intervall*math.sqrt(float(
            Bcoll)/float(Bmain))]
292 Efcw_RMS=std(Efcw)
293 Efc_RMS=std(Efc)
294 Efcw_mean=average(Efcw)
295 Efc_mean=average(Efc)
296
297 #Calculating emittance growth at center
298 m0=938.272e6
299 print "Proton Rest mass = "+str(m0)+" eV"
300 if (LHC): Etot=4e12
301 else: Etot=980e9
302 print "Proton Energy = "+str(Etot)+" eV"
303 q=1
304 print "Elementary Charge is "+str(q)+" electron
    charge"
305 Er_center=Efcw_RMS
306 Er_center_4=Efcw_RMS*(6.75e-3*math.sqrt(float(
            Bcoll)/float(Bmain)))/(4*sigma)
307 Er_center_6=Efcw_RMS*(6.75e-3*math.sqrt(float(
            Bcoll)/float(Bmain)))/(6*sigma)
308 print "Maximum electric field in center is "+str(
            Er_center)+" V/m"
309 L=2.65
310 print "Length of interaction region is "+str(L)+"
    m"
311 gamma=Etot/m0
312 print "gamma is "+str(Etot/m0)
313 if (LHC): beta=250
314 else: beta=150
315 print "beta is "+str(beta)

```

```

316 if(LHC): R_freq=1.12e4
317 else: R_freq=4.7e4
318 t_rev=1/R_freq
319 print "revolution time is "+str(t_rev)
320 if(LHC):
321     Emit=3.75e-6
322     print "Emittance of LHC is "+str(Emit)
323 else:
324     Emit=2.5e-6
325     print "Emittance of TEV is "+str(Emit)
326 kick_center=math.atan(Etot*q*Er_center*L/(Etot**2
-m0**2))
327 kick_center_4=math.atan(Etot*q*Er_center_4*L/(
Etot**2-m0**2))
328 kick_center_6=math.atan(Etot*q*Er_center_6*L/(
Etot**2-m0**2))
329 print "The kick is "+str(kick_center)
330 delepsilon_center=beta*kick_center**2*gamma
331 delepsilon_center_4=beta*kick_center_4**2*gamma
332 delepsilon_center_6=beta*kick_center_6**2*gamma
333 gr_center=delepsilon_center/(t_rev*Emit)
334 gr_center_4=delepsilon_center_4/(t_rev*Emit)
335 gr_center_6=delepsilon_center_6/(t_rev*Emit)
336 print "Emittance growth is "+str(
delepsilon_center)+" m/turn"
337 print "emittance growth rate is "+str(gr_center)+
" 1/s at cathode radius"
338 print "emittance growth rate is "+str(gr_center_4
)+" 1/s at 4 sigma"
339 print "emittance growth rate is "+str(gr_center_6
)+" 1/s at 6 sigma"
340 print "\n"
341 print str(item[38:-4])
342 print "\n Calculating Emittance Growth overall \n
"
343
344 name = "Results/H1"+item[38:-4]+"_E_max_Gaussian.
txt"
345 print "Saving data to text file: "+str(name)+"\n"
346 out = open(name, 'wb')
347 titleline = item[38:-4)+"\tE_max [kV/m]\tKick []\
tEmittance Growth [m/turn]\tEmittance Growth
Rate [1/s]\n"
348 out.write(titleline)
349 line = "Center:\t"+str(Er_center)+"\t"+str(
kick_center)+"\t"+str(delepsilon_center)+"\t"+
str(gr_center)+"\n"
350 out.write(line)
351 line = "Center_6s:\t"+str(Er_center_6)+"\t"+str(
kick_center_6)+"\t"+str(delepsilon_center_6)+"\t
"+str(gr_center_6)+"\n"
352 out.write(line)
353 line = "Center_4s:\t"+str(Er_center_4)+"\t"+str(
kick_center_4)+"\t"+str(delepsilon_center_4)+"\t
"+str(gr_center_4)+"\n"
354 out.write(line)
355 out.close()

```

Attachments/Fieldsolver_single_app.py

C.3 Numerical WARP simulations

```

1 #####
2 # NAME: tbench_complex.py
3 # AUTHOR: Vince Moens, Giulio Stancari
4 # LAST MODIFIED: 05.08.2013
5 # PURPOSE: 3D Simulations in WARP using gun or
profile injection
6 #####
7
8 # NOTES ON EMITTANCE TYPES
9 # GUN: The code automatically injects particles
from the cathode conductor using Child Langmuir
law.
10 # PROFILE: Profiles measured in the test bench
are injected into the lattice. The gun is
omitted from the lattice. Injection takes
place at the end of that anode.
11
12 #####
13 # >>> Package Loading <<< #
14 #####
15
16 from warp import * # warp code
17 from datetime import *
18
19 #####
20 # >>> File Loading <<< #
21 #####
22
23 # --- Profiles ---#
24 fns = [
25 # new profiles acquired with ACL script
26 "../HG1b/Profile/Results/Chart_Colors/
HG1b_121218_9p25A_3-3-3
kG_500V_51mA_b_57_8102_particles.txt", #0
...
91 "../HG1b/Profile/Results/Chart_Colors/
HG1b_130521_9p25A_06-24-06
kG_4kV_1368mA_136_8192_particles.txt" #63
92 ]
93
94 Bgun=[3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 1, 1, 1, 2.5,
2, 2.5, 2.5, 2.5, 2.5, 2, 2, 2, 1.5, 1.5, 1.5,
3, 2.5, 3, 3, 3, 3, 3, 1, 1, 0.8, 0.8, 0.8, 0.8,
0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 1, 1, 1,
0.6, 0.4, 0.4, 1, 1, 1, 0.6, 1, 0.4, 1, 0.4,
0.4, 0.4, 0.6, 0.6, 0.6]
95 Bmain=[3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 1, 1, 1,
2.5, 2, 2.5, 2.5, 2.5, 2.5, 2.5, 2, 2, 2, 1.5, 1.5,
1.5, 3, 2.5, 3, 3, 3, 3, 3, 3, 3.2, 3.2, 3.2,
3.2, 3.2, 3.2, 3.2, 3.2, 3.2, 3.2, 4, 4,
4, 2.4, 1.6, 1.6, 4, 4, 4, 2.4, 4, 1.6, 4, 1.6,
1.6, 1.6, 2.4, 2.4, 2.4]

```

```

96 Bcoll=[3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 1, 1, 1,
    2.5, 2, 2.5, 2.5, 2.5, 2.5, 2, 2, 2, 1.5, 1.5,
    1.5, 3, 2.5, 3, 3, 3, 3, 3, 3, 2, 0.8, 0.8, 0.8,
    0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 0.8, 1, 1,
    1, 0.6, 0.4, 0.4, 1, 1, 1, 0.6, 1, 0.4, 1, 0.4,
    0.4, 0.4, 0.6, 0.6, 0.6]
97
98 Voltage=[500, 8000, 4000, 2000, 1000, 6000, 3000,
    7000, 8000, 8000, 889, 2000, 3000, 5556, 3556,
    5000, 2083, 3472, 5000, 1333, 2222, 3111, 750,
    2000, 1250, 3000, 500, 500, 500, 500, 500, 500,
    500, 500, 500, 2000, 4000, 1000, 8000, 7000,
    250, 125, 3000, 5000, 6000, 3125, 1000, 6250,
    500, 1000, 500, 500, 2000, 4000, 1000, 5000,
    2000, 8000, 750, 1500, 2500, 2000, 3000, 4000]
99 Current=[0.051, 2.940, 1.100, 0.388, 0.140,
    1.924, 0.694, 2.394, 0.440, 0.027, 0.118, 0.398,
    0.726, 1.770, 0.928, 1.484, 0.412, 0.865,
    1.460, 0.213, 0.448, 0.744, 0.090, 0.390, 0.192,
    0.582, 0.051, 0.050, 0.050, 0.050, 0.050,
    0.050, 0.070, 0.070, 0.073, 0.526, 1.450, 0.195,
    3.7, 3.1, 0.026, 0.009, 0.944, 1.99, 2.53,
    1.022, 0.196, 2.754, 0.073, 0.195, 0.072, 0.073,
    0.534, 1.44, 0.196, 1.98, 0.488, 3.88, 0.125,
    0.332, 0.658, 0.526, 0.924, 1.368]
100
101 # ---Selecting profile ---#
102 item = 51
103 file_ending = "test"
104 Bmain = float(Bmain[item])/10
105 print("Magnetic Field in Main Solenoid: %g " %
    Bmain)
106 Bgun = float(Bgun[item])/10
107 Bcoll = float(Bcoll[item])/10
108 Cathode_Potential = -Voltage[item]
109 print("Cathode Potential: %g " %
    Cathode_Potential)
110 Current = Current[item]
111 print("Current: %g " % Current)
112 npart = -50*Cathode_Potential/500
113
114 #####
115 # >>> Options <<< #
116 #####
117 machine_injtype = "profile"
118 print("Injection type is:" + machine_injtype)
119 if (machine_injtype=="gun"): machine_emitttype = 2
120 elif (machine_injtype=="profile"):
121     machine_emitttype = 1
122 else:
123     print("Wrong machine_injtype!!")
124     quit()
125 machine_type = "tbench"
126 #####
127 # >>> Headers <<< #
128 #####
129 now=datetime.now()
130 date=now.strftime("%y%m%d")
131 time=now.strftime("%H%M")
132 if not os.path.exists("../Results/"+date+"/"):
133     os.makedirs("../Results/"+date+"/")
134 os.system("cp tbench_complex.py* ../Results/"+
    date+"/tbench_"+date+time+"_test.py")
135 top.runid = machine_type+"_"+date+time+"_"+
    machine_injtype+"_"+file_ending
136 if machine_type == "tbench": top.pline2 = "
    Electron Lens Test Bench"
137 else: top.pline2 = "Tevatron Electron Lens 2"
138 if machine_emitttype == 1: top.pline1 = "Constant-
    injection_" + machine_injtype
139 elif machine_emitttype == 2: top.pline1 = "Child-
    Langmuir_" + machine_injtype
140 else: top.pline1 = "other injection method"
141 top.runmaker = "V. Moens"
142
143 #####
144 # >>> Variables <<< #
145 #####
146 # ---Machine Parameters ---#
147 machine_zstart = .0e0
148 machine_syslen = 2.86
149 machine_zplat = machine_syslen
150 machine_piperad = 3*cm
151 zfinal = machine_zstart + machine_syslen
152
153 # ---Electron Gun ---#
154 # - Cathode
155 Cathode_zstart = -29.25*mm
156 Cathode_zend = 0.0*mm
157 Cathode_radi = 6.75*mm
158 Cathode_rado = 12.7*mm
159 Cathode_radcurvb = 10*mm
160 Cathode_radcurvs = 0.5*mm
161 Cathode_voltage = Cathode_Potential
162 # - Anode
163 Anode_zstart = 9.48*mm
164 Anode_z1 = Anode_zstart + 1.5*mm
165 Anode_z2 = Anode_zstart + 3.5*mm
166 Anode_z3 = Anode_z1 + 9*mm
167 Anode_z4 = Anode_z3 + 11.25*mm
168 Anode_z5 = Anode_z4 + 5.625*mm
169 Anode_zend = Anode_z5 + 58.5*mm
170 Anode_ri = 14.25*mm
171 Anode_ro = Anode_ri+5.33*mm
172 Anode_r1 = Anode_ri
173 Anode_r2 = Anode_ro
174 Anode_r3 = Anode_ri
175 Anode_r4 = Anode_ri + 0.675*mm
176 Anode_radtipi = Anode_ri + 1.5*mm
177 Anode_radtipo = Anode_ro -3.5*mm
178 Anode_r5 = Anode_ri + 5.625*mm
179 Anode_rendi = Anode_r5
180 Anode_rendo = Anode_rendi + 1.35*mm
181 Anode_radcurvb = 3.5*mm
182 Anode_radcurvs = -1.5*mm
183 Anode_voltage = 0.0e0
184 # - Electrode F
185 ElectrodeF_zstart = Cathode_zstart
186 ElectrodeF_zend = 0.98*mm
187 ElectrodeF_z1 = ElectrodeF_zend -0.5*mm
188 ElectrodeF_z2 = ElectrodeF_zend -1.4*mm
189 ElectrodeF_ri = 13.1*mm
190 ElectrodeF_ro = ElectrodeF_ri + 1.9*mm
191 ElectrodeF_r1 = ElectrodeF_ri + 0.5*mm

```



```

192 ElectrodeF_radcurvs = -0.5*mm
193 ElectrodeF_radcurvb = 1.4*mm
194 ElectrodeF_voltage = Cathode_Potential
195 # - Electrode C
196 ElectrodeC_zstart = Cathode_zstart
197 ElectrodeC_zend = 1.97*mm
198 ElectrodeC_ri = 20.5*mm
199 ElectrodeC_ro = 22.0*mm
200 ElectrodeC_radcurv = 0.75*mm
201 ElectrodeC_z1 = ElectrodeC_zend-0.75*mm
202 ElectrodeC_voltage = Cathode_Potential
203 # - Gun drift pipe
204 Gun_pipe_zstart = 84.375*mm
205 Gun_pipe_zend = 178.875*mm
206 Gun_pipe_ri = 36*mm #Should this not be 3 cm?
207 Gun_pipe_ro = 33.75*mm
208 Gun_pipe_voltage = 0.0
209
210 # ---- Solenoids ----#
211 # - Gun Solenoid
212 tbench_solenoid_gun_zstart = -13*cm
213 tbench_solenoid_gun_zend = 37*cm
214 tbench_solenoid_gun_radi = 28*cm
215 tbench_solenoid_gun_rado =
    tbench_solenoid_gun_radi+5.433*cm
216 tbench_solenoid_gun_b = Bgun
217 tbench_solenoid_gun_voltage = 0.0
218 # - Main Solenoid
219 tbench_solenoid_main_zstart = 0.60
220 tbench_solenoid_main_zend = 2.52
221 tbench_solenoid_main_radi = 0.20
222 tbench_solenoid_main_rado =
    tbench_solenoid_main_radi+14.48*cm
223 tbench_solenoid_main_b = Bmain
224 tbench_solenoid_main_voltage = 0.0
225 # - Collector Solenoid
226 tbench_solenoid_col_zstart = 2.67
227 tbench_solenoid_col_zend = 3.17
228 tbench_solenoid_col_radi = 28*cm
229 tbench_solenoid_col_rado =
    tbench_solenoid_col_radi + 5.433*cm
230 tbench_solenoid_col_b = Bcoll
231 tbench_solenoid_col_voltage = 0.0
232
233 # --- Drift Spaces ---#
234 # - First Drift
235 tbench_drift1_zstart = 37*cm
236 tbench_drift1_zend = 0.60
237 tbench_drift1_ap = machine_piperad
238 # - Second Drift
239 tbench_drift2_zstart = 2.52
240 tbench_drift2_zend = 2.67
241 tbench_drift2_ap = machine_piperad
242
243 # --- Beam size & position ---#
244 beama0 = 17.5e0*mm
245 beamb0 = 17.5e0*mm
246 beamap0 = .0e0*mm
247 beamp0 = .0e0*mm
248 beamx0 = .0e0*mm
249 beamy0 = .0e0*mm
250 beamxp0 = .0e0*mm
251 beamyp0 = .0e0*mm
252
253 # --- Beam inject parameters ---#
254 beamxinject = .0e0*mm
255 beamyinject = .0e0*mm
256 beamxpinject = .0e0*mm
257 beamypinject = .0e0*mm
258 beamainject = 17.5*mm
259 beambinject = 17.5*mm
260 beamapinject = .0e0*mm
261 beampinject = .0e0*mm
262 beamainjmin = 6.75*mm
263 beambinjmin = 6.75*mm
264 beamzinject = machine_zstart
265
266 #####
267 # >>> Script <<< #
268 #####
269
270 #-----#
271 #   Invoke setup routine   #
272 #-----#
273 setup(makepsfile=0)
274 # winon()
275 palette("ImageJ_Fire.gp")
276
277 #-----#
278 #   Particle Loading   #
279 #-----#
280 # We only need to load the particles if the
    inject type is profle
281 if (machine_injtype == "profile"):
282     print("Reading particle positions...")
283     posi = fromfile(fns[item], sep=' ')
284     npart = len(posi)/2
285     posi = reshape(posi, (npart,2))
286     print("Calculating charge density according to
        particle distribution...")
287 print("Number of particles = %e" % npart)
288
289 #-----#
290 #   Particle Properties   #
291 #-----#
292 # --- Particle parameters ---#
293 electron_Iz           = -Current
294 cyc_freq              = echarge*Bmain/emass
295 timestep              = pi/(2*cyc_freq)
296 electron_vz          = .0e0
297 electron_ekin         = -Cathode_Potential
298 electron_q            = -1.e0
299 vthz                  = .0e0
300 lrelativity            = true
301 relativity             = true
302 sw=int((-electron_Iz*timestep/echarge)/npart)
303 elec = Species(type=Electron,color=red,weight=sw)
304 elec.ibeam            = electron_Iz
305 print ("Beam Current: %g" % elec.ibeam)
306 elec.zion              = electron_q
307 print ("Particle charge: %g" % elec.zion)
308 top.dt                 = timestep
309 print ("Cyclotron Frequency: %g" % cyc_freq)
310 print ("Timestep: %g" % top.dt)
311 elec.vbeam             = electron_vz
312 print ("Particle velocity: %g" % elec.vbeam)

```

```

313 elec.ekin      = electron_ekin
314 elec.aion      = top.emass/top.amu
315 top.derivqty()
316 elec.lrelativ  = lrelativity
317 elec.rel原因ivity = relativity
318 elec.vthz      = vthz
319 nsteps = 1.3*machine_syslen/elec.vbeam/timestep
320 print("The number of time steps is: %f" % nsteps)
321
322 #-----#
323 #   Beam Design   #
324 #-----#
325 # - size
326 elec.a0 = Cathode_rado
327 elec.b0 = Cathode_rado
328 elec.ap0 = beamap0
329 elec.bp0 = beamp0
330 # - centroid
331 elec.x0 = beamx0
332 elec.xp0 = beamxp0
333 elec.y0 = beamy0
334 elec.yp0 = beamyp0
335
336 #-----#
337 #   Injection   #
338 #-----#
339 # ---Beam Injection ---#
340 elec.npmax = npart
341 top.inject = machine_emittype
342 top.zinject[0] = beamzinject
343 if (machine_injtype=="gun"):
344     elec.npinject = int(npart**2*sw*elec.sq/(elec.
345         ibeam*timestep*nsteps))
346     print("number of particles injected per time
347         step: %g" % elec.npinject)
348     top.xinject[0] = beamxinject
349     top.yinject[0] = beamyinject
350     top.xpinject[0] = beamxpinject
351     top.ypinject[0] = beamypinject
352     top.ainject[0] = elec.a0
353     top.binject[0] = elec.b0
354     top.ainjmin[0] = Cathode_radi
355     top.binjmin[0] = Cathode_radi
356     top.apinject[0] = beamapinject
357     top.bpinject[0] = beampinject
358     top.vzinject[0,0] = 0.0
359     top.vinject[0] = -500.0
360
361 # ---Profile Injection ---#
362 if machine_injtype == 'profile':
363     xinit = posi[:,0] * mm #+ Xoff*mm
364     yinit = posi[:,1] * mm #+ Yoff*mm
365     zinit = zeros(npart)
366     vxinit = zeros(npart)
367     vyinit = zeros(npart)
368     vzinit = zeros(npart) + elec.vbeam
369     def hollow_cathode_source():
370         if w3d.inj_js == elec.jslist[0]:
371             w3d.npgrp = npart
372             gchange('Setpwork3d')
373             w3d.xt[:] = xinit
374             w3d.yt[:] = yinit
375             w3d.zt[:] = top.zinject
376             w3d.uxt[:] = vthz
377             w3d.uyt[:] = vthz
378             w3d.uzt[:] = elec.vbeam
379             installuserparticlesinjection(
380                 hollow_cathode_source)
381
382 #-----#
383 #   Lattice   #
384 #-----#
385 # - Gun Solenoid
386 addnewsolenoid(zi=tbench_solenoid_gun_zstart, zf=
387     tbench_solenoid_gun_zend, ri=
388     tbench_solenoid_gun_radi, ro=
389     tbench_solenoid_gun_rado, maxbz=
390     tbench_solenoid_gun_b)
391 # - Drift before main solenoid
392 addnewdrft(zs=0.37, ze=0.60, ap=machine_piperad)
393 # - Main Solenoid
394 addnewsolenoid(zi=tbench_solenoid_main_zstart, zf
395     =tbench_solenoid_main_zend, ri=
396     tbench_solenoid_main_radi, ro=
397     tbench_solenoid_main_rado, maxbz=
398     tbench_solenoid_main_b)
399 # - Drift after main solenoid
400 addnewdrft(zs=2.52, ze=2.67, ap=machine_piperad)
401 # - Collector Solenoid
402 addnewsolenoid(zi=tbench_solenoid_col_zstart, zf=
403     tbench_solenoid_col_zend, ri=
404     tbench_solenoid_col_radi, ro=
405     tbench_solenoid_col_rado, maxbz=
406     tbench_solenoid_col_b)
407
408 # >>> Set input parameters describing the 3d
409 # simulation.
410 w3d.nx = 32
411 w3d.ny = 32
412 w3d.nz = 256
413 top.prwall = machine_piperad
414
415 # >>> Set to finite beam.
416 w3d.xmmin = -machine_piperad
417 w3d.xmmax = machine_piperad
418 w3d.ymmin = -machine_piperad
419 w3d.ymmax = machine_piperad
420 w3d.zmmin = machine_zstart
421 w3d.zmmax = machine_syslen
422 dx = (w3d.xmmax-w3d.xmmin) / w3d.nx
423 dy = (w3d.ymmax-w3d.ymmin) / w3d.ny
424 dz = (w3d.zmmax-w3d.zmmin) / w3d.nz
425
426 # >>> Set up some diagnostic windows.
427 top.xwindows[:,1] = [-5.e-2,5.e-2]
428 top.zwindows[:,1] = [machine_zstart,2*elec.vbeam*
429     top.dt]
430 top.zwindows[:,2] = [machine_syslen/2-elec.vbeam*
431     top.dt, machine_syslen/2+elec.vbeam*top.dt]
432 top.zwindows[:,3] = [machine_syslen-2*elec.vbeam*
433     top.dt, machine_syslen]
434
435 # >>> Time histories
436 elec.nhist = int(nsteps/10)
437 top.ifzmmnt = 2
438 top.itmomnts[0:3]=[0,nsteps,elec.nhist]

```



```

420 top.zmmntmin = machine_zstart
421 top.zmmntmax = machine_syslen
422 top.nzmmnt = w3d.nz
423
424 # --- Setup Plots
425 top.itplps[0:8] = [0,nsteps,nsteps
    /10,1,5,10,20,30]
426 top.itplalways[0:5] = [0,nsteps,nsteps/20,10,30]
427 top.itplseldom[0:5] = [0,nsteps,nsteps/10,10,30]
428 top.ipzx[0] = seldom
429 top.iptrace[1] = seldom
430 top.iptrace[2] = seldom
431 top.pboundnz = absorb
432 top.pbound0 = absorb
433 top.pboundxy = absorb
434
435 # >>> set up field solver
436 w3d.solvegeom = w3d.XYZgeom
437 w3d.bound0 = 1
438 w3d.boundnz = 1
439 w3d.boundxy = 0
440 if w3d.solvegeom == w3d.XYZgeom:
441     w3d.l4symtry = true
442     top.fstype = 7
443     f3d.mgparam = 1.2
444     f3d.downpasses = 1
445     f3d.uppasses = 1
446     f3d.gridmode = 1
447     f3d.mgverbose = 1
448     f3d.mgntverbose = 1
449     f3d.lcndbndy = true
450     f3d.lprecalccoeffs = true
451     f3d.laddconductor = false
452 top.lgridqnt = true
453 top.lvinject = true
454
455 # Setup Envelope Boundaries
456 env.zl = w3d.zmmin
457 env.zu = w3d.zmmax
458 env.dzenv = machine_syslen/1000
459
460 # Generate Envelope function
461 package("env");generate();step
462
463 # >>> Generate the PIC code (allocate storage,
    load ptcls, t=0 plots, etc.).
464 package("w3d");generate()
465
466 #-----#
467 #   Installing Conductors   #
468 #-----#
469 if (machine_injtype=="gun"):
470     # --- Electron Gun ---#
471     # - Gun Drift Pipe
472     gun_driftpipe=ZCylinderOut(radius=Gun_pipe_ri,
        zlower=Gun_pipe_zstart, zupper=Gun_pipe_zend,
        xcent=0.0, ycent=0.0, voltage=Gun_pipe_voltage)
473     # - Cathode
474     gun_cathode_r = [Cathode_radi, Cathode_radi,
        Cathode_rado, Cathode_rado]
475     gun_cathode_z = [Cathode_zstart, Cathode_zend,
        Cathode_zend, Cathode_zstart]
476     gun_cathode_radi=[None, Cathode_radcurvb, None,
        None]
477     gun_cathode=ZSrfvr(rsrf=gun_cathode_r, zsrf=
        gun_cathode_z, rad=gun_cathode_radi, voltage=
        Cathode_voltage, xcent=.0e0, ycent=.0e0, zcent=.0
        e0)
478     # - Anode
479     gun_anode_r = [Anode_r1, Anode_r3,
        Anode_r4, Anode_r5, Anode_rendi, Anode_rendo,
        Anode_rendo, Anode_r2, Anode_r2, Anode_radtipo,
        Anode_radtipi]
480     gun_anode_z = [Anode_z1, Anode_z3,
        Anode_z4, Anode_z5, Anode_zend, Anode_zend,
        Anode_z5, Anode_z4, Anode_z2, Anode_zstart,
        Anode_zstart]
481     gun_anode_radi = [None, None, None, None, None,
        None, None, None, Anode_radcurvb, None,
        Anode_radcurvs]
482     gun_anode = ZSrfvr(rsrf=gun_anode_r,
        zsrf=gun_anode_z, rad=gun_anode_radi, voltage=
        Anode_voltage, xcent=.0e0, ycent=.0e0, zcent=.0e0
        )
483     # - Electrode F
484     gun_electrodef_r = [ElectrodeF_r1,
        ElectrodeF_ro, ElectrodeF_ro, ElectrodeF_ri,
        ElectrodeF_ri]
485     gun_electrodef_z = [ElectrodeF_zend,
        ElectrodeF_z2, ElectrodeF_zstart,
        ElectrodeF_zstart, ElectrodeF_z1]
486     gun_electrodef_radi = [ElectrodeF_radcurvb, None
        , None, None, ElectrodeF_radcurvs]
487     gun_electrodef = ZSrfvr(rsrf=
        gun_electrodef_r, zsrf=gun_electrodef_z, rad=
        gun_electrodef_radi, voltage=ElectrodeF_voltage
        , xcent=0, ycent=0, zcent=.0e0)
488     # - Electrode C
489     gun_electrodeC_r = [ElectrodeC_ro,
        ElectrodeC_ro, ElectrodeC_ri, ElectrodeC_ri]
490     gun_electrodeC_z = [ElectrodeC_z1,
        ElectrodeC_zstart, ElectrodeC_zstart,
        ElectrodeC_z1]
491     gun_electrodeC_radi = [None, None, None,
        ElectrodeC_radcurv]
492     gun_electrodeC = ZSrfvr(rsrf=
        gun_electrodeC_r, zsrf=gun_electrodeC_z, rad=
        gun_electrodeC_radi, voltage=ElectrodeC_voltage
        , xcent=0, ycent=0, zcent=.0e0)
493     gun_conductors=[gun_driftpipe, gun_driftpipe,
        gun_cathode, gun_anode, gun_electrodef,
        gun_electrodeC]
494     installconductor(gun_conductors)
495
496 # --- Lattice ---#
497 pipe = ZCylinderOut(radius=machine_piperad, zlower
    =Gun_pipe_zstart, zupper=machine_syslen, voltage
    =0., xcent=0, ycent=0, zcent=0)
498 lattice_conductors=[pipe]
499 installconductor(lattice_conductors)
500 fieldsolve()
501
502 #-----#
503 #   Plotting Lattice   #
504 #-----#

```

```

505 # --- Plotting Envelope Function
506 penv(color="fg",marks=0,marker=None,msize=1.0,
      lframe=0,titles=1,ascale=None,bscale=None,zscale
      =None)
507 fma()
508
509 # --- Plotting Potential
510 if (machine_injtype=="gun"):
511     gun_driftpipe.draw(filled=190,color="fg")
512     gun_cathode.draw(filled=160,color='fg')
513     gun_anode.draw(filled=100,color='fg')
514     gun_electrodef.draw(filled=150,color='fg')
515     gun_electrodeC.draw(filled=150,color='fg')
516 pfzr(fullplane=1,plotsg=1,cond=1,fill=1,plotphi
      =1,plotrho=0,plotselife=0,comp='z',titles=1)
517 limits(Cathode_zstart,Gun_pipe_zend,-1.2*
      machine_piperad,1.2*machine_piperad)
518 fma()
519
520 # --- Plotting Potential
521 if (machine_injtype=="gun"):
522     gun_driftpipe.draw(filled=190,color="fg")
523     gun_cathode.draw(filled=160,color='fg')
524     gun_anode.draw(filled=100,color='fg')
525     gun_electrodef.draw(filled=150,color='fg')
526     gun_electrodeC.draw(filled=150,color='fg')
527 pfzr(fullplane=1,plotsg=1,cond=1,fill=1,plotphi
      =0,plotrho=1,plotselife=0,comp='E',titles=1)
528 limits(Cathode_zstart,Gun_pipe_zend,-1.2*
      machine_piperad,1.2*machine_piperad)
529 fma()
530
531 # --- Plotting Potential
532 if (machine_injtype=="gun"):
533     gun_driftpipe.draw(filled=190,color="fg")
534     gun_cathode.draw(filled=160,color='fg')
535     gun_anode.draw(filled=100,color='fg')
536     gun_electrodef.draw(filled=150,color='fg')
537     gun_electrodeC.draw(filled=150,color='fg')
538 pfzr(fullplane=1,plotsg=1,cond=1,fill=1,plotphi
      =0,plotrho=0,plotselife=1,comp='E',titles=1)
539 limits(Cathode_zstart,Gun_pipe_zend,-1.2*
      machine_piperad,1.2*machine_piperad)
540 fma()
541
542 # --- Plotting Electric Field
543 if (machine_injtype=="gun"):
544     gun_driftpipe.draw(filled=190,color="fg")
545     gun_cathode.draw(filled=160,color='fg')
546     gun_anode.draw(filled=100,color='fg')
547     gun_electrodef.draw(filled=150,color='fg')
548     gun_electrodeC.draw(filled=150,color='fg')
549 pfzr(fullplane=1,plotsg=1,cond=1,fill=1,plotphi
      =0,plotrho=0,plotselife=1,comp='z',titles=1)
550 limits(Cathode_zstart,Gun_pipe_zend,-1.2*
      machine_piperad,1.2*machine_piperad)
551 fma()
552
553 ## --- REPETITIVE PLOTS
554 def myplots():
555     # --- Plotting Electric Field
556     if (machine_injtype=="gun"):
557         gun_driftpipe.draw(filled=190,color="fg")
558         gun_cathode.draw(filled=160,color='fg')
559         gun_anode.draw(filled=100,color='fg')
560         gun_electrodef.draw(filled=150,color='fg')
561         gun_electrodeC.draw(filled=150,color='fg')
562         limits(Cathode_zstart,machine_syslen,-1.2*
            machine_piperad,1.2*machine_piperad)
563         ppzx(color="density",ncolor=30)
564         fma()
565         pptrace(filled=1,particles=0,contours=30)
566         fma()
567     installplalways(myplots)
568
569 # >>> run time steps and dump the results.
570 step(nsteps)
571 # step(50)
572
573 os.system("mv "+machine_type+"_"+date+time+"_"+
      machine_injtype+"_"+file_ending+"* ../Results/"+
      date+"/")

```

Attachments/tbench_complex_app.py

Appendix D

Dimensions

D.1 Electron Guns

Hollow Electron Gun 1 Inch

Cathode	[mm]
Length	29.25
Inner Radius	6.75
Outer Radius	12.7
Radius of Curvature	10
Anode	[mm]
Distance to Cathode	9.48
Length	85.2
Inner radius	14.25
Outer Radius	22 d
Anode radius of Curvature	3.5
Electrode F	[mm]
Length	74
Inner Radius	13.1
Outer Radius	15
Radius of Curvature	1.4
Electrode C	[mm]
Length	49.5
Inner Radius	20.5
Outer Radius	22
Radius of Curvature	0.75

Hollow Electron Gun 0.6 Inch

Cathode	[mm]
Length	e
Inner Radius	9
Outer Radius	15.24
Radius of Curvature	10
Anode	[mm]
Distance to Cathode	9.48
Length	90
Aperture	18
Outer Radius	40
Electrode F	[mm]
Length	38.9
Inner Radius	8.05
Outer Radius	11.1
Electrode C	[mm]
Length	20.5
Inner Radius	17.0
Outer Radius	20.5

D.2 Electron Lenses

Tevatron Electron Lens 2

Bend Solenoids	[mm]
Width	90
Inner Radius	193
Outer Radius	265
Main Solenoid	[mm]
Length	2688.5
Inner Radius	200
Outer Radius	344.8
Collector and Gun Solenoid	[mm]
Length	500
Inner Radius	280
Outer Radius	334.3
Path lengths	[mm]
Main Solenoid - Nearest Bend	82.7
Inter Bend Distance	52.9
Cathode Surface - First Bend	281.6

Tevatron Electron Lens Test Stand

Main Solenoid	[mm]
Length	1920
Inner Radius	100
Collector and Gun Solenoid	[mm]
Length	500
Inner Radius	140
Drift Pipe	[mm]
Length	2860
Inner Radius	30
Path lengths	[mm]
Main Solenoid - Nearest Bend	82.7
Inter Bend Distance	52.9
Cathode Surface - First Bend	281.6

Appendix E

Maps

E.1 Map of LHC Collimators

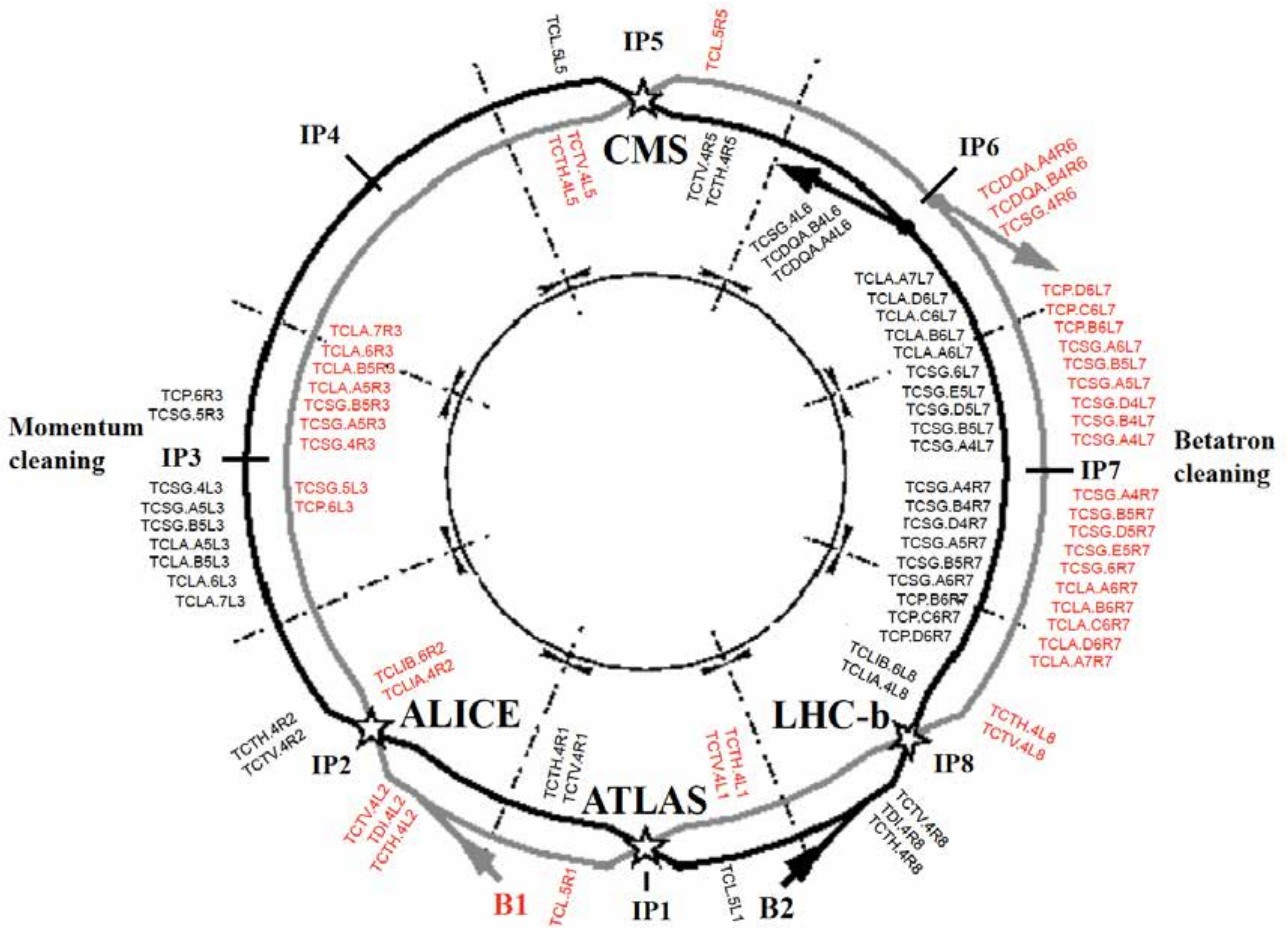


Figure E.1: The super-symmetry of the LHC. IP1, IP2, IP5 and IP8 are the experimental halls ALICE, ATLAS, CMS and LHC-b respectively. IP3 and IP7 are the momentum and betatron cleaning sites and IP6 contains the beam dumps.

E.2 Map of Tevatron

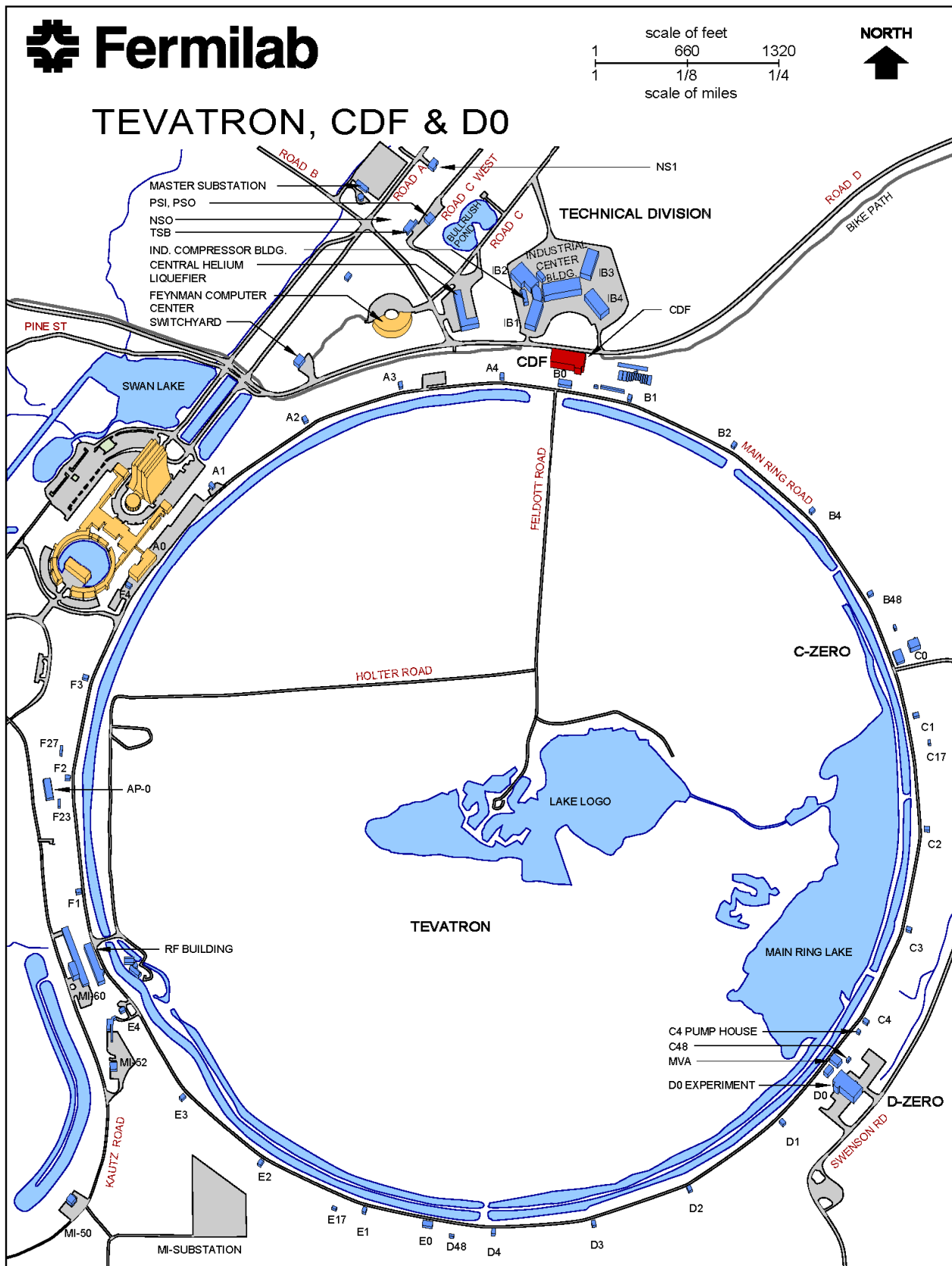


Figure E.2: Map of the tevatron and its various sectors