Dependence of Thermionic Gun Emittance on Beam Energy Calculated with EGUN

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Abstract

The dependence of the emittance of a thermionic diode gun on the gun voltage for a constant beam current density was investigated. Therefore the EGUN code for electron gun simulations had been installed for public access on the UNIX/RSPLUS network. It was used to calculate the transverse emittance at the exit of a thermionic diode gun which is an option in the main beam injector scheme of CTF-3. For a constant current density of 7.5 A/cm^2 and gun voltages from 65 kV to 260 kV the normalized transverse emittance was found to be constant at about 1.7 mm mrad.

1 The simulation code EGUN

The program EGUN was written by W.B. Hermannsfeldt [1] to simulate the dynamics of charged particle beams in electron guns. It solves the two dimensional Poisson equation with boundary conditions given by the gun geometry and the applied voltages. Magnetic fields are taken into account by the iterative solution algorithm. After convergence of the Poisson solver a maximum number of 52 microparticles can be tracked through the calculated electromagnetic field distribution.

Since the shareware version of the source code is written in FORTRAN for use on VAX/VMS machines a modification was necessary in order to run the program on the UNIX/RSPLUS cluster at CERN. The source code fitted to UNIX and an executable file are available to the public at
/afs/cern.ch/user/g/groening/public/egun_code/ .

Beside the EGUN code some auxiliary programs for further data processing are available at the same location. All programs can be executed from the local account of the specific user. Users need to copy the file 'calc_gun.cmd' to their local account and need to have an input file containing the parameters of their specific problem. However, an example input file 'example.dat' can be found at the given path as well.

Since the program is not self explaining the users must be familiar with it or refer to the manual which can be demanded from lars.groening@cern.ch. The auxiliary programs mentioned above might not be suited to the specific problem of each user. In general it is the users responsibility to care for further processing of the program output.

2 Thermal diode gun emittance

In the CTF-3 main beam injector 2400 bunches of 2.33 nC have to be accelerated to an energy of 26 MeV before they enter the main beam accelerator. One option foresees the beam extraction from a thermionic diode gun. The required 3 GHz bunch structure is imposed in the subsequent bunching system comprising a sub harmonic buncher at 1.5 GHz, prebunchers and a buncher. The whole bunching system, but not the gun itself, is embedded in the magnetic field of a solenoid. At the injector exit the normalized transverse beam emittance should be smaller than 100 mm mrad. The major contribution to this final emittance is acquired in the bunching system and in the subsequent acceleration. Nevertheless the contribution of the electron gun should be minimized. Therefore the dependence of this contribution on the gun voltage was investigated for a constant beam current of 10 A and a current density of 7.5 A/cm^2. A range of voltages between 65 kV and 260 kV was chosen.
The emittance at the exit of the gun comprises a thermal part and a part due to electrostatic acceleration including heating by space charge. The unavoidable thermal emittance ϵ_{therm} raises from the electrons temperature at the cathode surface of about 1200 K corresponding to 0.1 eV. Using the expression [2]

$$\frac{\beta\gamma\epsilon_{therm}}{\text{mm mrad}} = \frac{1}{\sqrt{2}}\frac{R_{cath}}{\text{mm}}\sqrt{\frac{T_{cath}}{\text{eV}}} \approx \frac{1}{4}\frac{R_{cath}}{\text{mm}} \qquad (1)$$

the normalized thermal emittance can be calculated. It depends only on the cathode temperature T_{cath} and surface area, i.e. the cathode radius R_{cath}.
The emittance increase due to the electrostatic acceleration in the diode gun depends on the gun geometry and the applied voltages, i.e. the electron beam current and energy. Since in a diode gun (Fig. 1) the beam is extracted and accelerated by the same electrode the beam current I and beam energy E are coupled via Child–Langmuir's law

$$I = P \cdot E^{\frac{3}{2}} \qquad (2)$$

in case of space charge limited emission, where P is the perveance of the gun. It depends on the geometry and scales roughly like

$$P \approx 5.2\,\mu\text{Perv} \cdot \frac{A_{cath}}{d_{ext}^2}. \qquad (3)$$

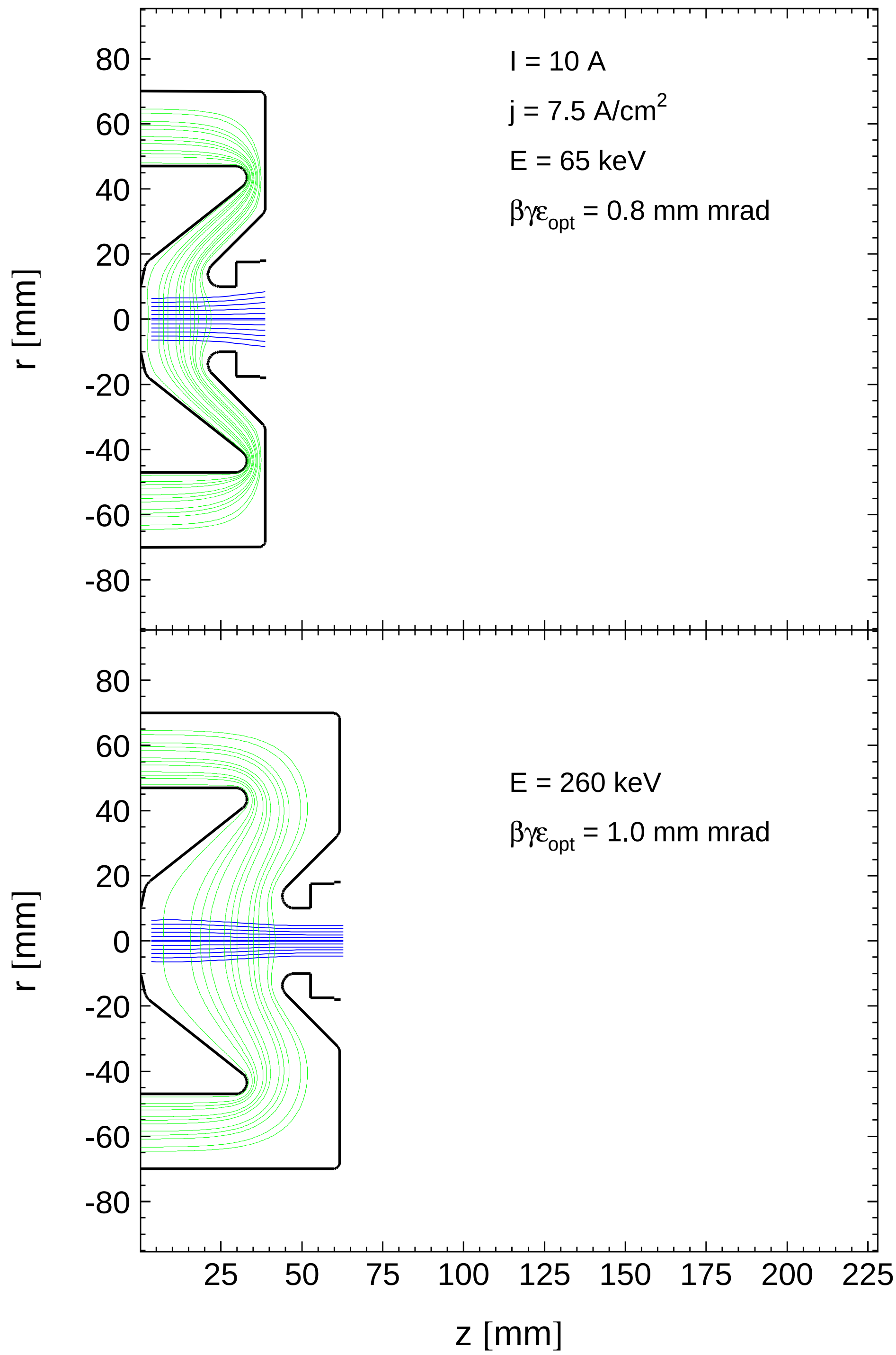

Figure 1: Extraction of an electron beam of 10 A in a thermionic diode gun according to a simulation with EGUN. The upper part shows the case with a beam energy of 65 keV and a normalized optical rms–emittance of 0.8 mm mrad. In the lower part the energy is 260 keV and the normalized optical rms–emittance is 1.0 mm mrad.

Here A_{cath} is the cathode surface and d_{ext} is a measure for the distance of the extracting electrode from the cathode. To calculate the increase of the emittance due to the extraction in the gun, which will be called optical emittance ϵ_{opt}, simulation codes [1, 3] must be used. The way to obtain the final emittance from the thermal and optical emittance is not straight forward and here the quadratic sum

$$\epsilon_{tot}^2 = \epsilon_{therm}^2 + \epsilon_{opt}^2 \quad (4)$$

is applied.

3 Calculation of the optical emittance

In order to calculate the optical emittance of a diode gun the code EGUN is applied to cylindrical symmetry. The code tracks microparticles with a different distance r_i from the beam axis from the emitting cathode to the exit of the gun. As result the trajectories $(r, r', z')_i$ as function of the longitudinal coordinate z are given for a maximum of 52 microparticles. Additionally the partial current I_i included in the beam slice i is calculated by the program as well since it scales different from r_i due to space charge forces. To obtain physical coordinates $(x, y, z)_i$ random azimut angles $(\varphi, \varphi')_i$ are created and linked to the radial coordinates $(r, r')_i$

$$x_{i,j} = r_i \cdot cos\,\varphi_{i,j} \quad (5)$$

$$y_{i,j} = r_i \cdot sin\,\varphi_{i,j} \quad (6)$$

$$x'_{i,l} = r'_i \cdot cos\,\varphi_{i,l} \quad (7)$$

$$y'_{i,l} = r'_i \cdot sin\,\varphi_{i,l} \quad (8)$$

and the corresponding number of angles n_i per microparticle is proportional to the partial current I_i. The resulting distribution in the transverse phasespace (Fig. 2) is used to calculate the transverse optical rms–emittance using

$$\epsilon_{opt,v} = \sqrt{\langle v^2\rangle\langle v'^2\rangle - (\langle vv'\rangle - \langle v\rangle\langle v'\rangle)^2}, \quad (9)$$

where v represents a transverse coordinate.

4 Results of simulations

For the simulations the geometry of a RF gun currently used in the S-band Test Linac at DESY [4] was chosen. According to [4] the measured emittance agreed well with the one calculated using the EGUN code. In order to calculate the emittances for different energies but a constant current and a constant current density of 10 A and 7.5 A/cm^2, respectively, the distance between cathode and

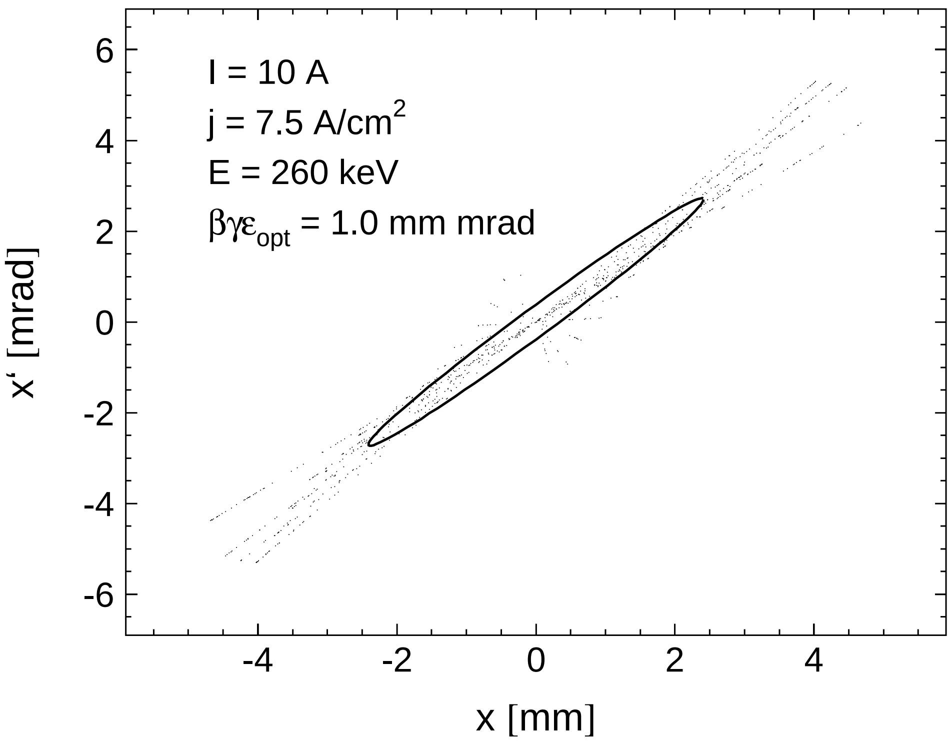

Figure 2: Distribution of microparticles in the horizontal phasespace at the exit of the thermionic diode gun. The beam current is 10 A and the energy is 260 keV. The rms–ellipse is drawn as well. The normalized rms–emittance is 1.0 mm mrad.

anode was changed. For higher energies this distance was increased and for lower energies it was decreased. The cathode radius was kept to a constant value of 6.5 mm. Afterwards the potential of the extracting and accelerating anode was set to a value resulting in the required constant current of 10 A. Thus the perveance P of the gun was different for each energy. According to eqs. (2) and (3) the perveance is lower for higher energies and constant beam current.
Figure 1 shows the extraction and acceleration of an electron beam with a voltage of 65 kV and 260 kV, respectively. Beside the gun geometry and the electron beam the lines of constant electrical potential are drawn as well. Due to small transverse components in the accelerating electric field the beam diameter is changed. This field is the superposition of the field imposed by the potentials on the electrodes and the space charge field of the electron beam itself. Its transverse components which depend nonlinearly from the distance from the beam axis result in the optical emittance of the beam.
The distribution in the horizontal phasespace for a voltage of 260 kV is shown in Fig. 2. Since the space charge expands the beam it is highly correlated. The rays in the distribution are due to the limited number of microparticles tracked by the EGUN code. Beside the distribution the corresponding rms–ellipse is drawn.

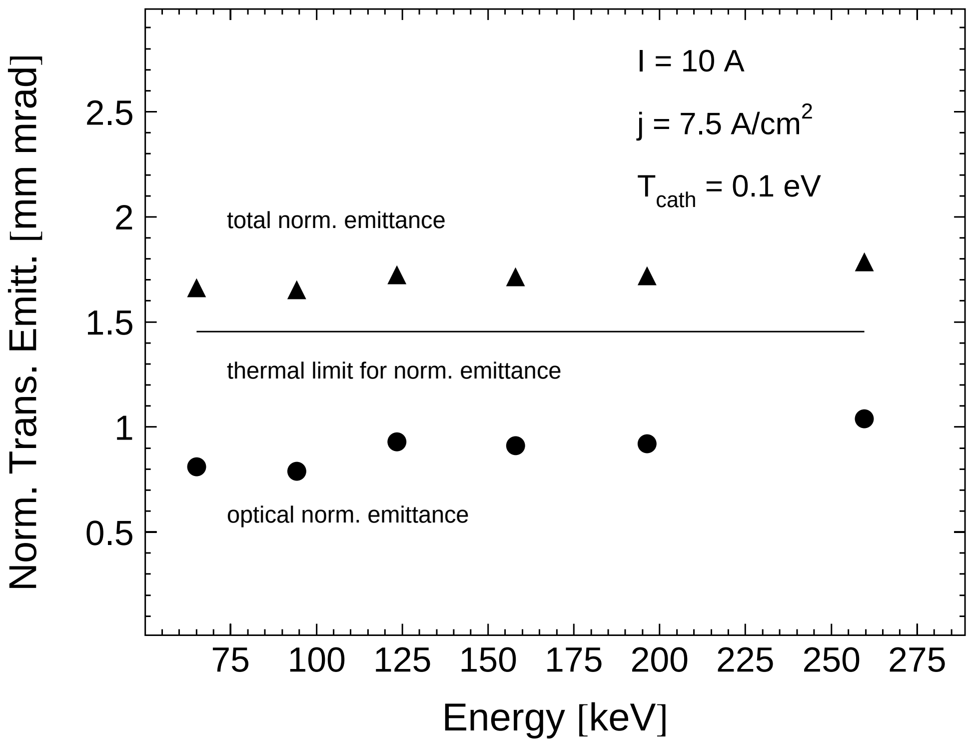

Figure 3: The normalized transverse rms–emittance of the thermionic diode gun as function of the beam energy for a constant beam current of 10 A. The constant thermal emittance due to a cathode temperature of 0.1 eV is indicated by a straight line. The optical and total emittances are plotted as well.

The transverse normalized rms–emittance was calculated for six different energies by using EGUN and eq. (4). Figure 3 shows that the optical emittance and thus the total emittance do not depend on the electron beam energy at the diode gun exit. The total emittance is about 1.7 mm mrad.
The constant thermal contribution to the total emittance amounts 1.46 mm mrad and is indicated by a straight line. Accordingly, the total emittance is dominated by this thermal contribution which can by reduced by further increase of the current density unless the temperature needs to be increased significantly in order to maintain the higher current density. However, it must be mentioned that the optical emittance depends on the gun geometry. Its contribution is small for a sufficiently well designed geometry. The guns designed and used today match this requirement and their emittances are dominated by the temperature of the emitting cathode.

5 Aknowledgement

I like to thank E. McIntosh for his support and the discussions during the modification of the source code from the VAX/VMS to the UNIX network and also M. Schmitz who supplied me with the geometry of the diode gun.

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