BEAM DYNAMICS SIMULATIONS FOR THE PITZ RF-GUN*

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Abstract

The Photo Injector Test Facility at DESY Zeuthen (PITZ) is dedicated to the optimisation of laser driven RF guns as applied for free electron lasers (FELs) and linear colliders. The RF gun currently under study is a 1.5 cell copper cavity operated in the π-mode at 1.3 GHz. It is designed for operation as electron source at the TESLA Test Facility (TTF). Beam dynamics simulations deliver an essential contribution to the understanding of the emittance growth within the gun hence assisting in the achievement of high quality beams. We investigated in our simulations possible reasons for emittance growth of which we present here the influence of initial transverse beam offsets with respect to the field symmetry axis. For our simulations we used the TS2 and TS3 modules of the MAFIA programme which are particle in cell (PIC) codes for two and three dimensions.

1 INTRODUCTION

Laser driven RF guns are capable to deliver beams with high phase space density as required notably by FELs. At PITZ, the electrons generated by photo emission from a Cs_2Te cathode are accelerated by a 1.3 GHz RF field excited in a 1.5 cell copper cavity. The photo cathode is irradiated with laser light of 263 nm (UV range), the laser system being a development of the Max-Born-Institute in Berlin [1]. The input power for the RF cavity is delivered by a 5 MW klystron, which will later be enhanced to 10 MW. One quadrupole triplet serves for beam focusing after the gun. A dipole magnet with a subsequent view screen allows the precise determination of the beam energy. Except for the energy measurement the facility is well equipped with a wide range of beam diagnostics for the transverse and longitudinal phase space described in ref. [2]. The control of the machine is based on a distributed object-oriented control system (DOOCS). During the initial commissioning phase of the PITZ facility in January 2002 the collaboration succeeded in producing first photo electrons [3].

A sketch of the electron gun is shown in Fig. 1. The gun cavity, with a total length of 265.0 mm from cathode to end flange, is operated in the π-mode. The axial-symmetric input coupler, designed at DESY, prevents field asymmetries which are known to contribute to the emittance growth in the gun [4]. The cavity is surrounded by a pair of solenoids. The main solenoid acts as a DC lens and serves for the focusing of the beam as well as for the compensation of the emittance formation caused by space charge effects [5]. With the aid of the compensation solenoid the magnetic field at the cathode can be set to zero thus avoiding an azimuthal momentum of the electron beam at the gun exit.

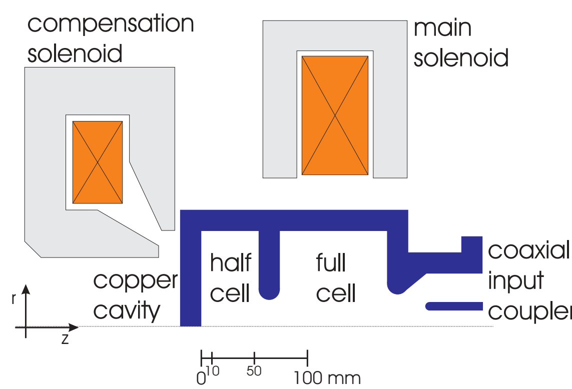

Figure 1: Vertical cross section of the PITZ electron gun. As the arrangement is axis-symmetric only half of the structure is drawn.

2 SIMULATIONS

2.1 Method of simulation

The beam dynamics simulations presented here investigate the additional emittance growth in the RF gun caused by an initial transverse beam offset at the cathode. The basis of our simulations is a model of the PITZ gun set up with the programme MAFIA [6]. This enabled us to calculate the relevant eigenmode of the cavity (module E) and the static magnetic field of the solenoids (module S) as well as to carry out beam dynamics simulation with the PIC code integrated in the modules TS2 and TS3. The main parameters taken for the beam dynamics calculation are listed in Tab. 1. The charge distribution of the beam in radial direction is uniform. The bunch length and the rise/fall time given in Tab. 1 refer to a flat-top (plateau) distribution that was applied longitudinally.

Table 1: Main simulation parameters.

Beam Parameter	**Value**
Bunch Radius	r_0 = 1.5 mm
Bunch Charge	q = -1.0 nC
Bunch Length	τ_{FWHM} = 20.0 ps
Rise/Fall Time	t_{rise} = 2.0 ps
Reference Phase	φ_0 = -32.0°
Field at cathode	E_{cath} = -40.0 MV/m

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2.2 Emittance without initial beam offset

The parameters from Tab. 1 were taken as input for a beam dynamics simulation with MAFIA TS2, at first assuming that the beam starts from the centre of the photo cathode. To study the impact of the static magnetic field of the solenoids on the emittance two simulations were performed one including the solenoid field another one omitting it. The space coordinates and the momentum of all 10,000 macro particles were stored at 50 positions along z. This information was then used to calculate the projected radial rms-emittance of the bunch defined by

$$\varepsilon_{r,proj} = \sqrt{\langle r^2\rangle\langle p_r^2\rangle - \langle rp_r\rangle^2}\,, \qquad (1)$$

where p_r denotes the canonical momentum of the macro particles. The result of these simulations is shown in Fig. 2.2, the boxes representing the emittance values with solenoid field, the circles giving the emittance without solenoid field. In both cases the emittance growth right behind the cathode is determined by the non-linear radial space charge force leading to an projected emittance of approximately 5.0 mm mrad. As we deal with a rotational symmetric problem this corresponds to an x- resp. y-emittance of 2.5 mm mrad. If the simulation is performed without applying the solenoid field the emittance behaviour downstream is determined by RF effects and fringe fields of the irises (the positions of the two irises are shown in the graph as vertical lines) which lead to focusing and defocusing forces that depend on the z-position and the RF phase. If the solenoid field is taken into account it dominates the course of the emittance resulting in an increase by a factor of two followed by a decline back to a value of about 5.0 mm mrad. In this case the emittance compensation scheme is realised which counteracts longitudinal phase space correlations within the bunch. One should not be perplexed by the fact that both calculations almost deliver the same final emittance, as the main difference is found in the slope of the phase space ellipse. Without solenoid the beam exits the gun in a divergent state whereas it converges with solenoid.

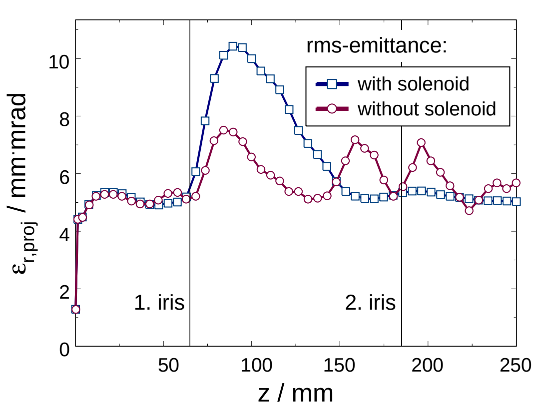

Figure 2: Projected radial emittance with (boxes) and without (circles) solenoid field as function of the z-position. The vertical lines mark the positions of the cavity irises.

2.3 Beams with initial offset

As the magnetic fields, the solenoid field as well as the RF field, vanish on the symmetry axis, a particle leaving the cathode at $x = y = 0$ will not experience any transverse Lorentz forces. The situation changes if the particle is emitted with an initial transverse offset which might be caused by a misadjusted laser beam. The r-component of the solenoidal fringe field and the z-component of the particle velocity results in an transverse momentum. This momentum in interaction with the z-component of the solenoid field forces the particle to move on a trajectory that is similar to a helix. A formula for the azimuthal velocity v_φ can be derived from the conservation of angular momentum using the paraxial ray approximation [7]. It reveals that it is a function of the particle's axis offset r and the flux function ψ:

$$v_\varphi = -\left(\frac{e}{2\pi\gamma m_0 r}\right)(\psi - \psi_{ini})\,, \qquad (2)$$

where e, m_0 are the electron charge and mass and γ the Lorentz factor. ψ is defined as the flux of the axial magnetic field enclosed in a circle of radius r and ψ_{ini} is taken as the flux through the cathode plane enclosed in the circle defined by the initial offset. A more detailed study shows that the trajectory meets the z-axis with each revolution [8]. For a beam of particles equation (2) gives only an estimation as space charge effects are not taken into account.

The effect of an initial electron beam offset was simulated in an x-y-z-geometry with MAFIA TS3, tracking 17,700 macro particles. The horizontal start coordinate x_{ini} was varied between 0.0 mm and 6.0 mm in steps of 1.0 mm, the vertical start coordinate remained y_{ini} = 0.0 mm. The trajectories of the bunch centre of mass are displayed in Fig. 3 in a projection on the x-y-plane. In this illustration the helix trajectory becomes a circle. The acceleration process, a non-uniform solenoid field along the cavity and additional forces due to the RF magnetic field disturb the pure circle shape.

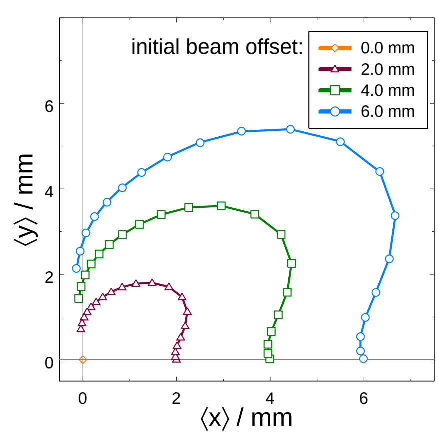

Figure 3: Beam trajectory of the bunch centre of mass projected on the x-y-plane for initial beam offsets of 0.0, 2.0, 4.0 and 6.0 mm.

2.4 Influence of beam offsets on emittance

With an external programme the particle data obtained from the MAFIA simulation were evaluated with respect to the emittances in both transverse phase spaces. As described above the initial beam spot position on the cathode was shifted only horizontally which implies that the problem looses its rotational symmetry. As a result a coupling of the transverse phase spaces occurs and the x- and y-emittance do not show the same behaviour. The projected emittance at the gun exit plotted versus the initial x-position is shown in Fig. 4(a). The ordinate does not show the emittance in absolute values but the relative increase of the emittance in relation to the emittance ε_0 at the gun exit without a transverse offset. For initial offsets of 1.0 mm the raise is in the range of 10% whereas for a rather large offset of 6.0 mm the emittance increases by more than a factor of two regarding the y-emittance.

Additionally another quantity, the slice emittance, was calculated from the macro particle data. It is defined by

$$\varepsilon_{slice} = \frac{1}{\tau} \int_{\langle z\rangle-\tau/2}^{\langle z\rangle+\tau/2} \varepsilon_{proj}(z)\, dz\,, \tag{3}$$

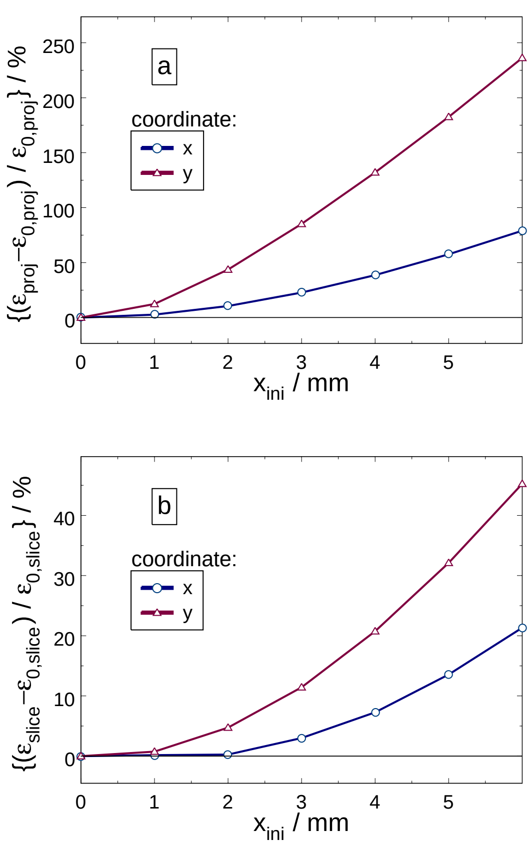

Figure 4: Projected emittance (a) and slice emittance (b) at the gun exit as a function of the initial x-position of the electron beam at the cathode.

where τ denotes the FWHM bunch length and $\varepsilon_{proj}(z)$ the projected emittance from equation (1) of particles belonging to the beam slice at position z. Whereas the projected emittance is a global quantity representing the total emittance of all particles in a bunch (which is the emittance delivered by measurements), the slice emittance reflects the emittance of sub-bunches arising from a longitudinal division of the bunch. In fact such slices appear in an FEL by the interaction of the electrons with the periodic transverse magnetic field and the electromagnetic radiation in the undulator [9]. The laser process does not occur over the whole bunch length but only between particles within the same slice which means that the slice emittance is the relevant quantity with respect to FEL operation. From Fig. 4(b) we see that the additional enhancement of the slice emittance for 1.0 mm initial offset is in the order of 1%. Comparing the two plots of Fig. 4 it can be seen that the relative increase of the slice emittance appears by a factor of three to ten less than the one of the projected emittance which suggests that the increase is mainly caused by longitudinal correlations of the transverse phase space.

3 CONCLUSION

We have simulated the beam dynamics in the RF gun of the Photo Injector Test Facility at DESY Zeuthen using the programme MAFIA with the objective to estimate the influence of an initial transverse beam offset on the emittance at the gun exit. According to our simulations the additional emittance growth caused by a misplaced beam spot will be less than 10% for the projected emittance and 1% for the slice emittance if the adjustment accuracy of the laser spot on the cathode surface can be kept below 1.0 mm.

4 REFERENCES

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