SIMULATION OF DARK CURRENTS IN A FEL RF-GUN*

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Abstract

Dark currents caused by field emission are dramatically limiting the lifetime of photocathodes used in RF-guns needed for successful FEL operation. Due to the mismatch of the dark current electrons to the transport channel they are also a serious hazard to beam diagnostic systems an may cause severe radiation damage. In the past high dark currents emitted from the laser driven RF-guns have been observed during substantial time of linac operation. For a better understanding of the dark current dynamics the transport through the injector part of the PITZ accelerator has been investigated with the help of an appropriate tracking algorithm. Additionally, potential emission spots inside the rf-gun have been located by RF field mapping. Furthermore, the dependency of the dark current on the accelerating field inside the RF-gun as well as on the strength of the focusing solenoid has been studied.

INTRODUCTION

For the successful operation of future linear colliders as well as free electron lasers the generation of a low emittance electron beam with bunch charges is of fundamental importance. Therefore rf-guns employing laser driven photcathodes are used as particle sources. The main contribution to the beam emittance is caused by space charge dominated processes in the vicinity of the cathode [1]. To minimize these effects, high accelerating gradients are favorable, resulting in large amplitudes of the electric field inside the rf-gun which benefits the generation of dark currents. The dark current density for a specific electric field on a metallic surface can be calculated from the well known FOWLER-NORDHEIM equation [2]

$$j = \frac{1.54 \cdot 10^{-6} \cdot 10^{4.52\phi^{-0.5}} (\beta E)^2}{\phi} \exp\left(-\frac{k\phi^{1.5}}{\beta E}\right), \quad (1)$$

where $k = 6.53 \cdot 10^9$ and ϕ corresponds to the work function of the metal in eV. Due to geometrical imperfections of the metal surface, the electric field is enhanced by a factor β. Usually only the time averaged dark current of an rf driven structure is measured. In this case equation (1) has to be slightly modified:

$$\bar{j} = \frac{5.7 \cdot 10^{-}12 \cdot 10^{4.52\phi^{-0.5}} (\beta E)^{2.5}}{\phi^{1.75}} \exp\left(-\frac{k\phi^{1.5}}{\beta E}\right). \quad (2)$$

* Work supported in part by DESY
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In an actual measurement of the dark current only the electrons leaving the structure are taken into account. To gain better insight into the dark current dynamics inside the complete structure a numerical tracking method has to be applied.

TRACKING ALGORITHM

For the tracking of the dark current electrons a fast and efficient three dimensional leap-frog algorithm, being second order accurate, has been implemented [3]. Based on the equations of motion

$$\frac{\partial \vec{u}}{\partial t} = \frac{q}{m_0 c}\left(\vec{E} + \vec{v} \times \vec{B}\right) \quad (3)$$

$$\frac{\partial \vec{x}}{\partial t} = \vec{v} \quad (4)$$

$$\vec{u} = \frac{m\vec{v}}{m_0 c} = \gamma\vec{\beta} \quad (5)$$

the discrete time integration scheme

$$\vec{u}^{\,n+1} = \vec{u}^{\,n} + \Delta t\frac{q}{m_0 c}\left(\vec{E}^{\,n+1/2} + \vec{v}^{\,n+1/2} \times \vec{B}^{\,n+1/2}\right) \quad (6)$$

$$\vec{x}^{\,n+3/2} = \vec{x}^{\,n+1/2} + \Delta t\frac{c}{\gamma^{n+1}}\vec{u}^{\,n+1} \quad (7)$$

can be derived. To avoid an implicit formulation in equation (6), an explicit approximation is introduced [4]:

$$\vec{u}^{\,-} = \vec{u}^{\,n} + 0.5\Delta t\frac{q}{m_0 c}\vec{E}^{\,n+1/2} \quad (8)$$

$$\vec{u}^{\,*} = \vec{u}^{\,-} + \vec{u}^{\,-} \times \vec{T} \quad (9)$$

$$\vec{u}^{\,+} = \vec{u}^{\,-} + \vec{u}^{\,*} \times \vec{S} \quad (10)$$

$$\vec{u}^{\,n+1} = \vec{u}^{\,+} + 0.5\Delta t\frac{q}{m_0 c}\vec{E}^{\,n+1/2} \quad (11)$$

where

$$\vec{T} = \Delta t\frac{q\vec{B}^{\,n+1/2}}{2m_0\gamma^{n+1/2}}, \quad (12)$$

$$\vec{S} = \frac{2\vec{T}}{1 + |\vec{T}|^2}, \quad (13)$$

$$\gamma^{n+1/2} = \sqrt{1 + |\vec{u}^{\,-}|^2}. \quad (14)$$

The charges of the individual particles used for the tracking are adjusted individually according to equation (1) for a given field enhancement factor β.

SIMULATION RESULTS

The dark current tracking algorithm has been applied to the normal conducting rf-gun operated at 1.3 GHz which is installed at DESY Zeuthen (PITZ). The electromagnetic fields of the accelerating mode inside the complete gun cavity as well as the external static magnetic fields have been calculated with the help of the electromagnetic simulation package MAFIA [5]. The rf-gun is capable of providing accelerating fields on the cathode of up to 40 MV/m. To minimize the resulting beam emittance a solenoid based emittance compensation scheme is applied [6]. The maximum of the magnetic flux density is located at z = 27.85 cm with respect to the cathode. Additionally, a bucking coil ensures that the magnetic flux density vanishes at the cathode. The absolute value of the accelerating electric field distribution inside the rf-gun is shown in fig. 1. Inside the gun cavity

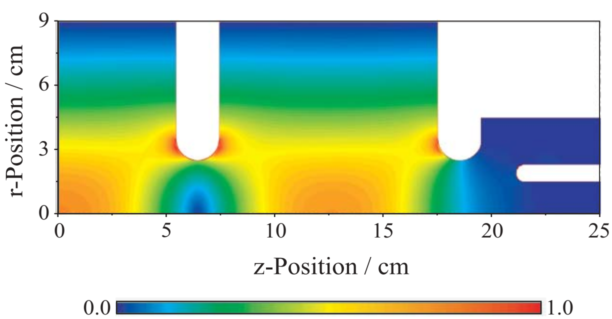

Figure 1: Normalized absolute value of the accelerating electric field inside the rf-gun.

areas of high electric fields are located at the irises. The results of a tracking simulation for particles starting at the iris are depicted in fig. 2. The maximal electric field on the cathode was set to 30 MV/m and a magentic flux density of 100 mT has been applied while the particles are started at arbitrary phases and positions.

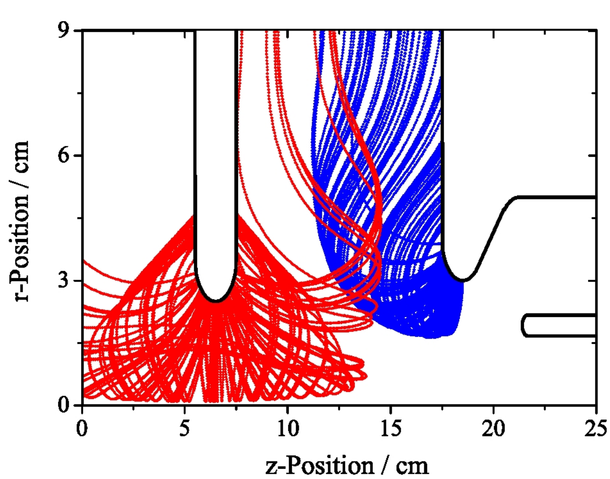

Figure 2: Trajectories of dark current electrons starting at the irises for an accelerating field of 30 MV/m on the cathode and a maximal magentic flux density of 100 mT.

The trajectories of the dark current electrons originated at the irises reveal that those particles can not leave the rf-gun and therefore do not contribute to the dark current measurements taken at a longitudinal position of z = 79 cm with respect to the cathode. Additionally, the kinetic energy of the particles hitting the rf-gun structure is greater than several tens of keV. This is why they are a potential hazard to the Cs_2Te cathode. Due to the high impact energy the secondary electron emission yield is very low, therefore the generation of secondary electrons is neglected in the presented studies. Only particles starting at the cathode (16 mm diameter) can leave the rf-gun close to the axis. This coincides with the fact that the measured dark current is reduced by a factor of 2.5 if the Cs_2Te cathode is exchanged with a molybdenum dummy [7]. Additionally, there is a strong dependency of the dark current on the strength of the external magnetic field for higher solenoid currents. The values obtained by a dark current measurement [7] as well as the corresponding simulation results for an electric field of 40 MV/m on the cathode at different solenoid currents are shown in fig. 3.

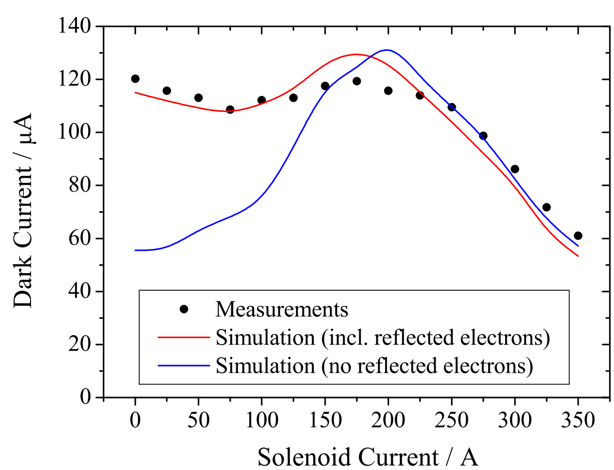

Figure 3: Comparison between simulated and measured dark current as a function of the solenoid current with and without relfected electrons taken into account. The elecric field on the cathode was set to 40 MV/m.

The measured dark currents show no significant dependency on the solenoid current up to 175 A and do not fit very well to the simulation results in this range. This can not easily be understood because the trajectories of the electrons for both cases are quite different. The simulated trajectories for a solenoid current of 0 A and 175 A of dark current electrons starting at the cathode at different rf phases are shown in fig. 4. In absence of a magnetic field some of the electrons hit the beam tube and do not contribute to the dark current in the simulations. When the solenoid current is set to 175 A all particles reach the end of the calculation area resulting in a much higher current. The discrepance between measurements and simulations for low solenoid currents can be overcome if those electrons hitting the beam tube at a very low angle are con-

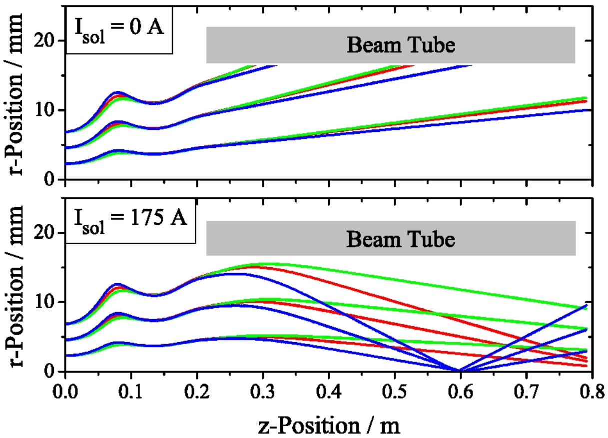

Figure 4: Trajectories of dark current electrons starting at the cathode at different rf-phases for two different solenoid currents. The electric field on the cathode was set to 40 MV/m.

sidered to be scattered at the surface. In this case the simulation results fit very well to the measurements (see fig. 3). By fitting the simulated and measured data it is possible to calculate a field enhancement factor of $\beta = 23$. With the help of the assumption that electrons might be scattered at the tube the dependency of the dark currents on the electric field on the cathode for different solenoid currents has been calculated. A comparison between simulated an measured [8] dark current is shown in fig. 5. Once again the simulated values are in very good agreement with the measurements. The field enhancement factor calculated from the results is $\beta = 18$ and fits well with the value extracted from the data at 40 MV/m.

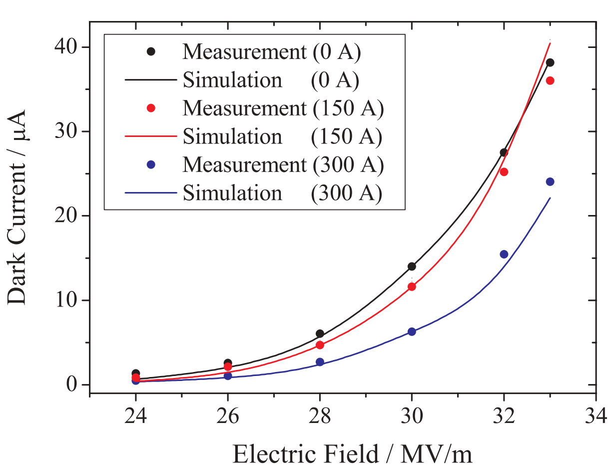

Figure 5: Comparison between simulated an measured dark current as a function of the electric field on the cathode for different solenoid currents.

CONCLUSIONS

With the help of detailed numerical tracking studies the dynamics of dark current electron inside an rf-gun have been investigated. Particles emitted at the high electric field areas located in the vicinity of the irises hit the walls of the rf-gun with energies of up to several tens of keV and are therefore a potential hazard to the Cs_2Te cathode. It was shown that the main part of the particles contributing to the measured dark current are originated at the cathode. By fitting the simulation data to the measured values a field enhancement factor of $\beta \approx 20$ has been estimated. Furthermore the dependency of the dark currents on the external magnetic field as well as on the electric field on the cathode can be be predicted by simulations if electrons hitting the beam tube at very low angles are considered to be scattered. To confirm this assumption further studies have to be carried out.

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