HALF CELL LENGTH OPTIMIZATION OF PHOTOCATHODE RF GUN

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Abstract

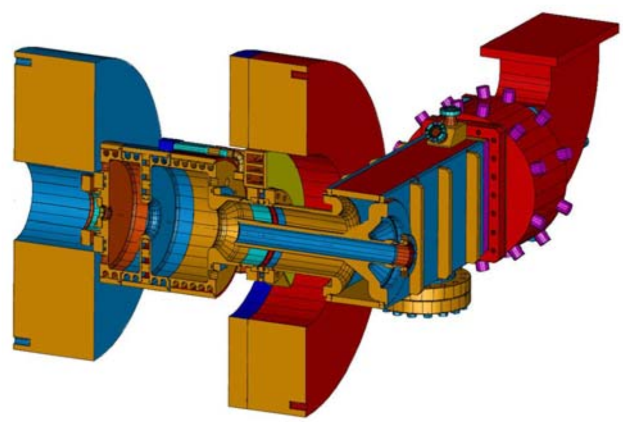
The very first acceleration in the first half cell of the RF gun cavity plays the most crucial role in the beam dynamics for the whole linear accelerator because the electron beam starts from zero velocity at the cathode, so the space charge force has the biggest effect. The operating emission phase of the electron beam changes with the length of the half cell. For a longer half cell length, the operating emission phase is shifted towards 0°. Since field emission is concentrated around an RF phase of 90°, where the field strength is maximum, the emission phases of beam and dark current can be separated by increasing the half cell length.

For the Free Electron Laser in Hamburg (FLASH) gun with 1.3 GHz resonance frequency, the RF field distribution has been calculated numerically for varying half cell length. Using the RF distribution, the transverse beam emittance has been calculated numerically. The transverse emittance does not change dramatically in the range of 64 - 70 mm half cell length. A reduction of dark current for a longer cell length is demonstrated with simulations. In addition, a modification of the dark current distribution in the momentum spectrum allows an improved collimation of the dark current.

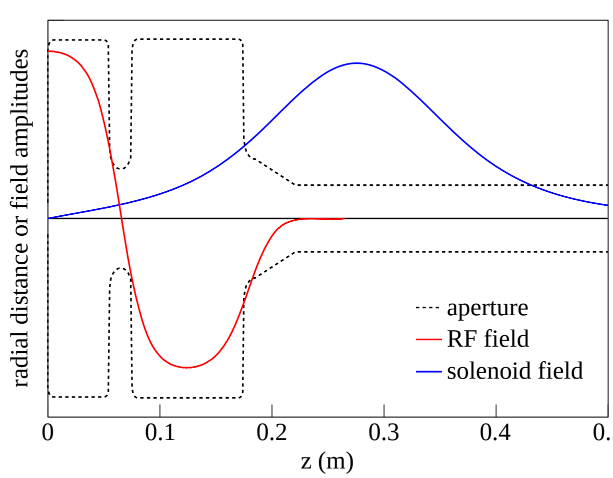
INTRODUCTION

The guns of the Free Electron Laser in Hamburg (FLASH) and the Photoinjector Test Facility at DESY in Zeuthen (PITZ) consist of a 1.5 cell gun cavity with a resonance frequency of 1.3 GHz (Fig. 1 a). The RF power is fed into the gun cavity through a coaxial coupler connected to the full cell of the cavity. This coaxial coupler allows a cylindrical symmetry of the gun cavity. Around the coupler is a focusing solenoid, called main solenoid. The magnetic field generated by the main solenoid extends to the cathode. To compensate the magnetic field at the cathode another solenoid is located behind the gun cavity, called bucking solenoid. The photocathode is inserted from the rear side to the back plane of the cavity. A manipulation system allows to exchange the photocathodes without breaking the ultra-high vacuum in the gun.

The emission phase of electron bunches to gain the highest momentum in RF guns is determined by the flight time of the bunch from the cathode to the full cell of the gun cavity so that the bunch can be accelerated in the full cell most efficiently. Since electrons start with almost zero velocity at the cathode and get accelerated with the RF field, the electrons need a flight time to the full cell of more than half an RF cycle. Therefore, the electrons must start at an RF phase of much earlier than 90° in order to reach the full cell when the field strength is at its maximum there. For example, the emission phase for highest momentum gain is typically 38° for the FLASH gun, which is operated at 42 MV/m maximum RF field at the cathode. For a higher RF gradient operation the emission phase is shifted towards 90° because the electrons get accelerated faster and need a shorter flight time to the full cell. For a lower gradient the



(a) FLASH gun.



(b) A simplified gun aperture and the field distributions.

Figure 1: The FLASH gun and the RF and solenoid field distributions. For the simulation study in this article, the RF field amplitude at the cathode is configured to be higher than that in the full cell by 12%. The magnetic field has a peak at the center of the main solenoid. At the cathode, the field is compensated to be zero with the bucking solenoid.

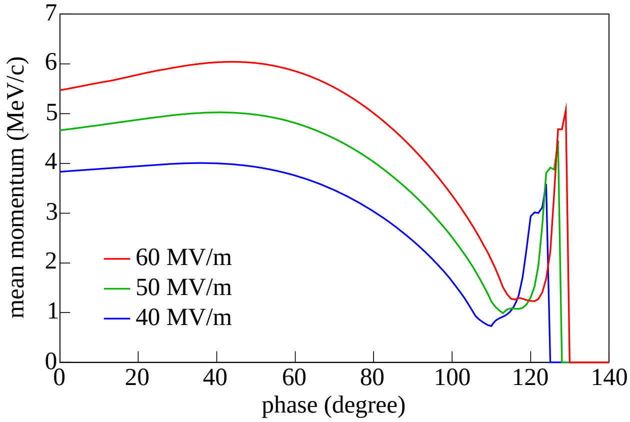


Figure 2: Beam momentum as a function of emission phase. Maximum mean momenta occur at 36° for 40 MV/m, 41° for 50 MV/m, and 44° for 60 MV/m, respectively. Electrons emitted at the phase at which the strongest dark current emission takes place, i.e. 90°, have a significantly lower momentum.

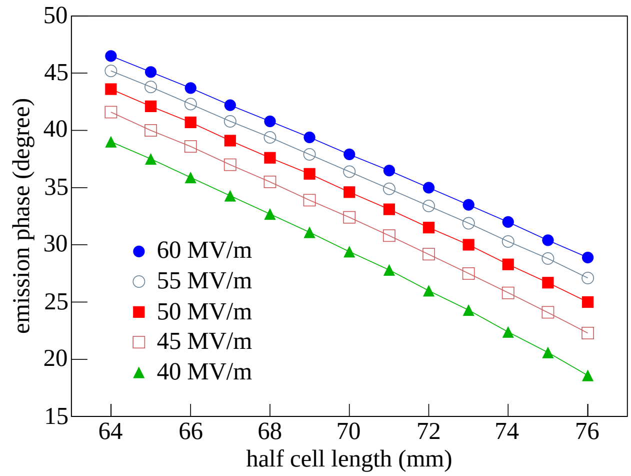


Figure 3: Variation of the optimum emission phase for the highest momentum gain as a function of the half cell length for several RF gradient cases.

emission phase is shifted towards 0° (see Fig. 2).

For the actual FLASH operation for the generation of Self-Amplified Spontaneous Emission (SASE), an emission phase is determined to minimize the transverse and longitudinal emittances. This emission phase is near to the emission phase of the highest momentum gain but shifted towards 0° by a few degrees.

The dark current has its origin in the field emission due to the strong RF field at the inner surface of the gun cavity. The dark current emission has the highest level when the field strength at the emission surface is maximum over the RF cycle, i.e. at 90°, and the current varies with the RF phase following the Fowler-Nordheim relation [4]

$$I_{\mathrm{DC}} = C_1(\beta E \sin\theta)^2 \times \exp[-C_2/(\beta E \sin\theta)], \qquad (1)$$

where I_{DC} is the dark current emitted at the surface, E is the amplitude of the RF field at the surface, θ is the RF phase, β is a field enhancement factor and C_1 and C_2 are constants.

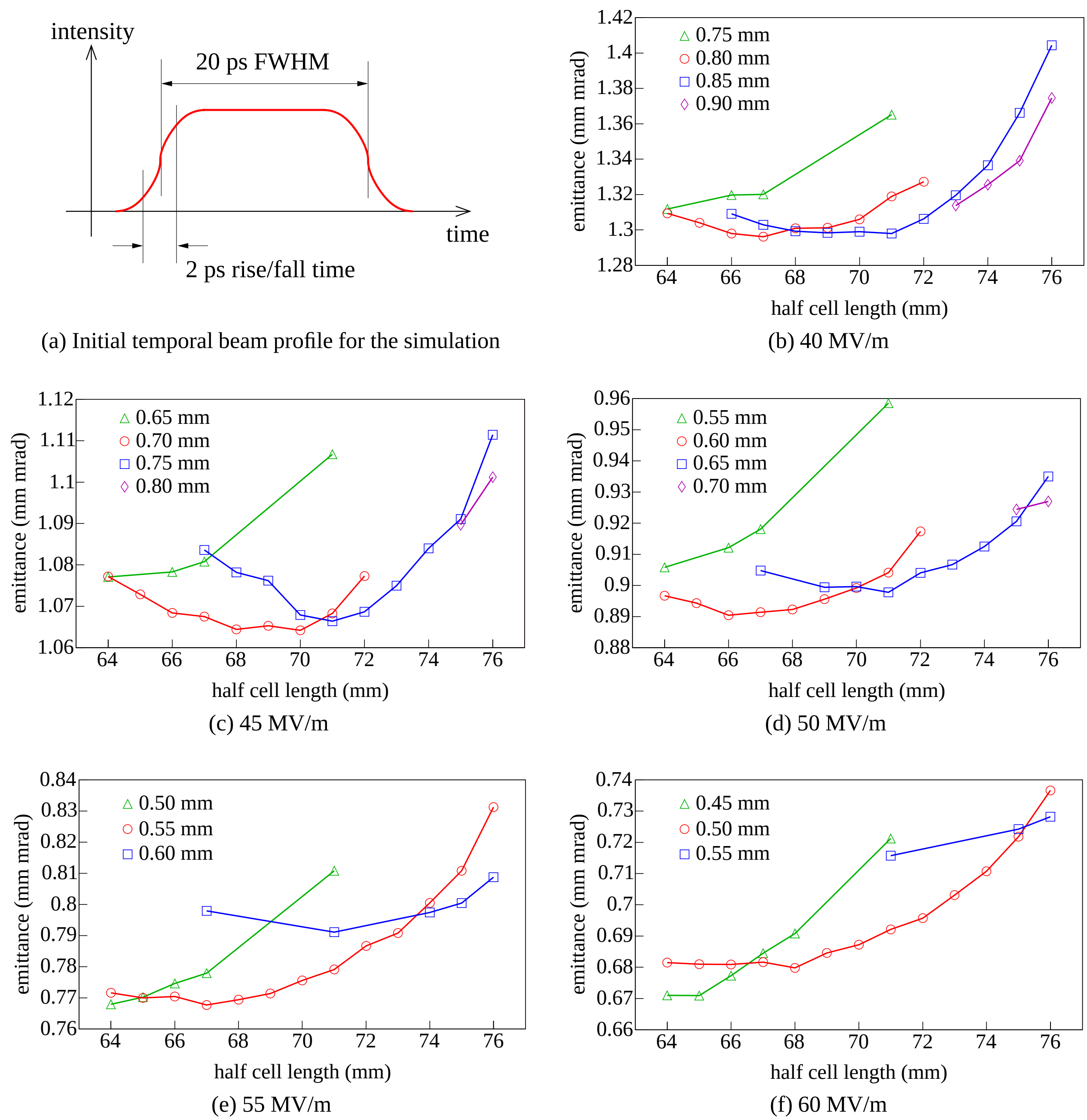
According to observations at PITZ and corresponding simulations, the dark current detected on the screen 0.8 m downstream from the cathode comes mainly from the cathode itself or its direct vicinity for the nominal operating conditions of FLASH, i.e. a maximum RF field at the cathode of 42 MV/m and a peak main solenoid field of 0.17 T [5]. Electrons field-emitted at the gun irises cannot escape from the gun but hit the cavity surface or the vacuum pipe to disappear.

Under the assumption that the dark current starts only at the cathode and its vicinity, the dark current emission is distributed around 90° RF phase at the cathode. Since the electron beam starts at an RF phase of several tens degree away from 90°, most of the dark current has a lower momentum than the electron beam (see Fig. 3). However, since a fraction of the dark current is emitted at a phase close to the emission phase of the electron beam, the momentum spectrum of the electron beam and the dark current overlaps partially (see Fig. 7). For higher RF gradient operation, the optimum beam emission phase is shifted towards 90°, thus the overlap in the momentum spectrum gets larger. These variations of the emission phase for different gradients and half cell lengths are shown in Fig. 3.

TRANSVERSE EMITTANCE VS. HALF CELL LENGTH

When the half cell length is changed the optimum emission phase is shifted as well. When the half cell length decreases, a shorter time is necessary for electrons emitted at the cathode to reach the full cell. Therefore, the emission phase is shifted towards 90°. For this case the RF field strength is stronger and the electron bunch suffers less space charge force during and just after emission. On the other hand, when the half cell length increases a longer flight time is required for electrons emitted at the cathode to reach the full cell and the emission phase is shifted towards 0°. For this case the RF field strength is weaker and the electron bunch suffers more space charge force during and just after emission. But, in this case the electron bunch get more energy in the half cell due to the longer acceleration length. These two effects, the RF field strength during emission and the acceleration length in the half cell, compete in maximizing the emittance preservation against the space charge force.

The normalized transverse emittance has been calculated with ASTRA [2] for the gun cavities with different half cell length (see Fig. 4). For these simulations an initial electron bunch with a uniform temporal distribution of 20 ps full width at half maximum (FWHM) and 2 ps rise/fall time and a variable transverse distribution with a flat-hat shape have been used (Fig. 4 (a)).



(a) Initial temporal beam profile for the simulation
(b) 40 MV/m
(c) 45 MV/m
(d) 50 MV/m
(e) 55 MV/m
(f) 60 MV/m

Figure 4: Transverse emittance vs. half cell length. (a) The initial temporal electron beam distribution determined by the cathode laser. The initial beam profile has a uniform shape with 20 ps full width at half maximum (FWHM) and 2 ps rise/fall time. In the transverse direction, the profile has a flat-hat shape with a variable rms size. (b) - (f) Transverse emittance calculated by ASTRA for maximum RF fields of 40, 45, 50, 55, and 60 MV/m at the cathode. The electron bunch charge is 1 nC. For each maximum RF field cases, the emittance has been calculated with different initial transverse beam sizes. The initial rms sizes of the beam are shown in the plots. The half cell lengths were varied from 64 mm to 76 mm. The present FLASH gun has 65 mm half cell length. This simulation has been made for the gun cavity only, i.e. without any acceleration module. The solenoid field strength and the position of the first acceleration module have been optimized. For each parameter point of the simulation, the minimum emittance appearing in the drift behind the gun has been chosen.

The RF field profile of the gun cavity has been calculated with SUPERFISH [6] with varying half cell length from 64 mm to 76 mm in 1 mm steps. The solenoid field profile data have been taken from a measurement with a hall probe [1]. 50 000 macro-particles have been numerically tracked through the gun and the beam pipe downstream with ASTRA. The electron bunch charge has been set to be 1 nC. The minimum emittance value after the gun has been chosen and plotted in Fig. 4.

A thermal emittance has been considered so that the emitted electrons have a kinetic energy of 0.55 eV which is estimated from theory [3]. Assuming an isotropic emission of the electrons at the surface, the thermal emittance is estimated as $\varepsilon_{\mathrm{thermal}} = 0.85 \times x_{\mathrm{rms}}$, where $\varepsilon_{\mathrm{thermal}}$ is the theoretical thermal emittance and x_{rms} is the rms size of the initial beam size at the cathode, or the cathode laser. This initial kinetic energy might change with the applied RF field strength at the cathode during the emission. For stronger RF field during the emission the kinetic energy increases [5]. However this effect is not considered in the numerical calculation with ASTRA.

For the case of a maximum RF field strength of 40 MV/m, the transverse emittance calculated with an initial beam size of 0.75 or 0.80 mm rms show a minimum value depending on the half cell length of the cavity. For the case with a smaller initial beam size, the emittance minimum appears at a shorter half cell length due to the stronger space charge effect. For the case of a longer half cell length, the RF field strength during emission is weaker and the electron beam suffers from the space charge force before being accelerated to become relativistic.

In Fig. 4 (d), the normalized projected transverse emittance is lower than 0.9 mm mrad for the 0.60 mm initial beam size case, which is the emittance requirement of the European XFEL injector. In the present design parameter of the XFEL gun, the maximum RF field is set to be 60 MV/m. But with decreasing the RF power in the gun cavity less dark current emission is expected and more stable RF operation might be possible, which is preferred for a stable gun operation. If we go to the 60 MV/m maximum RF field, an transverse emittance of lower than 0.7 mm mrad is expected.

For the 50 MV/m case, an ASTRA simulation has been made with a larger number of macro-particles: 200 000 including the first acceleration module (Fig. 5). The acceleration module consists of 8 TESLA type 9 cell cavities. For the configuration of the RF field in the acceleration module, the present FLASH operation condition has been considered; 13 MV/m average gradient in the first 4 cavities and 17.5 MV/m average gradient in the last 4 cavities. The cavity models with two different half cell length, 65 mm and 69 mm, have been used. With an initial beam size of 0.6 mm rms, a thermal emittance of 0.51 mm mrad has been calculated by ASTRA before starting the electron tracking simulation. The first cavity of the acceleration module starts at 2.73 m and 2.83 m downstream from the cathode for the cases with half cell length of 65 mm and 69 mm, respectively. After the first module, the transverse emittance has been calculated as about 0.8 mm mrad. Even considering the thermal emittance increase in the actual RF gun operation [5] the transverse emittance will be about 0.9 mm mrad.

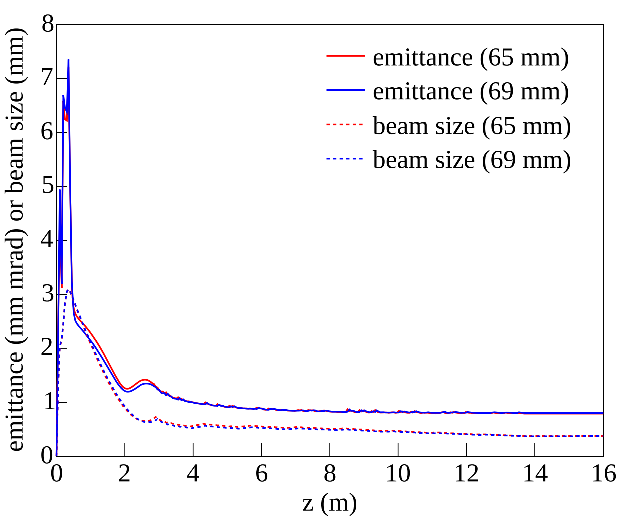


Figure 5: Normalized transverse emittance and beam size evolution for the gun cavities with half cell lengths of 65 mm and 69 mm. The simulations have been made with 1 nC bunch charge. The solenoid field has been configured to be 0.191 T peak field for the 65 mm half cell length case and 0.195 T for the 69 mm case. At z = 16 m, the emittance is 0.79 and 0.80 mm mrad for the cases with a half cell length of 65 mm and 69 mm, respectively. The beam size is 0.38 mm for both cases.

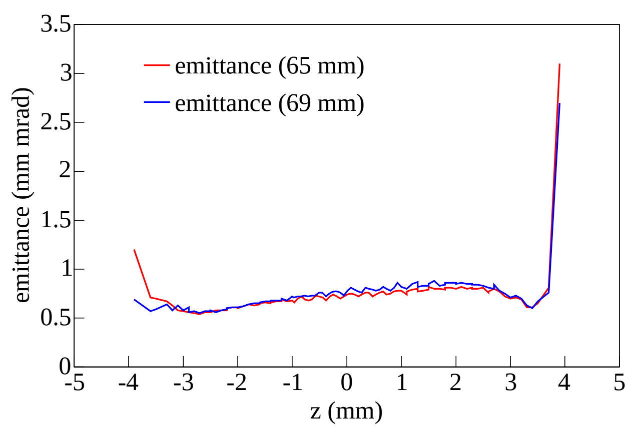


Figure 6: Simulation of the slice emittance for the electron beam with 1 nC bunch charge and a maximum RF field of 50 MV/m. The gun cavities with half cell lengths of 65 mm and 69 mm have been used. The electron bunch is longitudinally divided into 100 slices. Each slice has a charge of 10 pC. At z = 16 m, the emittance is 0.73 and 0.75 mm mrad at the central slices for the cases with a half cell length of 65 mm and 69 mm, respectively.

In Fig. 6, simulation results of the slice emittance after the first acceleration module are shown. The slice emittance has been calculated for the simulation shown in Fig. 5 at $z = 16$ m. The emittance is 0.73 and 0.75 mm mrad at the central slices for the cases with a half cell length of 65 mm and 69 mm, respectively. Ignoring the tails, the highest slice emittance appears around 2 mm from the center of the bunch. The values are 0.82 and 0.86 mm mrad for the two cases.

DARK CURRENT VS. HALF CELL LENGTH

As discussed above, the emission phase of the electron beam changes with the half cell length (see Fig. 3). On the other hand, the dark current field-emitted at the cathode area has a distribution with a peak at a fixed phase of 90°. The dark current distribution follows the Fowler-Nordheim relation (Eq. 1). The exact distribution is related to the field enhancement factor and the applied maximum RF field strength, however the shape resembles a Gaussian distribution with an rms width of 10° to 20° [5]. When the beam emission phase moves far away from 90°, the momentum distribution of the dark current becomes better separated from that of the electron beam.

The dark current simulation (shown in Fig. 7) has been made with an initial dark current starting at the cathode area with a Gaussian distribution of 2 mm rms transversally and with a Gaussian distribution of 15° rms RF phase temporally. For both half cell length, 65 mm and 69 mm, the initial dark current has been set to be the same. The difference in the dark current for the two cases is due to limiting apertures of the gun cavity and the vacuum pipe. The parameter for the electron beam simulation are the same as for Fig. 5 and 6.

If we compare the two cases the estimated amount of dark current reaching the first acceleration module for the 69 mm case is smaller than for the 65 mm case by about 20% (Fig. 7). Moreover, the overlapping fraction of the dark current and the electron beam in the momentum spectra is reduced so that the dark current can be over-focused with the solenoid field and can be collimated more effectively [7]. The dark current diminishes and the overlapping part in the momentum spectrum decreases in general when the half cell length becomes longer.

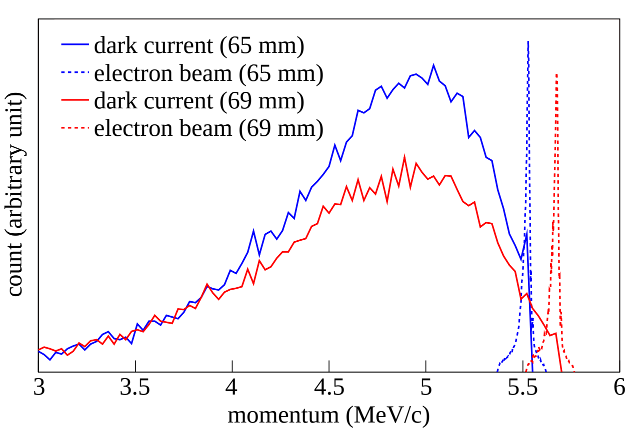


Figure 7: Simulation of the momentum distribution of the dark current and the 1 nC beam at the entrance of the first acceleration module.

CONCLUSION

Higher RF gradients of the gun cavity generate high level of dark current. To make matters worse the operating emission phase of the electron beam moves towards 90°, so that the overlap of the dark current and the electron beam in the momentum spectrum becomes larger. With increasing the half cell length of the gun cavity the transverse emittance is not degraded, but the amount of the dark current reaching the first acceleration module is reduced. In addition, the distribution of the electron beam and the dark current in the momentum spectrum can be separated. The separated dark current from the beam can be collimated more effectively.

According to simulations with a maximum RF field strength of 50 MV/m at the cathode, the transverse emittance fulfills the requirement of the European X-ray FEL injector. For half cell lengths of 65 mm to 69 mm the emittance stays below 0.9 mm mrad including the thermal emittance. The dark current from the gun shows a reduction up to 20% when the half cell length is changed from 65 mm to 69 mm even without extra collimation.

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