DARK CURRENT COLLIMATION AND MODIFIED GUN GEOMETRY FOR THE EUROPEAN X-RAY FEL PROJECT

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Abstract

An rf field of 60 MV/m will be applied at the L-band gun of the European X-ray FEL project. Such high rf gradient will allow to achieve a transverse emittance below 1 mm mrad for 1 nC electron bunches but will also produce a high dark current. The dark current generated in the gun shows a comparable dynamics as the electron beams because the same acceleration will be provided from the gun to the last acceleration module. The dark current from the gun might generate high radiation doses in the undulator and limit the long pulse operation of the SASE. To minimize dark current before the first acceleration module, a modified design of a gun cavity and collimator is investigated. The beam dynamics for minimal transverse emittance is optimized with the present and the new designed gun cavity and the resultant machine parameters are used to understand the dark current behavior.

INTRODUCTION

The Free Electron Laser in Hamburg (FLASH) gun operates with a max rf field of about 44 MV/m at cathode. The L-band Cu cavity with cylindrical symmetry is fed through the coaxial rf input coupler [1]. The photocathode is composed of a Mo cathode plug and a Cs_2Te film on the plug. The plug is a cylindrical rod with 16 mm diameter and the emissive film has typically 30 nm thickness and 5 mm diameter. The cathode has a high quantum efficiency (QE) of the order of 1%. Such high QE relaxes the requirement for the drive-laser producing photoelectrons from the cathode.

In August 2006, a long rf pulse of 800 μs has been applied into the gun cavity to produce 600 electron bunches per rf pulse. The number of bunches was limited only by the flat range of the rf pulse in the accelerator modules. In the near future, the bunch train will be expanded to fill out the rf pulse of the gun [2]. At the same time of the long rf pulse operation, the SASE lasing was also successfully achieved with the 600 bunches.

One critical factor limiting the long bunch train operation is the dark current generated in the gun cavity. At the exit of the gun, the dark current is 0.2 $\sim$ 0.3 mA. Simulations of dark current trajectories show that only the dark current emitted at the cathode area can escape from the gun cavity and flow downstream. The dark current starting at the cathode area is mostly released at an rf phase around 90°, i.e. when the rf field is maximum. At the FLASH gun, dark current starting at the cathode has a similar size as the election beams at the collimator position, 1.27 m downstream from the cathode (see Fig. 1). The inner ring-shape dark current seems to come from the boarder of the Cs_2Te film on the cathode plug [3]. The dark current has a larger radius at the emission position and obtains a lower kinetic energy through the gun than the beams. However, 1 nC beams are focused over a longer distance due to the space charge force and the higher momentum than the dark cur-

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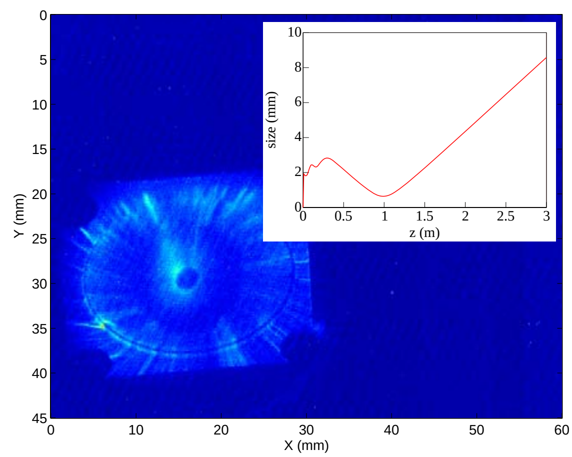
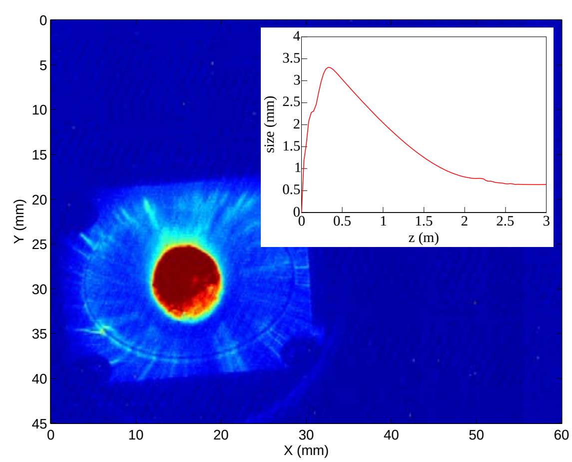


(a) Dark current image and simulation for the dark current from the cathode.



(b) Dark current and 1 nC beam image and beam simulation.

Figure 1: Dark current and beam images taken at the screen 1.27 m downstream from the cathode. Machine parameters for the nominal SASE operation are used. The simulations in the small boxes have been made with ASTRA [4]. A collimator is located at the same position as the screen. The dark current from the cathode has a similar size as the 1 nC bunch. Therefore, the dark current cannot be chopped with the collimator efficiently.

rent. With the influence of the focusing solenoid, the size of the dark current and the beams are similar at the collimator (see the simulations in Fig. 1).

For a better efficiency, the collimator should be located more downstream because the dark current is strongly overfocused. But, the collimator position is limited by the cryo tank of the first acceleration module. The dark current gets larger than beams as propagating downstream because the dark current has a lower momentum than the beams. This spreading dark current generates radiation doses at the accelerator modules, the bunch compressor and the other beamlines. After the first acceleration module, the dark current can get a kinetic energy of several tens MeV and possibly produce neutrons and γ rays especially at the first bunch compressor. Therefore, it is desirable to collimate the dark current before the first module. This situation is, however, significantly improved at the XFEL design parameters.

XFEL GUN

The XFEL gun will operate with 60 MV/m max rf field for a lower beam emittance and 700 μs rf pulse length for a long bunch train [5]. The dark current generated in the gun is an issue because the dark current might be very high due to the high rf field. Extrapolating the measured dark current level to gradients of 60 MV/m by means of the Fowler-Nordheim equation yields dark current levels in the mA range. This ignores conditioning effects. Moreover is a reduction of the dark current by improved cleaning techniques as dry-ice cleaning expected.

At FLASH a fraction of the dark current has a momentum as high as the electron beam [3]. As increasing the rf field in the gun cavity, the optimum emission phase for the highest momentum gain and the smallest transverse emittance is shifted toward 90° of the rf phase. At FLASH the optimum emission phase is about 38°. When 60 MV/m max field is applied to the FLASH gun cavity (type #1), the optimum emission phase will be shifted to 45°. This means that a larger fraction of the dark current emitted around 90° rf phase will overlap with the electron beam in the momentum spectrum.

In order to separate the momentum distribution of the dark current from the beam, the half cell of the gun cavity is elongated by 10 mm (type #2). The on-axis rf field profiles of the two cavity types are shown in Fig. 2. The rf field profile is calculated with SUPERFISH [6]. When the half cell is longer, the electrons have to start at an earlier rf phase to gain the most effective acceleration through the cavity. The dark current starting around 90° will be too late to be efficiently accelerated.

Beam dynamics

Machine parameters of the injector, including the gun and the first acceleration module, are optimized for a minimum emittance (Fig. 3 and Table 1). When the half cell is elongated, the optimum emission phase is shifted toward

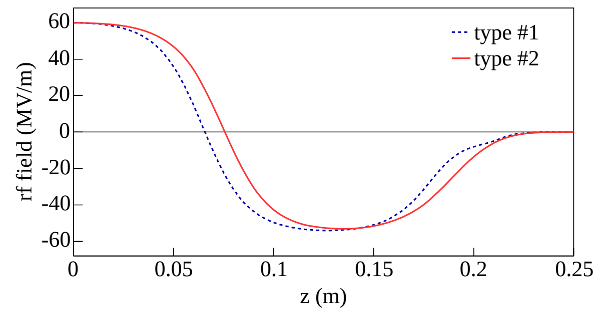


Figure 2: On-axis rf field profile for two gun types.

0°. For cavity type #1, the optimum emission phase is 45°, resulting in an rf field of 42 MV/m at cathode during emission. For cavity type #2, optimum emission phase is 31° and the rf field during emission is 31 MV/m.

In photocathode rf guns, a strong rf field suppresses the beam expansion due to the space charge forces during the emission of high charge density electron beams. Because the emission field is lower in gun type #2, the initial beam size at cathode need to be larger in order to reduce the space charge force.

The kinetic energy of the emitted electrons is assumed to be 0.55 keV and an isotropic emission is assumed according to Ref. [7]. The kinetic energy of electrons emitted from Cs_2Te cathode has been measured in laboratory condition with a very low electric field at cathode [8].

In a high rf field, a Cs_2Te cathode changes its surface properties and the kinetic energy of the emitted electrons increases with the field strength [9]. For the case of gun type #1, the kinetic energy of the emitted elec-

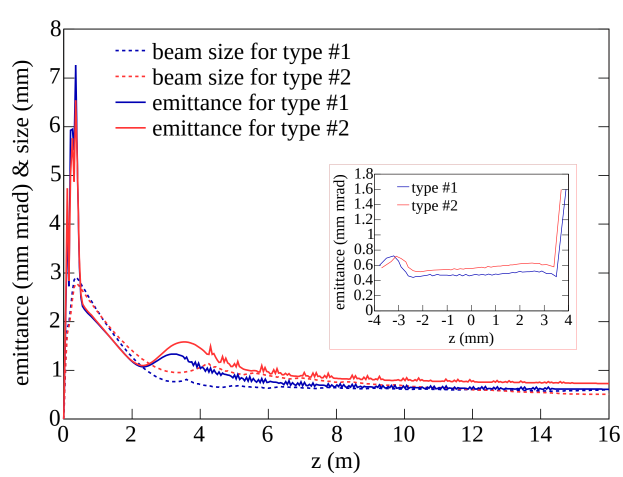


Figure 3: Rms beam size and normalized emittance evolution simulated with ASTRA. The simulation parameters are summarized in Table 1. The transverse slice emittances at z = 30 m are shown in the small box. The temporal profile of the electron bunches at z = 30 m is a hat-shape similar to the initial distribution of the bunch, i.e. the temporal profile of the drive-laser.

Table 1: Simulation parameters for two gun types.

Parameter	Type #1	Type #2
Initial distributions of electrons[a]		
transverse[b]	0.45 mm rms	0.55 mm rms
temporal (flat-top)	2 ps rise/fall and 20 ps fwhm	
thermal ε [c]	0.37 mm mrad	0.47 mm mrad
Gun		
max rf field		
at cathode	60 MV/m	60 MV/m
at full cell	54 MV/m	53 MV/m
emission phase	45°	31°
rf field at emission	42 MV/m	31 MV/m
max solenoid field	0.222 T at 0.28 m	0.226 T at 0.29 m
Accelerator[d]		
max rf field	20 MV/m	20 MV/m
start of 1st module	3.43 m	4.05 m
Simulation result[e]		
bunch charge	1 nC	1 nC
trans. projected ε	0.60 mm mrad	0.64 mm mrad
trans. slice ε [f]	0.47 mm mrad	0.56 mm mrad
bunch length	2.05 mm	1.95 mm
mean energy	90.1 MeV	90.4 MeV
energy spread	1.19 MeV rms	1.12 MeV rms
long. emittance	302 mm keV	262 mm keV

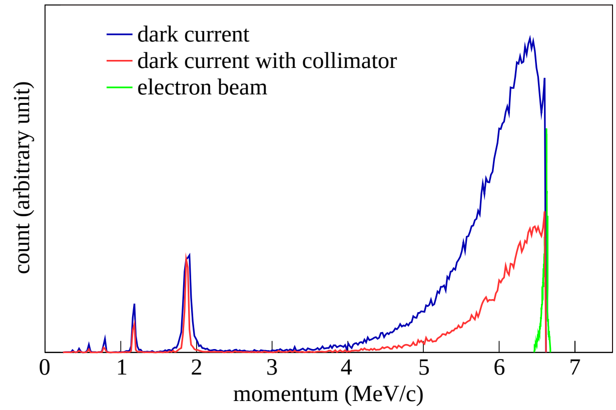
a This initial distribution is determined by controlling the three dimensional shape of the drive-laser at the cathode.
b Homogeneous distribution.
c Assuming the kinetic energy of emitted electrons to be 0.55 eV.
d Simulations include the acceleration with 8×9 cell TESLA type cavities.
e 200 000 macro particles are used for the tracking simulation with ASTRA.
f At the center of bunch.

trons is 0.738 eV according to the emission model in Ref. [9]. This kinetic energy rise and the field enhancement for photoemission increases the thermal emittance up to 0.59 mm mrad. For the case of gun type #2, the kinetic energy of the emitted electrons is 0.675 eV and the thermal emittance is estimated to 0.69 mm mrad.

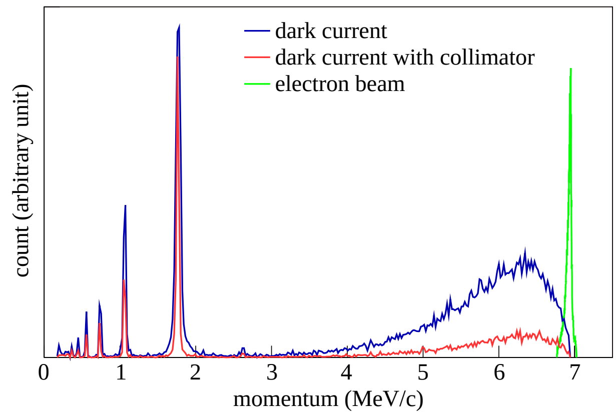
Dark current

With the machine parameters obtained with the beam optimizations, dark current has been simulated (Fig. 4). For the two gun types, the same amount of dark current from the cathode is tracked with ASTRA. The inner structure of the cavities and beam pipe with 35 mm diameter is considered as aperture.

When machine parameters for the beam optimization are used, the amount of the surviving dark current to the entrance of the first acceleration module is below 40% for gun type #2 compared to the gun type #1 case. The overlapping of the momentum distribution with the beam is significantly reduced, which is of great benefit for the dark current collimator.



(a) Gun type #1.



(b) Gun type #2.

Figure 4: Simulated momentum spectra of dark current and 1 nC beam. The machine parameters for the beam optimization are used. The dark current surviving to the entrance of the first acceleration module is shown. Because the emission phase of dark current is higher that the optimum emission phase, some part of the dark current stays in the gun cavity for several rf cycles. When the dark current finally escape from the gun cavity, the dark current can have certain definite momentum, appeared as spikes. The dark current reduction by the geometrical collimator is shown as well.

COLLIMATION IN THE GUN SECTION

In the gun section, two kinds of collimators can be used. The first one is a geometrical collimator for different transverse sizes (Fig. 5). Dark current with lower momentum is strongly overfocused by the solenoid field which is optimized for the beam focusing. The overfocused dark current is lost at the beam pipe. If a circular collimator is inserted inside the pipe, the dark current with larger transverse size can be cut out. Due to the cryo tank, a possible last position

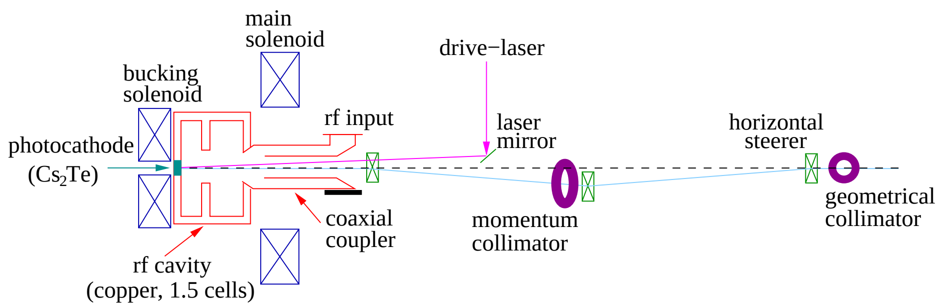


Figure 5: Schematic of gun section. The light blue line shows the reference path of beams. The circular shape collimator chops the dark current with larger transverse size. The elliptical shape collimator uses a difference in the momentum distributions of beams and dark current. The first horizontal steerer projects the momentum distributions of beams and dark current to the horizontal axis.

of the collimators is 1.2 m upstream from the entrance of the first acceleration module. For gun type #1, the position for the collimator is at 2.2 m. At that position, the electron beam size is 1.13 mm rms (Fig. 3) and a collimator with 10 mm diameter can be applied. With this collimator, the dark current from the gun can be reduced by 66%. For gun type #2, the position for the collimator is 2.8 m. The electron beam size will be 1.03 mm rms and a collimator with 10 mm diameter can be applied. With this collimator, the dark current current from the gun can be reduced by more than 70%. Taking into account the high losses at the beam pipe for gun type #2, the dark current behind the circular collimator is only 30% for type #2 compared to type #1.

The second possibility is a momentum collimator. This collimator is combined with a series of steerers and possibly has an elliptical shape with the major axis in the horizontal direction. If the first steerer kicks the beam and the dark current, the dark current with lower momentum is deflected more and can be chopped with a collimator. The minor axis length of the inner ellipsoid is determined by the beam size and the major axis length is determined by the beam size and the momentum distribution at the collimator position. When the dark current lower than 6.2 MeV/c, i.e. 10% lower than the mean momentum of the beam, is cut out with the elliptical collimator, again 75% of the dark current is possibly reduced for gun type #2. For gun type #1, 35% of the dark current is possibly reduced when the dark current lower than 5.9 MeV/c, again 10% of the mean momentum of the beam, is cut out.

The momentum collimator can be used to block the dark current from the acceleration modules which might have a momentum of several tens or even hundreds MeV/c. When the high energy dark current hits the Cs_2Te cathode, the emissive film might be seriously damaged.

CONCLUSION

The XFEL gun requires an rf field as high as 60 MV/m for 1 nC bunches with an transverse emittance below 1 mm mrad. But, such high rf field might generate very high dark current. With elonging the half cell length of the gun cavity, the dark current can be separated from the beam in the momentum spectrum. Collimators can be efficiently used to chop the dark current with lower momentum before the first acceleration module.

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