DARK CURRENT IN SUPERCONDUCTING RF PHOTOINJECTORS – MEASUREMENTS AND MITIGATION

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Abstract

Unwanted beam can cause beam losses and may produce acute or chronic damages of the accelerator. Furthermore it can considerably disturb experiments or increase its back-ground. The operation of the superconducting RF photo gun at the ELBE accelerator has delivered the first experimental information on that topic for this gun type. It was found, that dark current is an important issue, similar to that of normal conducting RF photo injectors. In the presentation the measurement of dark current, its properties and analysis will be shown and we will discuss ways for mitigation, especially the construction of a dark current kicker.

INTRODUCTION

ELBE is a user facility with a superconducting electron linear accelerator based on TESLA-type RF cavities and operates in continuous wave (CW) mode with original design values of maximum beam energy of 40 MeV and average beam current of 1 mA. In 2012 an upgrade in beam current to 1.6 mA was realized. The facility serves for manifold applications of electromagnetic radiation and particle beams ranging from the operation of two free-electron lasers (FEL) for infrared light, the production of gamma rays for nuclear astrophysics, positrons for material science, neutrons for transmutation studies, and beams for oncological radiations. For high-current applications like FELs or gamma ray production, small fractions of beam loss of 0.1 % or less can damage accelerator components. For the other low-current applications like radiation treatment of cells, tests of new particle detectors, or Compton backscattering experiments unwanted beam produces irradiation dose errors or additional measurement background. A thermionic electron gun has served as injector since the commissioning of the accelerator in 2001. Unwanted beam derives from field emission in the acceleration cavities and beam halo due to jitter or other instabilities.

A new superconducting RF photo-injector (SRF gun) has been developed and installed at ELBE which produces beams of higher brightness and allows for higher bunch charges than the thermionic injector. The design of the SRF gun and its present status and properties are presented elsewhere [1, 2]. The SRF gun will replace step by step the thermionic injector.

Normal-conducting RF photo-injectors are known to produce a high amount of dark current due to field emission [3, 4]. Especially for RF photo-injectors with long bunch trains like at FLASH or the future European XFEL, dark current is a serious problem and requires counter measures as the installation of a dark current kicker [5]. Dark current might be also a problem for SRF guns, especially due to their CW operation. For the SRF gun at ELBE we therefore performed dark current measurements.

SRF GUN DESCRIPTION

The SRF gun at ELBE comprises a 3½-cell niobium cavity for 1.3 GHz with a 12 mm hole in the half-cell back wall for the insertion of the photo cathode as it is shown in Fig 1. The photo cathode is hold by the cathode cooler and its 10 mm diameter stem extends through the choke filter cell into the hole of the half-cell. There is a 1 mm circular gap between the cathode stem and cavity. Thus the cathode is electrically and thermally insolated off the cavity. The front part (plug) of the cathode stem consists of Mo whereas the other part is Cu. The Cs_2Te photo layer is deposited on the front surface of the Mo plug. Usually the cathode is about 2.5 mm retracted with respect to the half-cell wall resulting in a lower cathode surface field.

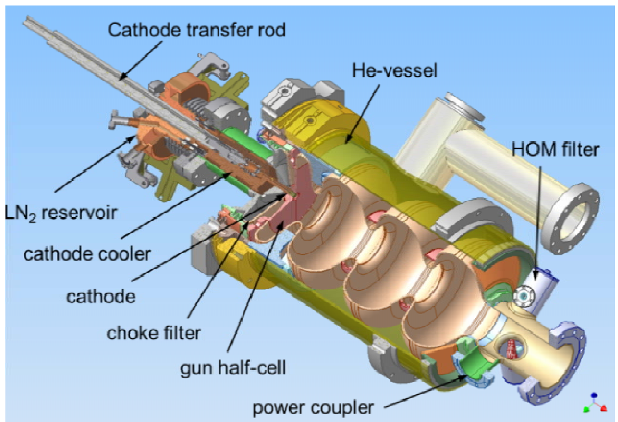

Figure 1: SRF gun cavity with liquid He vessel and cathode cooling system.

The on-axis acceleration field of the cavity is presented in Fig. 2a and the corresponding surface electric field is shown in Fig. 2b. The calculation was carried for the design value of 50 MV/m peak field but the relative field distributions are true also for the lower field values used in the measurements. Compared to the peak field in the three TESLA cells, the maximum on-axis field in the half-cell is 60 %, and at the cathode the value is 40 % caused by the retracted cathode. The details of the geometry near the cathode are shown in Fig. 3. For high-field areas, significant for field emission, the simulation delivers 80 % of the peak value at the cathode boring

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edge and 110 % at the iris between half-cell and first TESLA cell.

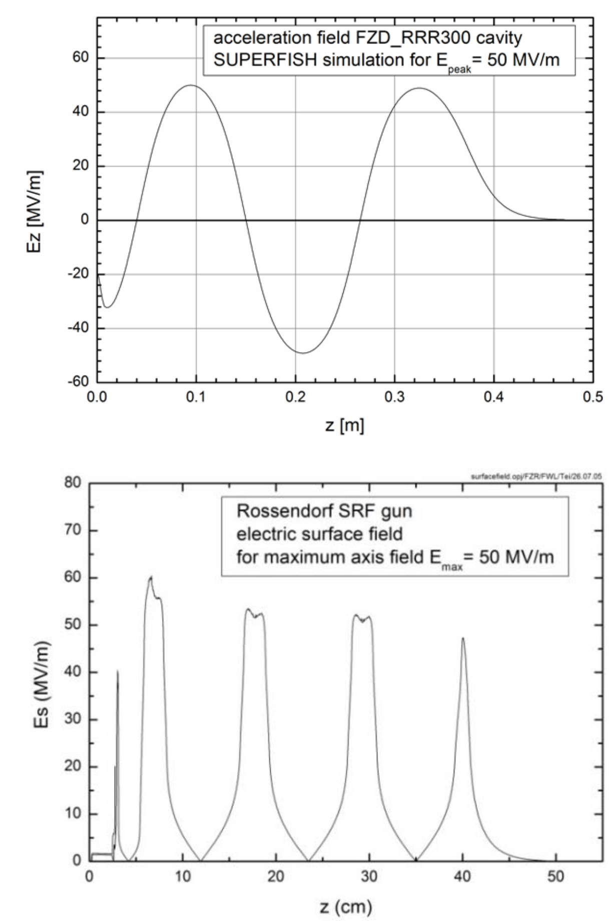

Figure 2: On-axis acceleration field (a), and electric surface field (b) versus cavity length coordinate.

Beam dynamic simulation showed that field-emitted electrons from the iris regions have wrong energy and do not leave the cavity. Thus, they do not contribute to the dark current. The dark current electrons must be emitted from the cathode or adjacent cavity areas. It is obvious that the simulation delivers probable field emission areas but the actual intensity depends on the local field enhancement and work function.

The standard operation of the SRF gun is CW mode. In this case the gun delivers an electron beam with a kinetic energy of 3 MeV and the acceleration gradient amounts to about 16.5 MV/m. Due to the lower field in the half-cell, the retracted photo cathode and the early launch phase, the field in front of the cathode which the electron bunch sees is rather low (see Table 1). In order to obtain higher gradients with the present cavity and simultaneously to keep the load to the liquid helium system low, the input RF power can be pulsed. The typical repetition rates are 1 to 10 Hz and the pulse length can be adjusted between 5 and 20 ms. In this case the peak field can be increased up to 21.5 MV/m and the corresponding final kinetic energy is 4 MeV. In both operation modes, CW or pulsed, a bias of -5 kV was usually applied to the cathode. This additional voltage increases the field at the cathode and improves slightly the beam quality.

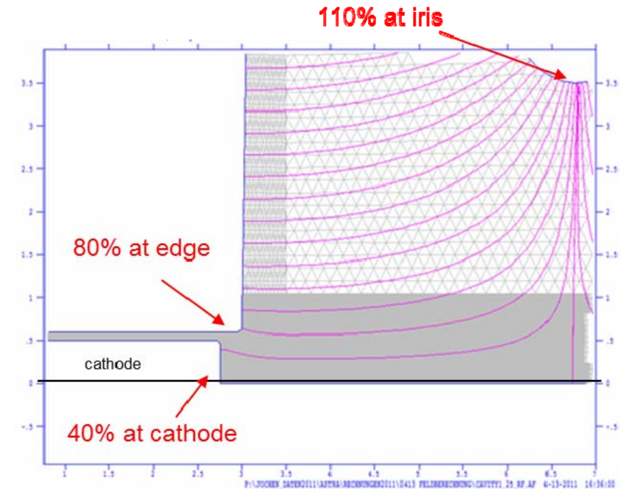

Figure 3: Electric field distribution in the cavity half-cell near the cathode (Superfish simulation).

In the SRF gun cavity the acceleration gradient is limited by the strong field emission in the half-cell, which has been in detail discussed in earlier papers [1, 2]. But it is important to note that the main reason for the field emission is a scratch near the cathode boring in the half-cell. As discussed above, the field emitted electrons originating from this near-cathode scratch contribute to the dark current leaving the gun.

DARK CURRENT MEASUREMENTS

Dark current has been measured with a removable Faraday cup located approximately 1460 mm downstream from the cathode. At the same position a YAG screen can be inserted for observing the beam spot. Together with a solenoid located in between, the cathode can be imaged with the dark current electrons onto this screen. The momentum distributions of the dark current electrons were measured with a 180° bending magnet and a following YAG screen in the diagnostic beamline.

First studies of the dark current emission of the gun were carried out in 2011. Figure 4 shows the dark current as function of the on-axis peak field for the measurements with two different Cs_2Te photo cathodes and for the gun without cathode. The curves show the typical Fowler-Nordheim dependence on the field strength. A comparison shows that the larger fraction comes from the cavity. Probably, the scratch in the cavity emits most of the electrons. The dark current contribution of one cathode (#250310Mo) is about 20 %. For the second cathode (#060410Mo) the dark current was, within the measurement accuracy, equal to that without cathode. But due to the long time between these two measurements a decrease of the cavity dark current contribution cannot be excluded.

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Table 1: Typical values for gradients and fields in the HZDR SRF gun for CW and pulsed mode

gun operation mode	CW	pulsed RF
acceleration gradient	6.0 MV/m	8 MV/m
electron kinetic energy	3 MeV	4 MeV
peak field on axis	16.5 MV/m	21.5 MV/m
peak field at cathode (2.5 mm retracted)	6.5 MV/m	8.4 MV/m
cathode field at launch phase (10°)	1.1 MV/m	1.5 MV/m
cathode field at 10° and -5 kV bias	2.2 MV/m	2.6 MV/m

In a second series, four different cathodes were compared within one measurement shift. The first cathode (Nb/Pb cathode) had the standard design but a Nb plug and a Pb photo emission layer deposited by arc discharge at Soltan Institute, Swierk [6]. Further two cathodes had molybdenum plugs with modified head designs (HZB_cap_CsTe and HZB_plug_clean), and the forth cathode was a standard HZDR photo cathode with Mo plug (#300311Mo). For all the cathodes the plug front surfaces were polished to optical quality and cleaned at HZDR. Two of the photo cathodes had a Cs_2Te layer (HZB_cap_CsTe and #300311Mo) and one had a clean Mo surface (HZB_plug_clean).

The dark current results of the four photo cathodes and of a reference measurement without cathode are shown in Fig. 5. The dark current level is nearly the same as in the previous measurements (Fig. 4) and it is confirmed that the main dark current source is the cavity. The cathodes with Cs_2Te layer contribute with about 20 %, whereas the Nb/Pb and the pure Mo cathode do not significantly contribute to the dark current.

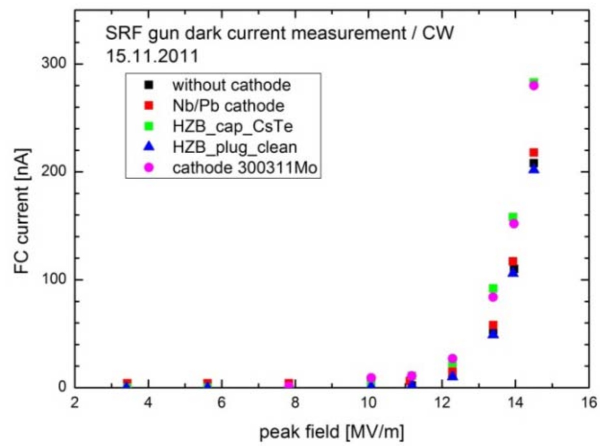

Figure 5: Dark current measurement results (Faraday cup current) for four photo cathodes of different shape or material tested in the SRF gun in fall 2011.

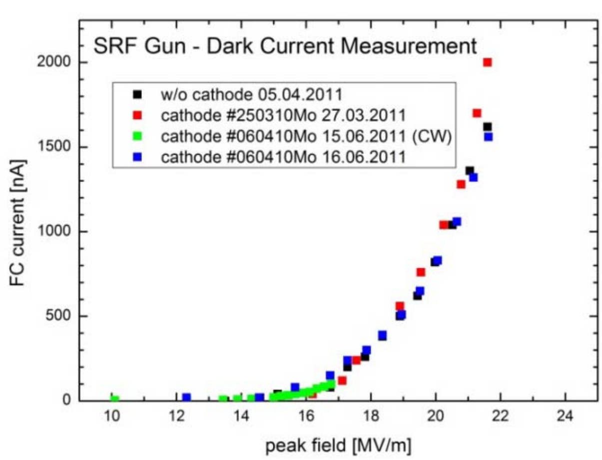

Figure 4: Dark current measurement results (Faraday cup current) for two photo cathode operated in the SRF gun in the 1st and 2nd run 2011.

The dark current measurements presented in Fig. 4 were analyzed using the field emission model for a time-dependent RF field [7]. The Fowler-Nordheim plot is shown in Fig. 6 with a fit curve delivers a field enhancement factor of 591 and an effective area of 0.63 nm^2.

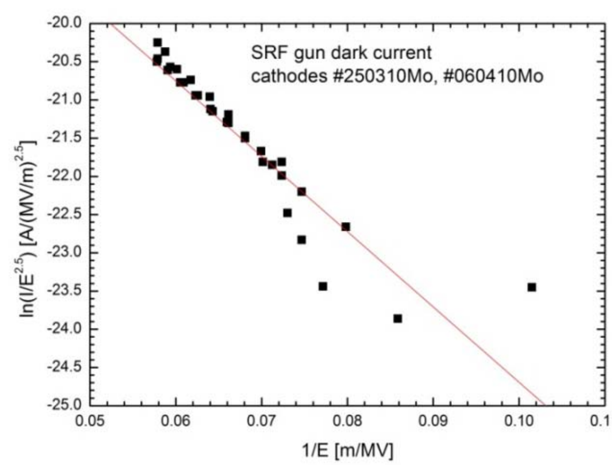

Figure 6: Fowler-Nordheim plot of the two photo cathodes operated in the SRF gun in 2011. (Data are shown in Fig. 4.)

For the SRF gun at ELBE two new cavities have been built in collaboration with Jlab. The first one (Compared to the used one, in the design slightly modified cavity made of fine grain Nb.) has been tested in the vertical cryostat until a peak field of 43 MV/m (E_{acc}=16 MV/m). During this test the measured field emission was very low. Since the beam quality requires a gradient as high as possible, the new cavity will be operated at its limits. It is therefore interesting to estimate the dark current for the

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new cavity. The results are shown in Fig. 7. The green curve shows the extrapolation for the cavity in use. The blue curve is the estimation for the new cavity. Since this cavity reaches a two times higher acceleration gradient, the surface treatment is accordingly better and we assumed the same dark current contribution of about 1.5 µA when operating at the gradient of 16 MV/m. Concerning the photo cathodes, the 20% contribution measured in the existing gun has been extrapolated. Here no decrease is assumed. It yields about 40 µA at 16 MV/m acceleration gradient, which is obviously too high for future operation in CW accelerators. Thus further effort is needed to reduce the field emission of photo cathodes at high gradients.

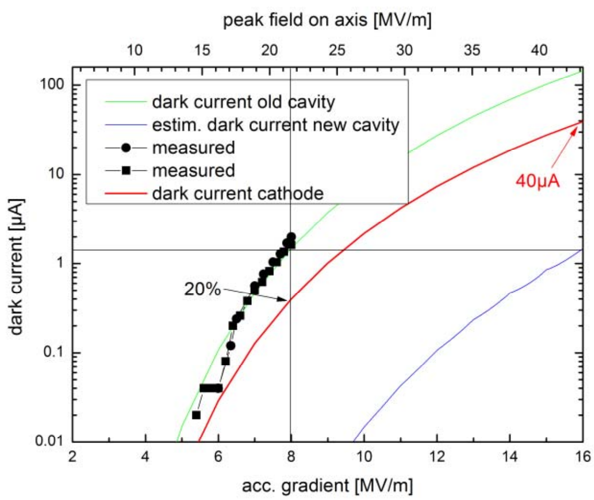

Figure 7: Estimation of dark current for higher gradients based on the Fowler-Nordheim data of the measurements; green curve: extrapolation of the existing cavity, blue curve: field emission assumption for the new cavity without surface damage and with lower field emission, red curve: extrapolation of photo cathode field emission.

Fig. 8 shows screen pictures in the dispersive part behind the 180° dipole magnet for a real beam with 30 pC bunch charge (1.5 µA @ 50 kHz) and an momentum of 3.3 MeV/c (E_{acc} = 6 MV/m) as well as for the accompanying dark current of 120 nA. The energy difference between electron beam and dark current was found to be less than 50 keV. This is nearly equal to the energy spread of the electron beam.

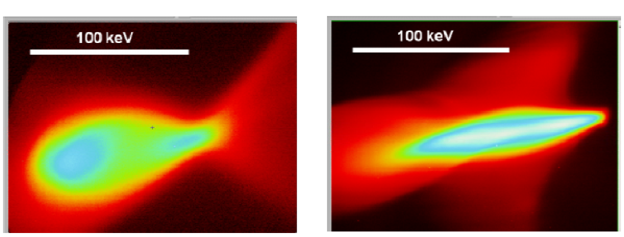

Figure 8: Dark current (left) and electron beam (right) images in the dispersive beamline behind the 180° dipole.

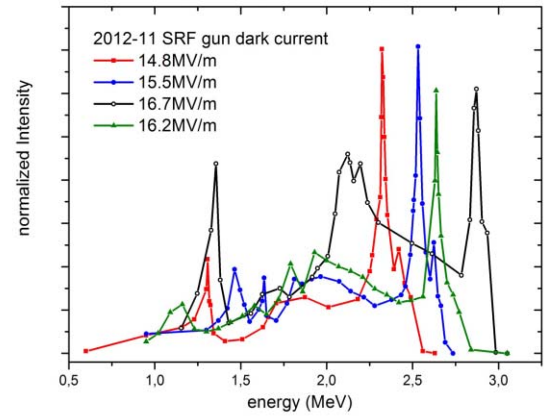

Figure 9: Dark current energy spectra for different acceleration gradients.

Detailed energy spectra of the dark current were measured as function of the cavity gradient and are shown in Fig. 9. The spectra are calibrated to each other by measuring the integral current with the Faraday cup at the same time. The high energy peak of each curve has nearly the beam energy as discussed earlier. The fraction of the high energy peak varies between 25 and 13 % depending on the gradient.

The high-energy fraction of the dark current can hardly be separated by dispersive methods. At ELBE the beam line acceptance is sufficient that this dark current is accelerated and transported to the user stations without further losses.

CONCLUSION

The dark current data measured up to now on several cathodes in the SRF gun at ELBE have been collected and analysed. Although the gradient is much lower than in normal-conducting RF guns, the data allow predictions to higher gradients. In the present measurements about 80% of the dark current emission comes from the cavity surface. The origin seems to be the damaged back wall surface near the cathode. For a new gun cavity which can reach about 40 MV/m peak field, the number of field emitters will be accordingly lower and the field emission level at its higher gradient nearly will be the same will or even lower. On the other side, the contribution from the photo cathodes will then increase to an estimated value of 40 µA. Experience at ELBE has shown that an unwanted beam level of 40 µA is too high for a CW accelerator. Thus an improvement of photo cathodes seems to be necessary. An alternative way is the installation of a dark current kicker. A schematic picture (Fig. 10) illustrates its function. The kicker should work with 13 MHz in CW mode with a sufficient amplitude to deflect the 1.3 GHz dark current pulses on a collimator. The kicker will be switched off for about 5 ps around the beam pulse. In this way the suppression is to 6.5 %.

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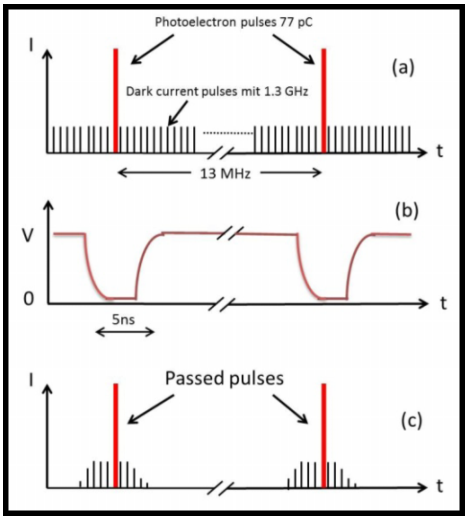

Figure 10: Dark current kicker functionality: (a) pulse distribution before the kicker, (b) kicker signal, (c) pulse distribution behind kicker and collimator.

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