DARK CURRENT TRANSPORT AND COLLIMATION STUDIES FOR SwissFEL

S. Bettoni, P. Craievich, M. Pedrozzi, S. Reiche, L. Stingelin, PSI, Villigen, Switzerland

Abstract

In all accelerating cavities a non negligible background of electrons can be generated by field emission (dark current), transported and further accelerated along the machine. The RF photoinjector guns, since operated at gradients also exceeding 100 MV/m, are critical sources of dark current. In nominal conditions a large fraction of this current is lost all along the machine, because of the phase mismatch at the entrance of the RF structures, a large mismatch of the optics and the energy acceptance limitations of the dispersive sections. In spite of this filtering a non negligible portion of unwanted charge can be transported and accelerated, therefore a careful estimate of the propagation is necessary to minimize radiation damages of the components and the activation of the machine. This paper describes the generation and the transport of dark current from the SwissFEL photo injector. The analysis is based on numerical simulations and experimental measurements performed at the SwissFEL Injector Test Facility (SITF). The model has been used to analyze the effect on the dark current transport of a low energy collimation system upstream the first travelling wave accelerating structure. A plate with several apertures has been installed in the SITF to benchmark the simulations and to verify the impact of the wakefields on the nominal beam.

THE DARK CURRENT ISSUE

The dark current in RF guns, due to the very high surface field they can reach, may be a very severe problem for the electronics sitting in the tunnel and the machine activation. A large fraction of this charge is typically lost in the low energy part upstream the first accelerating cavity. In spite of this, also if only a small fraction of the dark current is further transported downstream the accelerator, may be critical because lost at higher energy. The critical points in SwissFEL will be the two bunch compressors at 355 MeV and 2.1 GeV, the energy collimator, the septum and the undulators up to 5.8 GeV. To mitigate this problem we investigated the possibility of installing a collimator in the low energy region upstream the first accelerating cavity, where the charge can be lost in a controlled way and at low energy (maximum 7.1 MeV).

In theory all the accelerating cavities are sources of dark current, but we restricted our studies on the charge emitted by the gun, because simulations and measurements in the past indicated that for SwissFEL the other structures will not significantly contribute to the dark current due to the mismatch in the energy with the focusing optics[1].

THE SIMULATIONS

The emission of electrons from a surface with an electric field is a well known phenomenon, described by the Fowler-Nordheim equation:

$$I = A_e \cdot 1.54E-06 \cdot 10^{4.52\phi^{-0.5}} \frac{{\beta_0}^2 E^2}{\phi} \exp\left(-\frac{6.53E9\phi^{1.5}}{\beta_0 E}\right) \quad (1)$$

where A_e is the effective emitting area in m^2, ϕ is the work function of the material in eV, E is the macroscopic electric field on the surface in V/m and β_0 takes into account the field enhancement factor due to the microscopic structures of the surface. The latter parameter depends not only on the material but also on the details of the surface cleaning and roughness. For polished copper in literature we found values from 30 up to more than 80 [2].

Differently than what done in the past [1], without loosing in generality, we developed a 1D emission model along the gun aperture, considering the cylindrical symmetry of the low energy area (RF structure and surrounding solenoid). We assume that the charge is emitted from the line which defines the profile of the gun and, only to visualize the final results, we mirror the particle distributions with respect to the axis of symmetry. This and the fact that we can neglect the space charge allow running a meaningful simulation of the SwissFEL Injector Test Facility (SITF) [3], 22.9 m long, in less than 15 minutes on a single core machine. To describe the field experienced by the particles we used the 3D field map of the RF gun to take into account the transverse components of the off-axis field. For each longitudinal position on the gun aperture the radius and the field are defined for a starting time, and, using Eq. (1) we calculate the emitted charge from each point. For any other time step we multiply the values of the field map with a sine function to consider the time dependence of the emitted charge in one RF period. In the SwissFEL gun the maximum emission is from the cathode plane and from the points close to the cell restrictions, as shown in Fig. 1.

To consider the filling time of the gun we weighted the maximum amplitude in one RF period with a function taking into account the increase of the peak field per period versus time. The contribution to the transported dark current is less for smaller surface fields, not only because of Eq. (1), but also because the electrons emitted at lower fields are differently accelerated from the gun on and over focused by the solenoid. To introduce this effect we excluded the possibility of directly tracking the particles generated all along the 2 μs long RF pulse, because of the high number of particles we should consider. Due to the ratio between the filling time (805 ns) and the RF period (333 ps), in fact, to simulate the charges generated at peak fields above 80% we should

ISBN 978-3-95450-126-7

consider already 6000 periods. A more convenient way is to select only four instants during the filling time (nominal working point, 0.3, 0.6 and 0.8 of it) and to track the distribution generated at each one. At the end we recombined all the final distributions weighting them by the time interval between two consecutive cases. We tracked then this distribution in Astra [4].

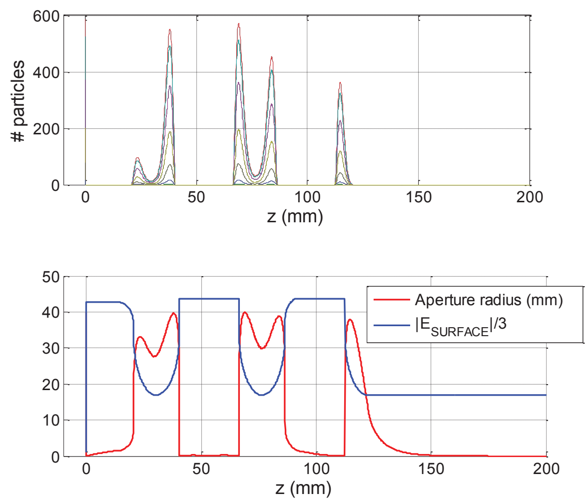

Figure 1: Macroparticles emitted according to the emission model. Each colour corresponds to a 9 degrees time step in one RF period (upper plot). Gun geometry and surface electric field on the aperture (bottom plot).

In Fig. 2 the first time steps during the charge emission according to the simulations in the SwissFEL gun are shown.

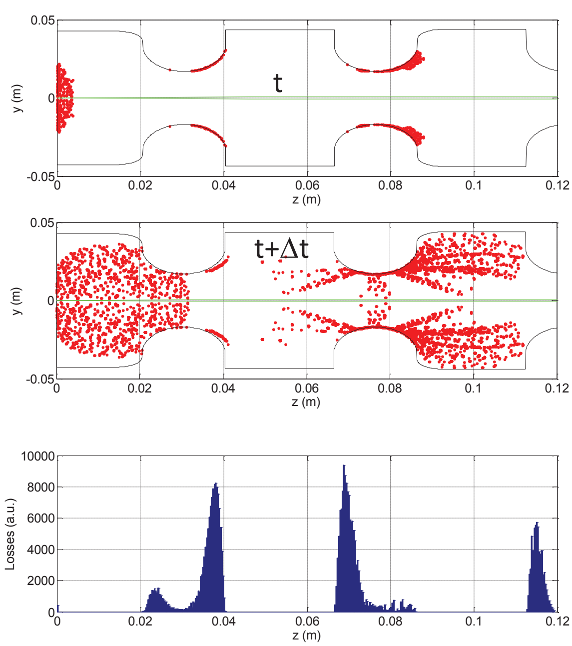

Figure 2: Simulated dark current in the SwissFEL gun during the emission. The locations of the losses in the gun are also indicated.

We used this model to simulate the reduction of the dark current obtained using a cylindrical collimator upstream the first accelerating cavity. We repeated the simulations for SITF to benchmark the model with measurements in the facility, where we installed a movable sled with holes of several diameters. We used this plate also to verify the effect of the geometric wakefields on the nominal beam for which, at this low energy, we didn't find any experimental verification.

The beam size (σ = 0.6 mm) 0.3 m upstream the waist in SITF where we could install the plate in SITF, is similar to the one at the location where we could install the collimator in SwissFEL, 0.1 m downstream the waist of the 200 pC SwissFEL operation mode, as sketched in Fig. 3.

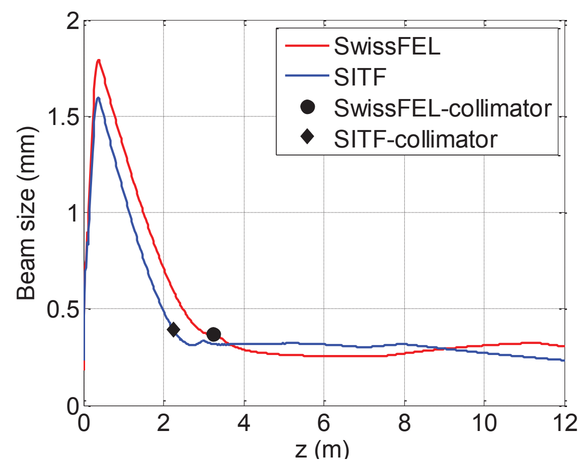

Figure 3: rms beam size of the 200 pC nominal beam and position of the collimators in the SITF and in the SwissFEL case.

The simulations indicate that the transport of the dark current can be drastically reduced in the injector upstream the first bunch compressor by the collimator, as shown in Fig. 4 in SwissFEL. The plot describes the fraction of the transported charge transported without the collimator.

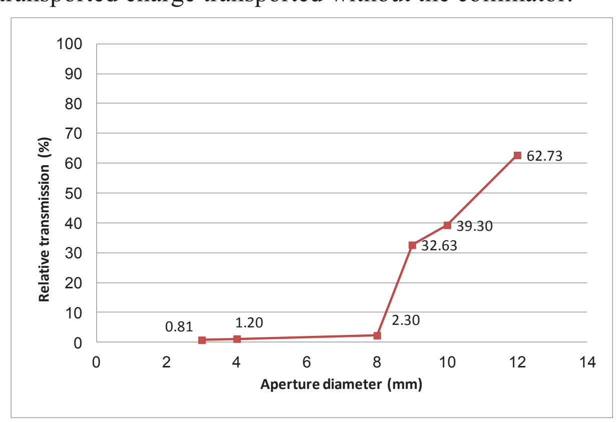

Figure 4: Transmission of the dark current renormalized to the transmission without the collimator.

The contribution to the final dark current from the charge emitted as a function of the cathode peak fields (filling time effect) assuming the same number of emitted particles is shown in Fig. 5. Furthermore E-dependence of the emitted current in Eq. (1) makes the contribution coming from lower peak fields absolutely negligible for the calculation of the final dark current.

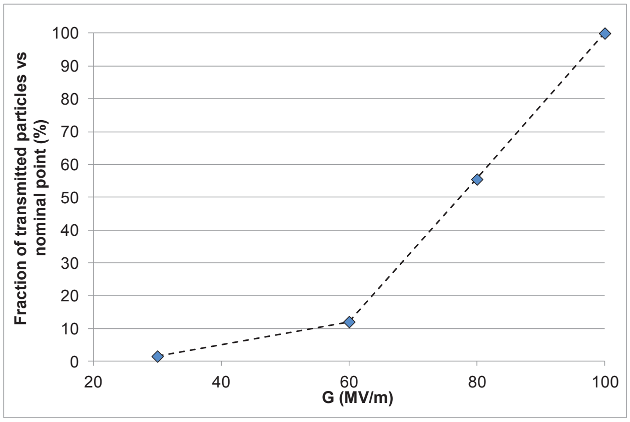

Figure 5: Dark current transmission as a function of the gun peak field on the cathode.

THE GUN EMITTED DARK CURRENT

In the low energy section of SITF between the gun and the collimator plate we used a Faraday cup to characterize the dark current emission of the CTF2 gun [3].

In Fig. 6 the typical signals from the oscilloscope connected to the Faraday cup after we maximized the signal by optimizing the current in the solenoid surrounding the gun are shown.

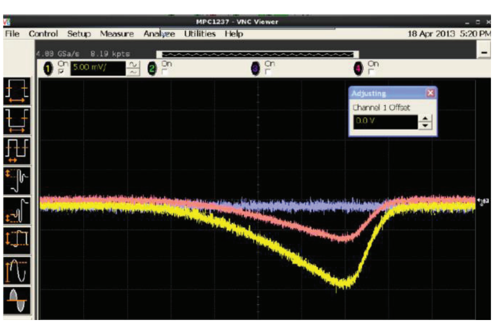

Figure 6: Signals from the Faraday cup during the measurement. Yellow trace: raw signal. Blue trace: background. Pink trace: signal after background subtraction. H-step = 200 ns/division.

The calibration of the signals is finely adjusted by comparing the BPM reading of the charge with the integral of the Faraday cup signal of Fig. 7. The calibration error of the Faraday cup reading is below 1%. At nominal operating conditions of the gun (85 V/m on the cathode surface), the dark current collected by the Faraday cup is 1.35±0.1 nC.

We measure the dark current transported to the Fraaday cup as a function of the maximum cathode peak field (value at the end of the filling time). The results are shown in Fig. 8. From this measurement, fitting Eq. (1) we estimated an enhancement factor of about 84, quite in agreement with other measurements done in the past [1].

In SwissFEL, due to the higher peack field at the cathode (100 MV/m) the emitted charge will be sensibly higher. By extrapolating the available measurements we expect a global charge of 6 nC behind the gun. The corresponding charge transported down to BC1 without collimation would be ~0.5 nC.

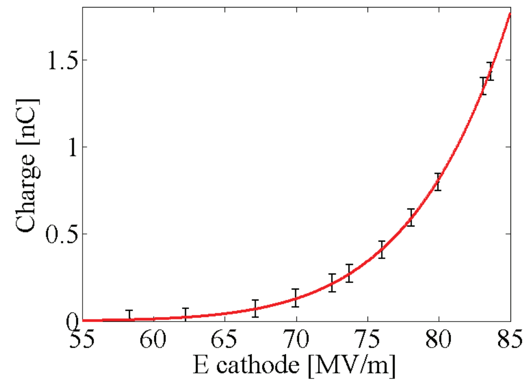

Figure 7: SITF gun charge emission as a function of peak cathode field. Solid line: fitting, black point: experimental data.

THE COLLIMATOR PLATE

The installation of the collimator in the low energy section of SwissFEL looks very promising in simulations for the suppression of the dark current suppression, but, before including it in the SwissFEL layout, we experimentally benchmarked the model and the impact of the geometric wakefield on the maximum charge for SwissFEL.

The plate has two holes with very small diameters (2 mm and 3 mm) to maximize the effect of the wakefields without scraping the nominal beam, three holes around the optimal aperture which was coming from the preliminary simulations for SwissFEL (9 mm, 10 mm and 11 mm), and one corresponding to the vacuum chamber aperture in SwissFEL (16 mm). The drawing of the plate is shown in Fig. 8.

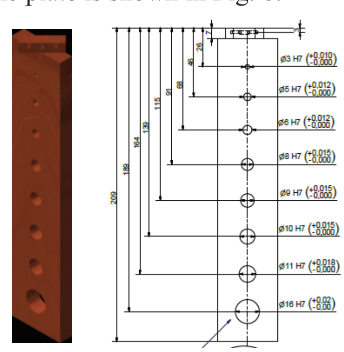

Figure 8: Collimator plate installed in SITF.

The plate is mounted on a motorized support which allows very easily measuring the nominal beam properties as a function the vertical offset. The material of the plate is copper but for a fix implementation in SwissFEL the

ISBN 978-3-95450-126-7

activation becomes an issue, and other materials like Tungsten will be better suitably.

Benchmark of the simulations

As an experimental verification of the simulations we compared the transmission of the dark current as a function of the diameter of the aperture with the model predictions. We focus our attention on the measurements done using the Integrating Current Transformer (ICT) at the end of the SITF [3].

Analogously to the measurements done in the gun area we calibrated the reading of the device for the losses in the cables by comparing the charge reading of the closest BPMs with the ICT response.

In Fig. 9 the screenshot of the oscilloscope for the 10 mm diameter hole is shown, as an example.

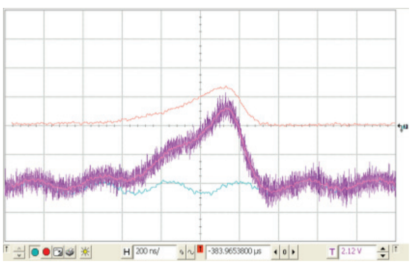

Figure 9: Oscilloscope reading of the 10 mm aperture measurements. Pink trace: raw signal. Cyan trace: background. Light pink: signal after background subtraction. H-step = 200 ns/division.

In Fig. 10 the comparison of the simulations with the measurements is shown.

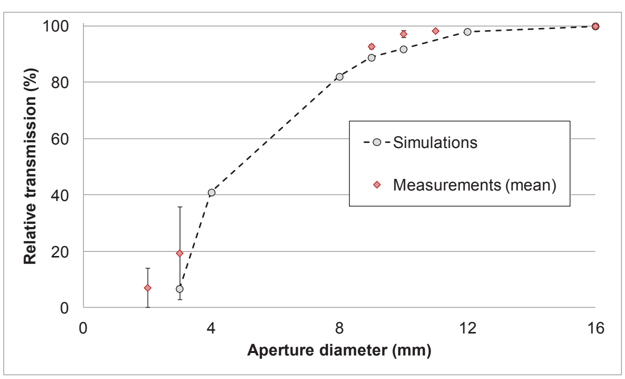

Figure 10: Charge transported at the end of SITF with the CTF2 gun as a function of the collimator aperture hole compared with the simulations. The charge is normalized to the transmitted charge without the collimator. The error bars are calculated from the difference of several sets of measurements.

In the plot we report the transmitted charge as a function of the collimator hole renormalized to the charge transported without the collimator compared with the simulations. The agreement is meaningful, also if to better investigate it in mid September we will install a new plate with intermediate 6 mm and 8 mm diameter holes also to come closer to the configuration considered optimal for SwissFEL.

Wakefield effect on the beam

The longitudinal and transverse geometric wake functions for the collimator are known for high energy, but we didn't find any experimental benchmark of these formulae at the low energy where we plan to install the collimator in SwissFEL (7.1 MeV). A verification of them is crucial. To investigate this effect we measured the emittance and the energy spread along the bunch as a function of the collimator aperture. We did all the measurements at 200 pC, the maximum charge of SwissFEL, using a 9.9 ps FWHM laser pulse length and a transverse radius of 0.42 mm. At the location of the collimator the beam size is about 0.6 mm in the present SwissFEL design.

In Fig. 11 the energy spread along the bunch for the different apertures and the comparison with the case with the case of the plate removed from the beam line is shown.

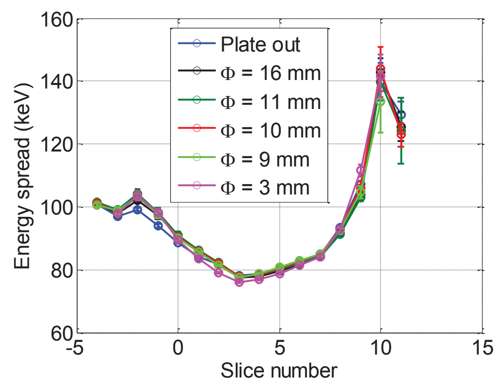

Figure 11: Slice energy spread measured for several collimator apertures along the bunch.

For all the apertures we didn't observe any appreciable energy spread increase along the bunch above the resolution limit of our system.

Also the projected emittance is not significantly perturbed by the collimator for anyone of the plate diameters, as shown in Fig. 12.

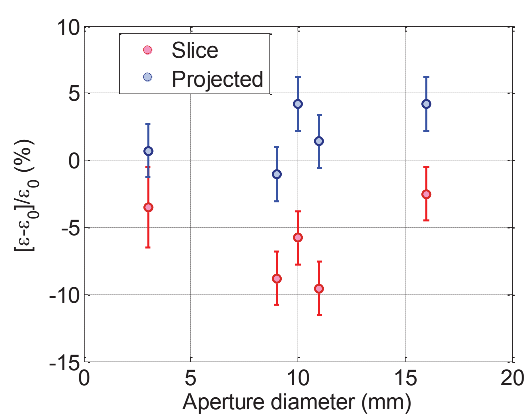

Figure 12: Projected emittance with respect to the case without the collimator as a function of the hole diameter. The central slice emittance is reported for comparison.

ISBN 978-3-95450-126-7

We didn't observe significant emittance or mismatch parameter variation along the bunch for the different hole diameters, as shown in Fig. 13.

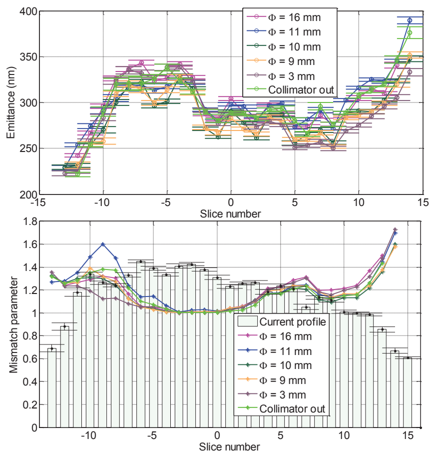

Figure 13: Emittance along the bunch, mismatch parameter and current profile for the several diameter holes.

From these measurements we can conclude that the longitudinal geometric wakefield produced by the low energy collimator wouldn't have a significant impact on the 200 pC SwissFEL nominal beam performances.

To investigate the impact of the transverse wakefield we inserted the 9 mm diameter aperture in the beam pipe (the most similar one to the optimal case for SwissFEL), we introduced an offset in the vertical position of the plate and we measured the projected vertical emittance. During these measurements we kept constant the orbit of the beam upstream and downstream the plate to avoid other possible bunch deformations due to other sources downstream the collimator.

SwissFEL will be very marginally sensitive to the transverse geometric wakefield generated by the 9 mm aperture collimator, only for orbit displacement above ±1 mm, as it can be concluded from Fig. 14.

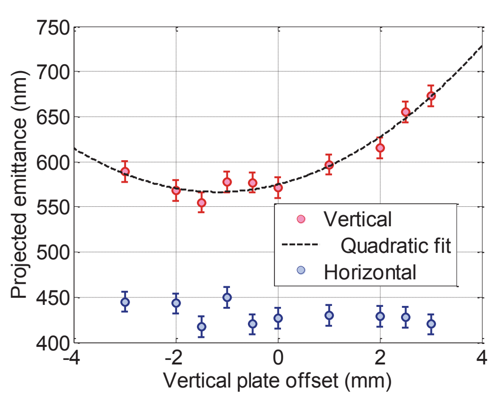

Figure 14: Vertical and horizontal projected emittance as a function of the plate vertical offset. A second order dependence of the emittance with respect to the beam offset is expected by the theory.

We consider therefore the effect of the geometric wakefields generated by a 9 mm diameter low energy collimator negligible for the SwissFEL injector.

CONCLUSIONS

The dark current emitted from the surface of RF cavities may be a severe problem for the protection of the components of the machine. Past measurements and simulations indicate that the main source of dark current for SwissFEL will be the gun from which we expect 6 nC due to a high surface peak field on the cathode plane. A possible solution to mitigate this effect is to install a collimator upstream the first accelerating cavity to loose the dark current in a controlled way at low energy. Simulations indicate that this collimator can be extremely efficient for SwissFEL, reducing the dark current transport upstream the first bunch compressor by more than an order of magnitude. We installed a plate with several apertures in SITF. We used it to benchmarked the simulations and to measure the effect of the geometric wakefields at the conditions of the maximum charge SwissFEL beam. These measurements indicate that the collimator would not significantly degrade the emittance in SwissFEL.

ACKNOLEDGEMENTS

We would like to thank M. Baldinger (PSI) for the manufacture and installation of the plate in the injector. We are grateful to him for the prompt reaction to any request we did. We would like also to thank M. Schaer (PSI) for providing us the field map from the gun in the format proper to be used in Astra.

REFERENCES

[1] F. Le Pimpec et al., "Dark current studies for SwissFEL", IPAC 2011 proceeding.
[2] L. Froelich, "Machine protection for FLASH and the European XFEL", Thesis, 2009.
[3] M. Pedrozzi et al., "SwissFEL injector conceptual design report", 2010.
[4] K. Flottman, Desy.

ISBN 978-3-95450-126-7