

DARK CURRENT STUDIES FOR SWISSFEL

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Abstract

Activation of the surrounding of an accelerator must be quantified and those data provided to the official agencies. This is a necessary step in obtaining the appropriate authorization to operate such accelerator. The SwissFEL, being a 4th generation light source, will produce more accelerated charges, which are dumped or lost, than any conventional 3rd generation light source, like the Swiss Light Source. We have simulated the propagation of a dark current beam produced in the photoelectron gun using tracking codes like ASTRA and Elegant for the current layout of the SwissFEL. Detailed experimental study have been carried out at the SwissFEL test facilities at PSI (C-Band RF Stand and SwissFEL Injector Test Facility), in order to provide necessary input data for detailed study of components using the simulation code OPAL. A summary of these studies are presented.

DARK CURRENT SIMULATIONS FOR SWISSFEL

The dark current is initially generated by field emission from the photocathode, in an RF gun, and around the irises of the cavities for all accelerating RF structures. The direction of propagation of the electrons obviously depends on the RF phase and the efficiency of propagation depends of the type of cavity, traveling or standing wave (TW, SW). Impinging electrons to the surrounding walls of the cavity will produce secondaries which can also be transported along the beam line and add to the dark current.

ASTRA Simulations

We have simulated the dark current of the SwissFEL [1] S-band standing wave photogun to the end of the second 4 m long S-band traveling wave structure, by using the tracking code ASTRA [2]. The initial electron bunch was produced by using the SwissFEL nominal bunch, spreading its dimension in time and space. The emission time was limited to 120 ps which is only covering one RF bucket $\pm 60^\circ$ around the on-crest phase. We turned off the space charge option. The dark current is in reality emitted at some threshold and at every RF bucket. This simple approximation is sufficient as every other dark current bucket propagating downstream of the RF gun will be transported identically by the machine optics. From the initial 300 k particles of the bunch, $\sim 22\%$ are lost on the cathode. The losses on the walls (in percent) are quantified along the first 13 m of the machine using the remaining ~ 234 k particles, Fig.1.

Only 9.7% of those remaining particles reach the beginning of the third S-band accelerating structures. As shown in Fig.1, more than 90% of the bunch is lost before even reaching the first S-band structure with a ~ 7 MeV kinetic energy. The 9.7% remaining particles are concentrated in the core of the initial bunch. The output distribution was reused as an input for the elegant tracker [3] starting from the beginning of the third S-band structure.

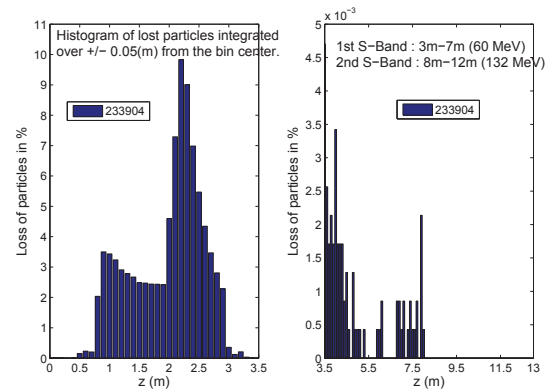


Figure 1: Histogram of the particle losses at the walls of the accelerator up to the end of the second S-band cavity (132 MeV)

Elegant Simulations

The leftover particles from the ASTRA simulation were not numerous enough to do a proper elegant simulation. We have multiplied the input distribution by cloning every particle with a small change in their positions and momenta. We hence produced 2.2 million particles. The tracking was done using the SwissFEL Elegant model which includes the physical apertures of the machine and by adding collimators toward the end of the Aramis beam line [1]. The space charge and wake field options were turned off. Fig.2 (bottom plot) and Fig.3 show the location where particles are lost and with which energy and energy spread. The energy spread for the lost particles is small, less than 1%, as can be seen by the small error bars displayed in the bottom plot of Fig.2. Losses are concentrated before the first bunch compressor ($s \sim 50$ m) and at the second bunch compressor ($s \sim 200$ m), as shown by Fig.3. No other losses are recorded after the second bunch compressor. The transverse collimators placed at the end of the machine ($s > 400$ m) induce dark current losses only for apertures

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smaller than 2 mm in radius.

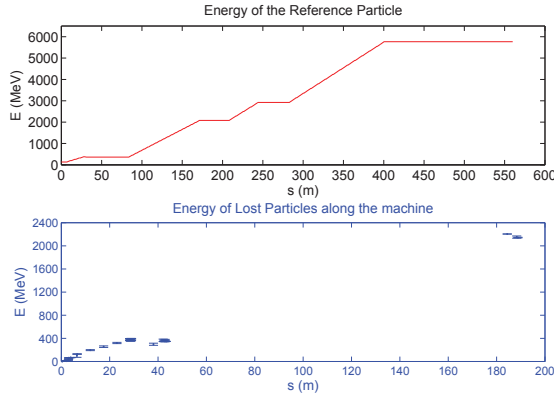


Figure 2: Top: Energy gained by the reference particle up to the end of the Aramis beam line. Bottom: Average energy and the standard deviation of the energy of the lost particles along the machine.

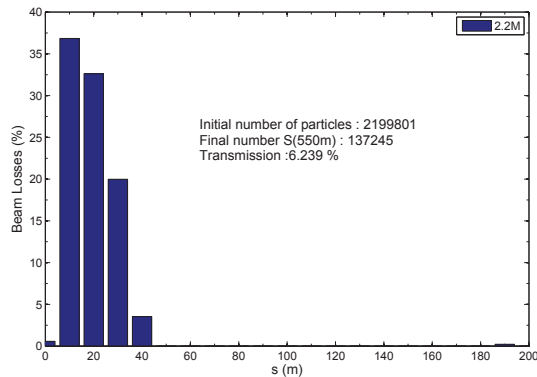


Figure 3: Histogram of the particle losses at the walls of the accelerator up to the end of the Aramis beam line (6 GeV)

Further simulations were carried out to find out the effects of different acceleration schemes on losses, due to potential SwissFEL operation conditions. The case presented in Fig.2 and 3 uses the full acceleration in LINAC 3 [1] up to ~ 6 GeV. The other acceleration mode are to accelerate the beam in the LINAC 2 to 3 GeV and then decelerate to 2.1 GeV : a) before LINAC 3 and b) at the end of LINAC 3. One last scenario is to accelerate in LINAC 3 to 3.5 GeV and then decelerate at the end of it to 2.1 GeV. The outcomes of those different simulation schemes are identical to the case presented here. They show no differences in losses when using collimators of 2 mm radius aperture. Small Differences arouse for collimator sizes below the 2 mm radius.

Finally, we used elegant to track back some potential dark current produced by the TW C-band RF structures [4]. In a TW structure the RF capture phase exists only in the direction of propagation of the RF wave. Due to the design

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of our C-band structure, we do not expect any dark current above a few MeV traveling upstream of the LINAC. In elegant reversing the linac model will also reverse the direction of propagation of the RF hence allowing captures of an upstream propagating electron beam. Despite this limitation, we find that no dark current produced by the last C-band structure of LINAC 3 makes it back to the beginning of the machine for an initial electron energy below 25 MeV. This energy exceed by far the energy gained by electrons accelerated through 2 or 3 cells in a structure.

OPAL Simulations

The preceding simulations have been carried out by using a blown up bunch based on the initial SwissFEL bunch. In order to use a more adequate bunch distribution, we have used the dark current module from OPAL [5], turning off the secondary electron emission switch. We have tested the emission and propagation of a dark current beam using a Fowler-Nordheim (FN) threshold for emission of 40 MV/m and a FN enhancement factor β of 80. For the component simulation, we have used the actual layout of the SwissFEL injector test facility gun, labeled CTF3 in Fig.4 [6]. The CTF3 gun is a two and a half cell SW RF structure. The RF peak field at $t=0$ ps is 100 MV/m on axis. For every picosecond the RF phase changes by 1° . The electrons are created at first on the cathode side and on the downstream side of the irises and electrons start propagating downstream of the beam line. 180° later the electrons are created in the upstream side of the irises and start propagating upstream (toward the cathode). Fig.4 shows a snapshot at $t=545$ ps of the propagation of the electrons. The 6D phase space output of the simulation can be used as an input for the OPAL or elegant trackers. The modified module also handle TW structures. We are planning to simulate the dark current production and propagation from an actual C-band test structure [4].

CTF3 gun, beta(FN)=80 Step # (ps): 545

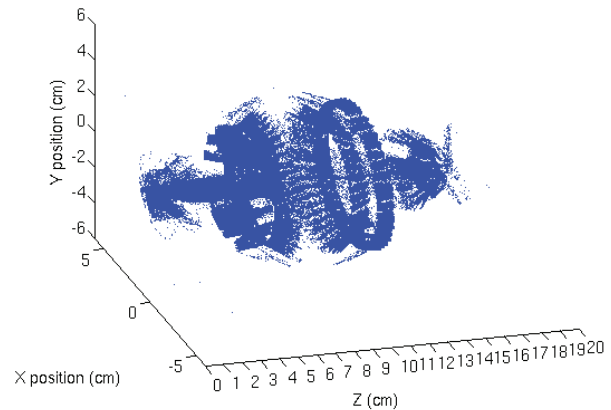


Figure 4: Propagation of the dark current in a SW photogun. The electron propagates upstream toward the cathode and downstream toward the exit of the gun.

EXPERIMENTAL RESULTS AT VARIOUS SWISSFEL FACILITIES

Dark Current at the SwissFEL Injector

In order to provide proper inputs for the simulation we measured the dark current produced by the injector RF photogun (CTF3), and by the 4 m long S-band TW structure. Its propagation along the beamline was also studied [6]. The CTF3 gun produces around 6 nC of dark current at nominal power (100 MV/m accelerating gradient). The charge is measured using the wall current monitor (WCM) located downstream of the gun. A second WCM is available downstream of the bunch compressor (BC). The emission of dark current in the gun is FN driven, as shown by the left plot in Fig.5. Using equation.1 in [7], we have extracted the FN enhancement factor $\beta = 78$ for such structure, Fig.5 (right plot).

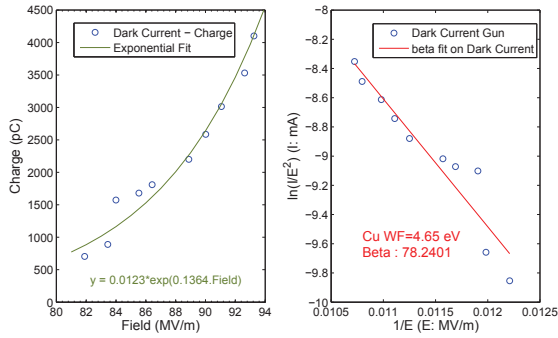


Figure 5: Left: CTF3 gun charge emission vs accelerating field. Right: Enhancement factor β determination.

$$\beta = \frac{6.83 \cdot 10^3 \times \Phi^{\frac{3}{2}}}{k_2} \quad (1)$$

Where $\Phi = 4.65 \text{ eV}$ is the work function, and k_2 is the slope of the fit. Warm RF cavities with β of ~ 50 are usually consider good structures.

In order to determine the energy spread of the dark current we have used two techniques. In one case, we have varied the input power at the gun and looked at the beam at the screen located at the dump of the energy spectrometer. In the other case, we swept the beam on the screen using the spectrometer dipole at nominal power. We measured a threshold for dark current at 4.3 MeV and a maximum energy of 7.2 MeV. The dark current energy on the lowest end could be lower than the measured 4.3 MeV, but we could not detect any electrons neither on the WCM nor on any scintillating screens of the beamline. The dark current emitted by the gun (6 nC) increased by a couple of nC over time (months). The transmission of this dark current through the injector accelerator (5%) is in agreement with elegant simulation (6%, Fig.3).

We have tried to observe the dark current emitted solely by the TW S-band structures, running at 28 MW of in-

put power (17 MV/m), on the upstream and downstream screens of each structures. No dark current was detected. A gamma ray spectrometer, facing the second S-band structure at a distance of 1 m and then 30 cm, showed no signal during the S-band operation. From these series of experiments, we concluded that the dark current measured downstream of the bunch compressor came solely from the gun dark current.

Offline radiation measurement performed at the injector were in qualitative agreement with the ASTRA results. Online radiation measurement shows a significant dose rate (mSv/h) at the entrance of the first and fourth TW S-band structures and at the entrance of the bunch compressor. The dose rate at the entrance of the BC is respectively four and two times higher than the dose rate measured at the first and fourth S-band structures. This seems contradictory to the simulations results, but one has to take into consideration the energy of the particles at the BC and at the entrance of the first S-band structure.

Nevertheless, in the overall the above results are in qualitative agreement with Elegant simulation results performed using the SwissFEL injector layout [1].

Dark Current of a C-band Test Structure

The main acceleration of the SwissFEL will be provided by C-band structures with an RF klystron pulse of 350 ns flat top and an on-axis maximum gradient of 28 MV/m [1]. It is of importance to test not only the quality of the mechanical production of such structures, but also their RF properties [4]. Two small prototypes have been RF tested, with a repetition rate of 10 Hz for the first structure and 100 Hz for the second one. Their dark currents were measured using the two Faraday cups (FCs) installed at each end of the beamline Fig.6. For the coming structures an Integrated Current Transformer (ICT) [8] will be installed in the beamline.

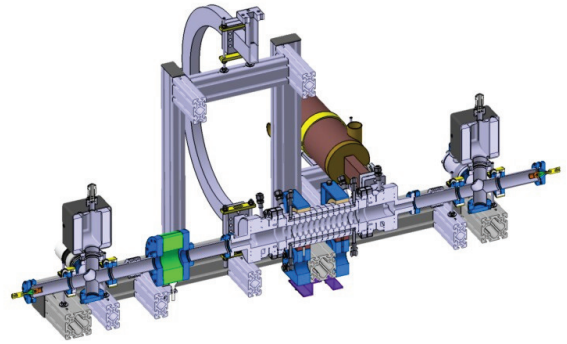


Figure 6: C-Band TW structure test stand, showing a faraday cup at each end of the beam line and an ICT.

We did not record any dark current on either the upstream or downstream FCs by running the C-band cavity for hours at an accelerating gradient of 38 MV/m, hence 10 MV/m above the design value, and with a 350 ns RF

flat top pulse. This amounts for ~ 51 MW of input power. The second C-band structure is currently RF tested with a flat top pulse already exceeding 500 ns. In both cases, dark current were solely detected on the faraday cups during breakdowns. The use of an X-ray scintillator [9], placed 1 m away from the structure, proves that it exists dark current inside the structure. Using the NIST [10] database, we determined that photons > 300 keV can make it through 40 mm of Cu. At 38 MV/m on axis field, an electron in 1 cell (2 cm) can acquire up to 750 keV. The X-ray signals is well fitted by the use of an exponential function, as expected for dark current coming from field emission, Fig.7.

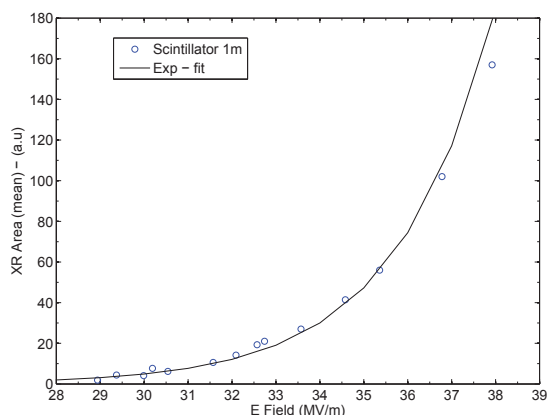


Figure 7: X-ray signal in function of the Electric Field inside the C-Band TW structure. The curve shows a FN type electron emission.

Using equation.1 and assuming that the integrated x-ray signal is proportional to the dark current, we estimated that the FN β is 68 (350 ns long pulse). This value is consistent for the two structures tested. The evolution of the FN β was also recorded after a major breakdown. β peaked to 150 and diminished to 65 after hours of conditioning.

CONCLUSIONS

In order to obtain the necessary official authorization to operate SwissFEL, the production of radiation along the machine must be quantified. We have produced a first set of simulation results using ASTRA, elegant and OPAL as well as carrying out measurements at two SwissFEL facilities. The outcomes are :

- * Like in many other facilities around the world, the dark current is essentially produced by the SW photogun.
- * Most of the dark current is lost at the first S-band structure.
- * The remaining of it is mostly lost before the first bunch compressor.

- * Only a small fraction of the dark current, mainly its core produced at the photocathode, goes to the end of SwissFEL.
- * The S-band do not produce any recordable dark current nor X-rays when running at nominal power.
- * At nominal power and pulse length, the C-band test structures produce no measurable dark current, although electrons are present in the structures (X-ray signal).
- * Radiation and dark current measurement results are in qualitative agreement with simulation results.

Finally, we are continuing the dark current investigation on subsequent C-band structures by installing an ICT closer to the exit/entrance of the structure. We will run OPAL using the C-band test structure geometry and use the X-ray data to benchmark the simulations. From the radiation measurements and simulations results, the SwissFEL layout infrastructure (air vents and shielding) is undergoing some modification.

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