DARK CURRENT TRANSPORT IN THE FLASH LINAC

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Abstract

The free electron laser facility FLASH at DESY Hamburg operates a low-emittance photoinjector and several acceleration modules with superconducting cavities to produce a high quality electron beam of up to 700 MeV. Since few months, the accelerator is routinely operated with its design RF pulse length of 800 µs instead of the prior length of 70–200 µs. As a result, the activation of components due to dark current emitted by the gun has reached critical proportions.

To improve the understanding of dark current transport through the linac, simulations have been conducted with the Astra tracking code. The generated phase space distributions are compared against a detailed 3-dimensional aperture model of the machine with the newly developed ApertureLib toolkit. The results are in agreement with the observed activities. Measures to reduce the activation of components like the planned redesign of the gun section are evaluated.

INTRODUCTION

FLASH—the Free Electron Laser in Hamburg—is a superconducting electron linac with a peak energy of 700 MeV [1, 2]. The particle bunches are generated in a photoinjector and compressed longitudinally in two magnetic chicanes *BCn* at energies of 127 MeV and 380 MeV. Behind the main linac, the beam is cleaned from off-axis and off-energy particles in two transverse and two energy collimators before it enters the undulator (Fig. 1).

The normal conducting RF gun constitutes a major source of dark current. Operated at the nominal gradient of 40–44 MV/m, the 1.5-cell L-band copper cavity produces a steady electron flux of 200–300 µA as measured with a Faraday cup near the exit of the structure. Tracking studies have shown that the predominant part of the dark current escaping the cavity is generated by field emission from the surface and the edges of the photocathode [3]; a substantial fraction is picked up by the first acceleration module *ACC1* and transported through the linac.

While the RF pulse length was typically limited to about 70 µs in the past, the gun is routinely operated with long pulses of 300–850 µs since October 2006. This has lead to a dramatic increase of the activation of components. Especially the first dipole magnets of the bunch compressors show equivalent dose rates of several mSv/h, which necessitates an increased effort in radiation protection (Fig. 2). It has therefore become necessary to study the transport of

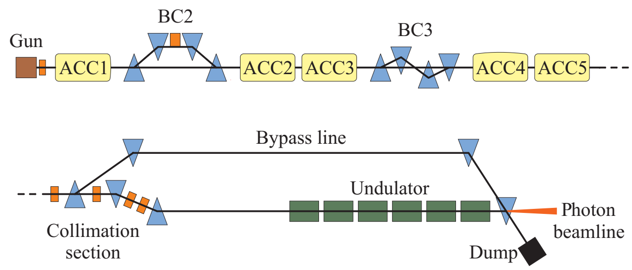

Figure 1: Schematic of the FLASH linac. The depicted elements include the five acceleration modules *ACCn*, and the two bunch compressors *BCn*. Collimators are shown in orange color.

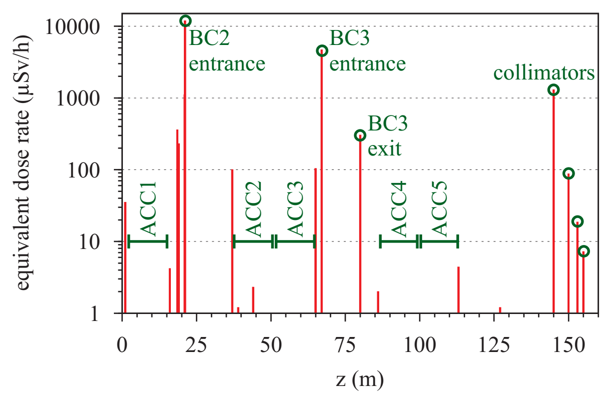

Figure 2: Equivalent dose rates along the linac. The plot shows an average of several measurements that have been taken few minutes after switching off the machine. No heightened radioactivity is observed in the undulator beamline. [4]

dark current in the linac in order to find an effective remedy.

START-TO-END SIMULATION

Simulation Setup

The parallelized tracking code Astra [5, 6] is used to simulate the emission and the transport of dark current from the RF gun to the beam dump. One million macroparticles are started at the cathode with a temporal Gaussian distribution of 16° width around the crest of the RF field, closely approximating the profile expected for field emission according to the Fowler-Nordheim formula [7]. The machine model is set up with the design optics and the phasing for a typical FEL run, which means that beam would be accelerated at an off-crest phase of -8° in module ACC1. Due

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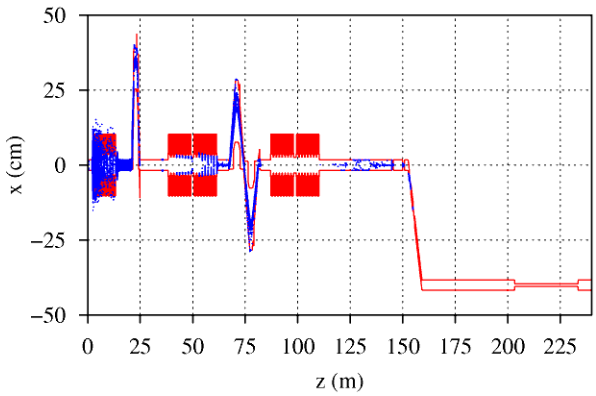

Figure 3: Horizontal aperture model of the machine. Lost dark current particles are marked by blue dots.

to the low charge densities involved, collective effects like space charge are neglected. During tracking, the phase space of the particle ensemble is saved to disk every 8 cm, producing approximately 100 GB of data.

The phase space files are then compared against a detailed 3-dimensional aperture model of the machine with the custom-made ApertureLib toolkit. ApertureLib is a portable C++ library that allows to specify aperture descriptions in XML files or by direct import of CAD drawings, and will be available to the public later this year. Figure 3 shows the horizontal aperture of the FLASH linac and the positions of dark current particles lost in the simulation.

Simulation Results

The simulation shows that approximately 70% of the emitted dark current is lost in the gun cavity and in the drift tube to the first acceleration module ACC1 (Fig. 4). In this region, the particles have energies below 5 MeV and therefore do not contribute to activation of the beamline.

The remaining 30% of the particles drift into the first cavity of ACC1. Because of their broad energy spectrum, they arrive on various—even decelerating—phases of the RF field, which leads to another 3% being rejected or lost in the module. If scaled to the measured current of ∼250 µA behind the gun, this means that an average current of 104 µA is transported through the RF structures of ACC1. Another consequence of the broad energy spectrum is that the dark current is captured in several successive RF buckets. As illustrated in Fig. 5, 92% of these 104 µA are confined in the first bucket, 6% in the second, and another 2% distributed over the following buckets. It is also apparent from the longitudinal phase space that the dark current occupies nearly the complete range of accelerating phases.

From the loss graph, several hot spots in the linac can be identified:

- The exit of cryogenic module ACC1, where the diameter of the beam pipe decreases from 5.2 cm to the usual 3.4 cm

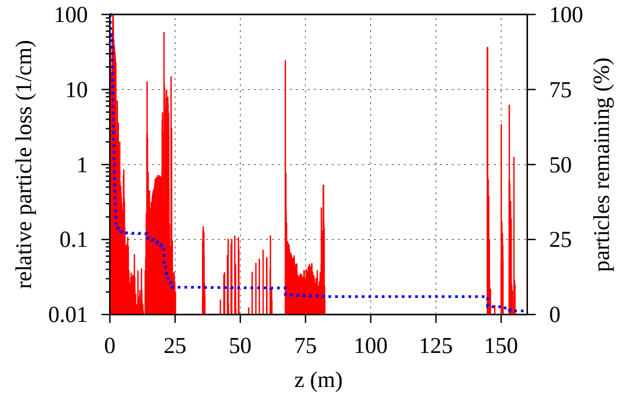

Figure 4: Simulated dark current losses along the FLASH linac. In the model, no further losses are observed downstream of the collimation section except in the dump region. *Red (logarithmic scale):* lost fraction of macroparticles, normalized to longitudinal step length. *Blue (linear scale):* remaining fraction of macroparticles.

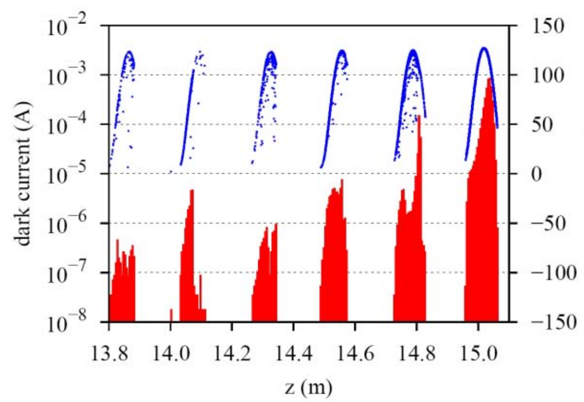

Figure 5: Longitudinal phase space after the first acceleration module. The dark current occupies several RF buckets. *Red (logarithmic scale):* longitudinal distribution of the dark current. *Blue (linear scale):* longitudinal particle momentum.

- The entrance of bunch compressor BC2 with its low vacuum chamber of only 8 mm height
- The entrance of bunch compressor BC3 with a similar vacuum chamber
- The transverse collimators with 4 mm diameter
- The energy collimators with 6 and 4 mm diameter

All of these locations coincide with the places of high measured radioactive dose rates except for the exit of ACC1, where the narrowing of the beam pipe inside the module housing is not accessible to measurement. As expected, the simulation shows that bunch compressor BC2 is most severely affected by dark current losses, with an average current of 54 µA dumped into the vacuum chamber over the duration of the RF pulse.

No losses are observed in the undulator vacuum chamber. This confirms the effectivity of the collimation system

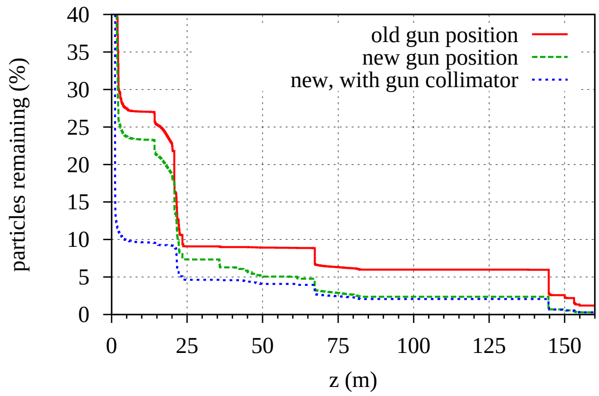

Figure 6: Comparison of dark current transmission with the old and new gun positions, and with the new gun collimator.

for the design optics. However, by incorrect matching and steering of the beam it is easily possible to dump the dark current partially or completely in the insertion device. Calculations with the Fluka particle transport code [8, 9] have shown that for the standard duty cycle of 5 Hz and 800 μs pulse length a complete loss of the remaining current of ∼5 μA in the undulator chamber would deposit a local dose rate of 30 Gy/minute in the permanent magnets. Therefore, an active machine protection system [10] constantly monitors the losses and suppresses the transport of dark current by disabling the RF input to ACC1 if necessary.

COUNTER MEASURES

Within the current configuration of the machine, only a movable beam scraper in BC2 (Fig. 1) can be used to mitigate the problem of dark current losses at full duty cycle. Inserted in the dispersive section of the chicane, it intercepts the low-energy part of the dark current. This eliminates losses at the second chicane BC3 almost completely and reduces the load on the fixed transverse and energy collimators. However, it obviously aggravates the problem of beamline activation in BC2 itself.

To minimize activation, the removal of dark current should take place at the lowest possible energy, i.e. between the gun and the first acceleration module. To facilitate this, a number of modifications to the respective part of the beamline are planned. As proposed in [11], the RF gun will be moved 30 cm away from the linac entry, and a new gun collimator with a circular aperture of 8 mm diameter will replace an old model that was not practically usable.

Figure 6 compares the simulated dark current transmission for the old and for the modified gun layouts. Already the added drift space leads to increased losses at the gun beam pipe and reduces the current transported through ACC1 by 14%; use of the new gun collimator even yields a reduction by 64%. The ratios for the dark current loss at BC2 are virtually the same.

While the beam is matched to the same betatron function for both injector layouts, the optics of the dark current changes significantly; this is the reason for an increased horizontal spot size in ACC3 and for higher losses in that module. The total amount of dark current transmitted through the collimation system to the undulator is reduced to 24% of its previous value.

CONCLUSION AND OUTLOOK

A set of tools for detailed simulation of beam and dark current losses has been developed. The results obtained with this toolkit for the FLASH linac are in good agreement with the measured activation of beamline and components. The simulation predicts that the redesign of the gun section will lead to a reduction of dark current losses in the BC2 chicane to about one third of their former amount. A rigid verification of the results by direct measurement of the dark current in various positions along the linac is planned.

Eventually, a similar simulation mechanism will be used to determine hot spots in the projected European XFEL and to take the necessary precautions in the design of its injector section.

ACKNOWLEDGEMENTS

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