Simulation of Dark Current Transport through the TESLA Test Facility Linac

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Abstract

The transported dark current in a high-duty cycle accelerator as the TESLA Test Facility linac (TTF) could significately contribute to radiation damages of components along the beamline. In the past high dark currents emitted from the laser driven rf gun have been observed during substantial time of linac operation. For a better understanding of the dark current transported through and lost in the entire linac, particularly in undulator magnets, numerical simulations are compared with experimental observations. In order to identify possible locations for collimators to remove the dark current, the beam and its halo have been investigated. The operation of an absorber recently installed in the dispersive section of TTF magnetic bunch compressor and its impact on the downstream collimator section is discussed.

1 INTRODUCTION

To perform a proof-of-principle experiment for a Free Electron Laser operating at VUV wavelengths an undulator has been installed in the TESLA Test Facility linac phase I. In order to protect the permanent magnets of the undulator from radiation a collimator section upstream of the undulator removes electrons with large betatron oscillations [1]. It is has been demonstrated by tracking calculations that the electrons passing the aligned collimator also pass the undulator without losses, provided their energy is within a bandwidth of $\triangle E/E = \pm 8.5\,\%$. The energy bandwidth is sufficient to guarantee a complete protection of the undulator during FEL operation. Experimentally, however, dose rates of several hundred Grey per week have been observed in the first section of the undulator during time periods with rf-duty cycles of 0.1% and a dark current level of about 10-30 μA. The observed dose rates are in disagreement with tracking calculations of the beam halo which energy spread is sufficiently small and around the design energy. To clarified the situation, the emission of dark current from the rf-gun cathode and its propagation through the TTF linac has been investigated in detail.

2 ORIGIN OF THE DARK CURRENT

The main components of the TTF linac are a radio frequency (rf) photocathode gun, delivering electron bunches of 7 ps rms length, 1 nC charge at an energy of 4 MeV, a 1.3 GHz superconducting (SC) booster cavity raising the energy to 16 MeV, two accelerator modules each containing 8 nine-cell 1.3 GHz SC cavities, increasing the energy to 230 MeV, a magnetic bunch compressor between the two modules, a two stage spoiler-absorber collimation system and three undulator magnets with total length of 13.5 m (see Fig. 1).

The dark current in the linac can be measured with a Faraday cup (FC) at the rf gun, at the entrance of the first SC module (ACC1) and in front of the first spoiler (SP1) by means of beam position monitor sum signals M1 and M2 [2].

The measured dark current in the linac is found to be dominantly emitted by the rf gun. Dark currents emitted from the SC modules are at least two orders of magnitude smaller than the one from the rf gun. They are below the resolution limit of the permanently installed dark current monitors (500 nA) [2]. Therefore, their contribution to the observed dose rates in the undulator can be neglected.

2.1 Dark current emission from the rf gun

The high electric field gradients at the surface of the rf gun cavity enhances the emission of dark current. Adapting the Fowler-Nordheim approach [3] to the rf case [4], it can be shown that the field emitted dark current is restricted to a narrow phase interval around the crest of the rf wave (see Fig. 2) [5]. The rms-width of the emission depends only weakly on the enhancement factor $\beta_{en} \approx$ 100-300 to be applied to obtain agreement between the Fowler-Nordheim equation and the observations.

A more complex subject than the emission time structure of the dark current from the surface is the location of the emitters in the 1.5 cell rf gun. Numerical simulations show that the escape probability of the electrons emitted in the vicinity of the cathode through the exit aperture are much higher compared to other locations like the middle or the exit iris [5]. The dark current simulations are in agreement with experimental observations at the photo-injector A0 at Fermilab [6].

Because the regular electron bunches are produced by photo-electric interaction of UV laser pulses impinging the cathode (Cs_2Te) injection phase and repetition rate (0.1, 1 and 2.25 MHz) can be adjusted. To achieve a low emittance electron beam the laser pulse is injected 50° before the peak acceleration field at the cathode is reached. For the simulation the emission time structure shown in Fig. 2 and an uniformly emitted dark current from a cathode with 10 mm diameter is assumed.

3 DARK CURRENT TRANSPORT

3.1 Impact of bunch compressor 2

The rf-phase of the acceleration structures in a linac are usually adjusted to achieve a maximum energy gain of the

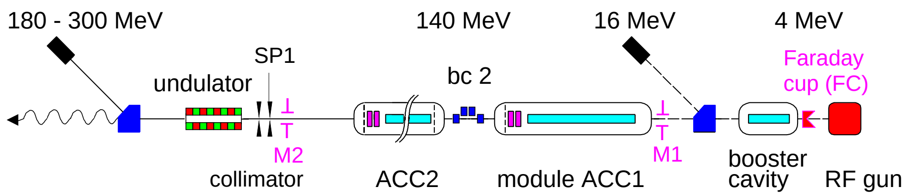

Figure 1: Schematic drawing of the TESLA Test Facility linac

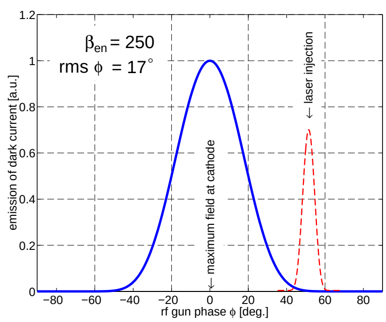

Figure 2: Emission of dark current versus rf gun phase.

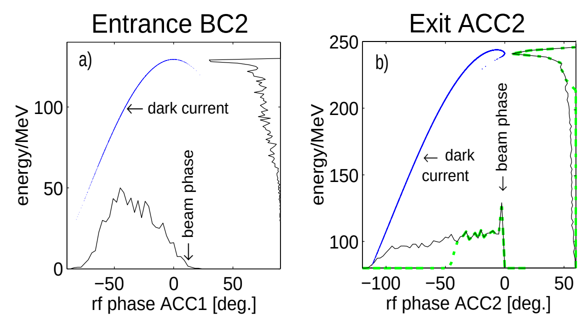

Figure 3: Distribution in the longitudinal phase space.

electron beam. Since the peak emission of the dark current is delayed with respect to the beam the dominant fraction of the dark current is accelerated off-crest of the rf wave. Thus, the dark current is either lost at the beamline aperture in a dispersive section or can be removed by collimators cutting the low energy electrons. Only a very small fraction of the dark current propagating close to the beam phase can survive.

The situation differs if magnetic bunch compressors are involved as the beam is now accelerated off-crest. In TTF 14° off-crest acceleration in ACC1 provides maximum bunch compression. The required positive rf-phase of ACC1 causes a significant high dark current transmission probability through the chicane. A part of the dark current even gains more energy then the beam (see Fig.3(a)). Due to longitudinal dispersion the time structure of the survived dark current has lost its separation from the electron bunch after passing the chicane. In addition, as shown in Fig.3(b), it is stretched in time toward negative phases. The second acceleration module, ACC2, is operated on-crest for the regular beam. The phase structure of dark current now causes an enormous spread in energy which varies between 80 MeV and 240 MeV or between −66% and +1% with respect to the beam energy of 237 MeV. For comparison, the energy acceptance of the bunch compressor due to the vacuum chamber is in the range between −14% and 20%. Hence, the spread of the low energy tail of the dark current is increased by more than a factor of 4 before and after acceleration in ACC2. Note that, the energy range covered with the dark current by far exceeds the energy bandwidth of the collimator section (±8.5%). Therefore, electrons of the dark current can be lost in the undulator.

3.2 Scraper in BC2

In order to reduce the energy acceptance of the bunch compressor 2 (BC2) a low-energy scraper has been implemented in the straight section of the chicane. Due to radiation protection reasons the scraper should not remove more than 1% of the regular beam. By tracking simulations of the electron beam from the rf gun to the center of BC2 the tightest energy collimation has been determined to be at −4% with respect to beam energy. With the proper positioning of the scraper the low energy tails are successfully cut, and at the exit of the ACC2, the lower energy limit of the dark current moves from about 80 MeV to 215 MeV, (green dashed curves in Fig.3(b)). The resulting energy distribution is sufficiently narrow and in the simulations the collimated dark current passes completely the undulator.

3.3 Transmission probability

In order to calculate the transmission probability of the dark current through the TTF linac the simulation has taken into account: particle propagation in forward and backward direction, non-relativistic energies, time dependent rf-focusing in the acceleration structures, chromaticity of the quadrupoles, high order magnetic fields in the undulator and the apertures along the machine including rectangular, cylindrical, and elliptical tapers. Figure 4 shows the results of two tracking simulations for magnet settings used in April 2000, differing only by a 15% setpoint of a quadrupole triplet downstream of BC2. From the tracked particles starting at the cathode about 75% escape the exit iris of the gun and reach the Faraday cup, 24% are transported through the injector, 10% pass the magnetic chicane, and less than 4% are transmitted through the collimator and reach the entrance of the undulator. No particles are lost

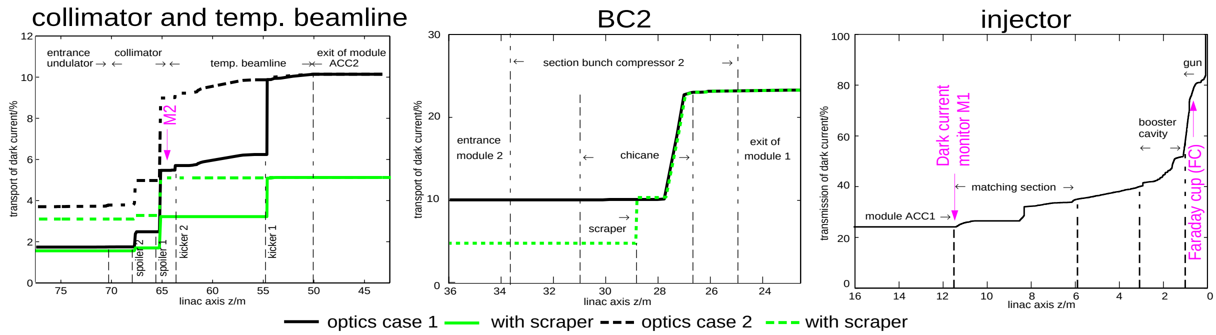

Figure 4: Transmission probability of dark current through the TTF linac

inside the SC modules important for cryogenic loss measurements at the 2 K level.

Downstream ACC1, the electron energy is sufficient to activate the beamline devices. During time periods with high dark currents significantly higher activation levels (typically few hundred μSv/h) have been measured at the entrance of the chicane, at the fast feedback kicker 1 and the first spoiler as expected from the simulations.

The dark current monitor M1 has been installed in autumn 2000. During the FEL-run August and September 2000 (optics similar to April 2000) the ratio of the measured dark currents FC:M1 varies between 3 and 6 and the one for M1:M2 varies from 2 to 3. The simulations predict for FC:M1 a ratio of 3 and for M1:M2 a ratio of 2.5 and 4.4 for the optics case 1 and case 2, respectively.

3.4 Induced dose rates

Without use of the scraper in BC2, the dark current passing the collimator is partly dumped in the undulator. For the optics case 1 about 0.007% of the tracked particles hit the vacuum chamber of the first undulator module and for case 2 an order of magnitude more particles are lost (0.07%). Thus, the distribution of the dark current in the transverse phase space has a significant influence on the amount of energy deposited in the undulator magnets. Small changes in the linac optics can cause large variation in the dose rate while at the same time the monitored dark currents changes only slightly. To estimate the deposited dose in the permanent magnets and in dosimeters distributed along the undulator, the electromagnetic showers induced by the lost particles are simulated by Monte-Carlo calculations. Figure 5 shows the incident energy distribution due to the dark current losses normalized to 1 kJ (blue curve), the equivalent absorbed dose in the undulator magnets (black triangles) and for comparison the absorbed dose in control dosimeters included in the simulation (magenta). In optics case 1 (case 2) already 100 μA dark current emitted from the rf gun operated at 0.1% duty cycle can add to 400 Gy (4 kGy) in the magnets within one week while in the dosimeters dose levels of 240 Gy (2.4 kGy) would be measured. The simulated longitudinal dose distribution and its magnitude provides important information to identify the origin and reason for observed dose rates in the undulator.

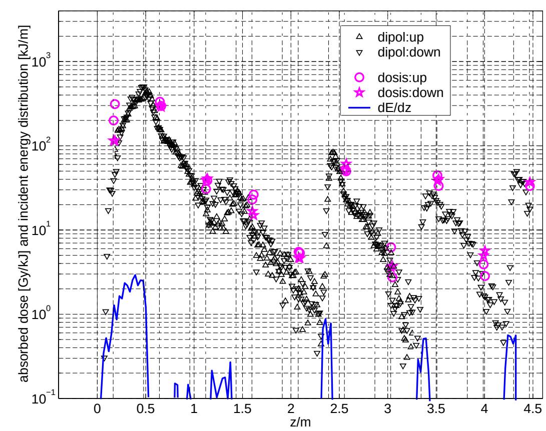

Figure 5: Absorbed dose in the first undulator module.

4 SUMMARY

The origin, the emission and the transport of the dark current in the TTF linac has been discussed. The simulated data are in agreement to the measured values. It is found that dark currents can significantly contribute to absorbed doses in the undulator. At higher dark current levels, the linac can only be operated with the proper use of a scraper installed in a magnetic chicane.

5 REFERENCES

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