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EXPERIMENTAL AND SIMULATED DARK CURRENT AND BEAM LOSS STUDIES FOR A SRF PHOTO-INJECTOR OF AN ERL INJECTOR*

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Abstract

The Superconducting RF (SRF)photo-injector with the prototype 1.4 $\lambda/2$-cell Niobium cavity of the bERLinPro Energy Recovery Linac (ERL), recently renamed to SEALab, was tested and characterized in a dedicated beam test facility called Gunlab to analyze its performance for the ERL. After dismantling and refurbishing of the cavity, a small surface defect was found close to the cathode opening and by simulated reconstruction of the set-up it was demonstrated to be the main source of the dark current measured at Gunlab. Later, a method was found to remove that defect, but still the question remains, what amount of dark current is acceptable for an ERL injector, especially for the SRF systems? In this contribution, we show a fully 3D simulation based emulation of the dark current measurements in Gunlab and extrapolate the impact on the complete injector at bERLinPro (SEALab). Here, it can be shown, that besides a small meshed beam loss diagnostics, methods need to be found to determine the amount of field emitted current dumped into the SRF systems.

INTRODUCTION

Energy Recovery Linacs have the potential to be one of the most efficient electron accelerator with respect to the ratio of beam power towards invested wall plug power level, as they recuperate the beam energy of the recirculator in the main driver Linac. This is of course only possible, when a highest level of beam recovery with lowest beam loss is achieved and is of major importance to safely and in a stable manner run a high intensity ERL at average beam currents in the several tens to 100 mA range. However, any unwanted beam can significantly add to beam loss, as especially so called dark current emitted in e.g. high field SRF cavities, here even more in the SRF photo-injector cavity can fill a similar longitudinal phase space as the beam from the cathode. This is the case, when the emitter is in vicinity of the cathode itself in the high electric field area of the half-cell's backwall center. Studies at KEK's CERL [1] already demonstrated, that even bunch tails alone can contribute to transverse beam halo formation and be the major driver for beam losses in the recirculator. But what may happen in the injector alone, when the field emitter was demonstrated to be close to the cathode opening in the cavity? This will be studied in the following, as such a field emitter was found in the prototype SRF photo-injector cavity, which was operated in a diagnostic beam line teststand after first module assembly [2, 3].

The bERLinPro SRF Photo-Injector

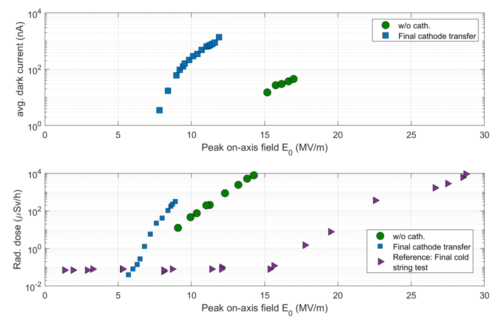

Figure 1: Radiation dose by field emission and measured dark current in a dedicated diagnostic beamline of the bERLinPro SRF photo-injector with the prototype cavity.

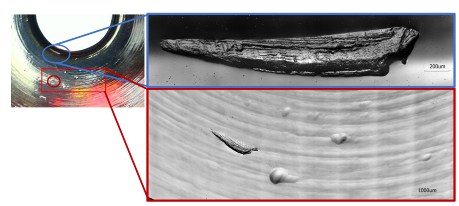

Figure 2: Confocal laser microscopy pictures of the two main defects found close to the SRF cavity cathode opening. The more smooth pit like surface structures were levelled by BCP cavity treatment. The defects showed no sign of any chemical polishing.

The prototype cavity of the SRF injector [**neumann:linac12-thpb066**] was produced in 2013 at JLab [5] and showed from the very first vertical tests field emission and multi-pacting behavior above an onset field of 15 MV/m on-axis peak electric field of the accelerating TM_{010}-π mode. After module assembly was completed, the photo-injector produced first beam with a full metal Cu cathode and here a further deterioration with respect to dark current was observed, as later a defect with the cathode plug holding mechanism was found. Figure 1 gives an overview of the radiation dose and dark current measured during this operation compared to the situation before cathode transfer. Here, always the measurement

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without cathode will be used as a reference for this study. When the cryo-module was disassembled to inspect the inner cavity, also surface samples were taken close to the cathode area. Here, two defects of about close to 100 μm depth and a surface dimension of 200x1000 μm were found, as displayed in Fig. 2. The full analysis and later repair procedure of those and similar defects in a second SRF photo-injector cavity can be found in Ref. [6].

Simulation Method

Using 3DS CST Microwave Studio Eigenmode (EM) and Particle in Cell (PIC) solver [7] a model of the first module test in Gunlab [2] was set up, including the cavity, the SC solenoid, the steerer magnets and the cathode DC bias voltage with the beam line geometry downstream the SRF photo-injector. The two identified emitters were placed and modelled as determined with the replica analysis, whereas all fields were calculated by the EM and static solver to be imported into the PIC solver. The mesh was especially emphasized to resolve the very small field emitter locations. As emission model, the Fowler-Nordheim (FN) field emission was chosen for obvious reasons. Any setting affecting the unwanted beam by DC bias voltage, cavity field level, SC solenoid field level or steerer setting will lead to variations of the measured amount of dark current at a further downstream viewscreen section or Faraday cup. To reconstruct the level of field emission measured with this cavity with the Gunlab beamline [8], see Fig. 1, the emitter intensity by varying the FN parameters were adjusted to the values measured at the first viewscreen, Faraday cup station. The result can be seen in Figure 4.

It is also already clear, that depending on the solenoid settings large fractions of the dark current are deposited upstream the viewscreen in the different beamline sections. This was e.g. observed during the experiment, that the SRF cavity's beam tube temperature at constant field varied with the solenoid settings, as dark current was directed partially into the Nb walls of the cavity. Besides the full phase space information of the beam or the field emitted electrons, the PIC solver also offers to place virtual 2D screens into the beamline to emulate the usage of viewscreens for beam diagnostics and surrounding material of the beam vacuum can be analyzed with particle monitors to extract information as collision energy, current and deposited power level. Figure 3 shows an example trajectory of a short 3 fs long field emission of emitter 1 and the simulation domain for the PIC solver. Here, the model was extended to the full bERLinPro/SEALab [9] injector.

RESULTS

The found scaling resulted into an average dark current of 100 μA at the cavity exit flange for the bERLinPro design field level of 30 MV/m of the photo-injector cavity, of which 50-70% are lost in the cryo-module, depending on the solenoid field level. Figures 5 and 6 display the energy spectra of the field emitted electrons colliding with the beam vacuum walls. Table 1 summarizes the power deposited in each component by the dark current. About 8 W are dissipated into the 1.8 K helium bath and also low energy electrons hit the surface in the regime of multipacting with energies below 1 keV, where Niobium has an secondary emission yield larger than one. The cathode plug receives 5 W, which is about 20% [10] of the power it can accept, before the CsK_2Sb layer will reach the temperature range, where it will start to evaporate into the Nb resonator. About

Table 1: Power loss distribution in Watt by dark current at E_0=30 MV/m. The blue marked losses will be dissipated into the 1.8 K Helium bath of the cavity.

Component	Solenoid off	Solenoid 75 mT
Cavity half-cell	5.4	5.9
Cavity full-cell	1.8	1.9
Cathode plug	4.6	5.0
HOM beam tube	43	0.75
Exit bellow	6.3	22.6
Beam taper	5.5	13.4
40mm ⌀beam tube	33.0	50.4

100 W of beam power are deposited by the dark current alone in the section before the Booster module, where 11% of the emitted dark current still arrive, still a significant level of 10 μA. In the given configuration, where the first Booster cavity is operated in zero-crossing, only about 0.2 W are dissipated in that cavity, followed by 2 and 0.5 W in average for the other two cavities. The remaining dark current, entering the merger section after the injector to the recirculartor is still at a level of about 1 μA filling a longitudinal phase space close to the bunched beam from the cathode. Thus, this will co-propagate with the beam and given the offset, the transverse momenta, eventually might form into a transverse beam halo, adding to the losses in the recirculator. To study this, is out of the scope of the simulation presented here. However, realistic dark current distributions found by the methods given can be fed into tracking codes to study beam losses, Halo formation and mitigation by scraper or beam optics manipulation to prevent this perturbation to the ERL process.

CONCLUSION

It was demonstrated, that the emitters found in the prototype photo-injector SRF cavity not only caused significant additional load to the cryogenics system, but would also add to cathode deterioration and be a major source for beam halo formation and by that beam losses in the recirculator of the ERL. Even though the cavity design aimed at separating the optimum emission phase from the maximum FN field emission phase [**neumann:linac12-thpb066**], still a quite large amount of unwanted beam would propagate in a similar phase space with the bunched wanted beam. As the second SRF cavity got damaged during final HPR at the vendor, a repair program had to be developed [6], which also allowed

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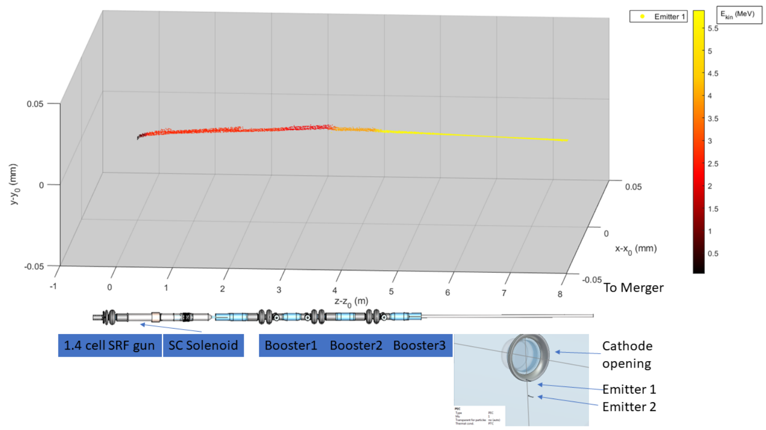

Figure 3: Trajectory of emitter 1 closer to the cathode iris, energy in color code is in MeV. Parameters were $E_{0,\mathrm{gun}}$=30 MV/m at ϕ_{emitt}=56 deg, $B_{\mathrm{SC,sol}}$=42 mT, $E_{0,\mathrm{B1}}$=9 MV/m, $E_{0,\mathrm{B2}}$=30 MV/m, $E_{0,\mathrm{B3}}$=30 MV/m, where the first Booster cavity was in zero-crossing and the other on-crest w.r.t. the bunched beam.

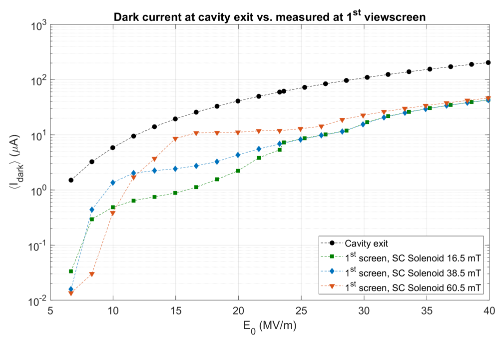

Figure 4: Simulated dark current at the cavity exit flange (black) versus on-axis field E_0 at the remaining amount measured downstream at the first viewscreen at various solenoid field settings.

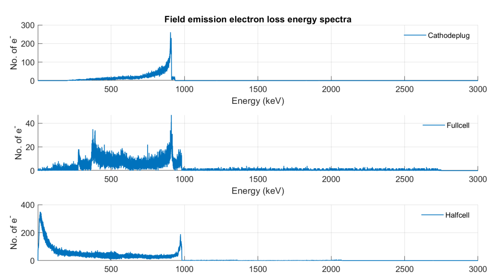

Figure 5: Collision energy spectra of the field emitted electrons for E_0=30 MV/m within the cavity for the cathode plug, the half- and full-cell.

to find and finally remove the two emitters causing the dark current of the first cavity. At least it can be derrived from this study, that any field emitter close to the cathode area is not acceptable for an ERL or even FEL photo-injector and alread during production period, a quality check in that direction has to be done by e.g. optical inspection and eventually replica analysis as done at HZB.

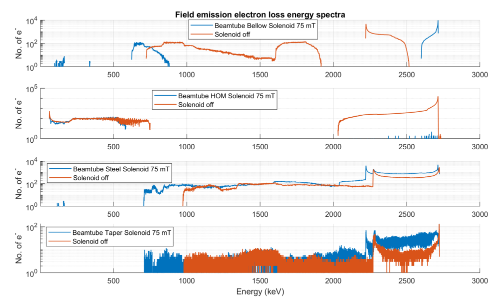

Figure 6: Collision energy spectra of the field emitted electrons for E_0=30 MV/m for the downstream beamline components.

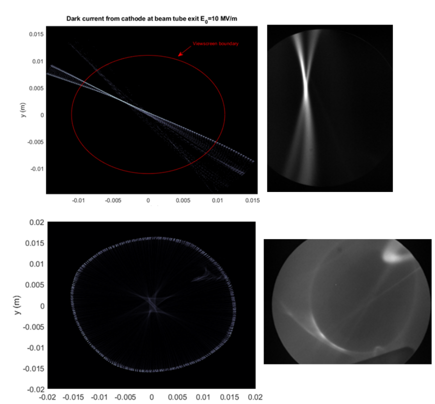

Figure 7: Left column displays the simulated viewscreen pictures of dark current emitted by the two defects close to the cathode opening. The same cross-like structure was also measured at E_0=10 MV/m (right column top), whereas the ring like shape appeared during a solenoid field scan using the first viewscreen.

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