FIELD EMISSION DARK CURRENT SIMULATION FOR eRHIC ERL CAVITIES

Chen Xu, Ilan Ben-Zvi[1], Yue Hao, Vadim Ptitsyn[1], Kevin Smith, Binping Xiao, Wencan Xu
Brookhaven National Laboratory, Upton, New York 11973-5000, USA
[1] also at Stony Brook University, Stony Brook, New York 11794, USA

Abstract

The eRHIC project will be a electron and proton collider proposed in BNL. These high repetition rates will require Super-Conducting Radio-Frequency cavities with fundamental frequency of 650MHZ for high current applications. Each with a string of two of those cavities. The strong electromagnetic fields in the SRF cavities will extract electrons from the cavity walls and will accelerate those. Most dark current will be deposited locally, although some electrons may reach several neighbour cyromodules, thereby gaining substantial energy before they hit a collimator or other aperture. Simulation of these effects is therefore crucial for the design of the machine. Track3P code was used to simulate field-emission electrons from different SRF cavities setup to optimize the field emission dark current characterizes..

INTRODUCTION

eRHIC project requires to build an electron linac ring on top of the existing RHIC ring. One of the design proposed by BNL is that an ERL based accelerator to increase electrons energy to collision energy ~18GeV and extract their energy after collision with proton. The accelerator would be equipped with Superconducting Radiofrequency resonators to achieve the energy boost and recover the RF energy. Currently, the proposed frequency is 647.5Mhz. The low frequency SRF cavities usually have larger iris and apertures than the high frequency cavities. These large apertures help damp the malicious RF energy out of the RF structure but also facilitates more field emission electrons to escape the RF structures. On the other hand, the SRF surfaces areas are inversely proportional to the fundamental frequency. A larger surface area supplies more possible emission sites due to the cleaning capability. Therefore, understanding the field emission electron characterizations will be a critical to estimate the dark current, to evaluating the radiation dosage and to prevent further propagation.

The estimation on radiation would give several malicious effects. 1, cryogenic loss; 2. RF waste on dark beam loading; 3. Radiation damage on cables and electronics; 4. Beamline vacuum deterioration and Beamline activation.

A CAVITY EMISSION

Currently, we plan to use beam pipe absorbers as our eRHIC HOM damping scheme. Room temperature absorbers will be placed on side of each. The distance between SRF cavity and RT beam pipe damping would be longer because of the temperature gradient and evanescent fundamental mode.

The cavity geometry net length is 1.96m which is 4.228 times of the wavelength of 647MHz. The cavity schematic is shown in Figure 1. [1]

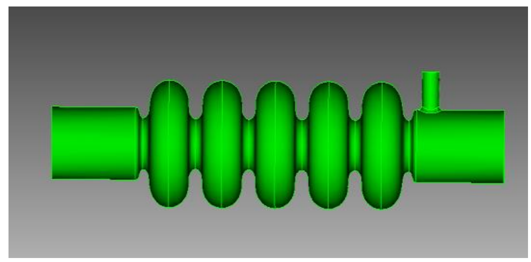

Figure 1: Cavity scheme for current eRHIC project.

Once the surface electric field is higher than the work function, surface electrons will escape the surface energy barrier and the emission current density is well-defined by Fowler–Nordheim equation in DC case. Empirically, field emission can occur when accelerator gradient is quite low. [2] Not all the SRF surfaces have high E field to emission. At the 18MeV/m accelerating gradient, the emission sites are plotted in Figure 2. The field emission dark current estimation is simulated in Omega 3P suite.

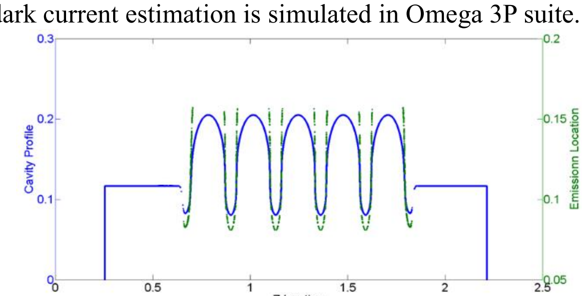

Figure 2: The initial field emission site on SRF cavity

The local surface electric field can be enhanced by geometrically protrusions. The typical enhancement factor is 120 in the tracking simulation.

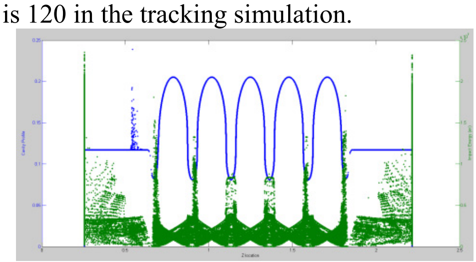

Figure 3: The impact site of field emission on SRF cavity.

Work supported by the US Department of Energy under contract number DE-SC0012704

From Figure 3, we found that most of emitted electrons hit on the iris area and those electrons have small impact energy. The number of escaped electrons out of the cavity is small, but they have large energy. In the simulation, the simulation gradient is 18MV/m. with the effective accelerating length of 1.15m, the total energy gain per a cavity is 20.7MV which is shown in the end pipes. The cavity design is symmetrical from upstream (left) to downstream (right), thus the impact locations are also symmetrical. One can plot the captured electrons in the beam pipe as a function of time in Figure 4. In this simulation, we emit 4 RF cycles and track them within 10 RF cycles.

In Figure 4, the cavity starts with empty. Emitted electrons take several RF cycles to reach the end pipe and escape the cavity. When the maximum energy is reached, we got a steady state. The fine structure in this figure show that the electrons' original location. The energy of electrons come in pair, because these electrons come from the two sides of an iris.

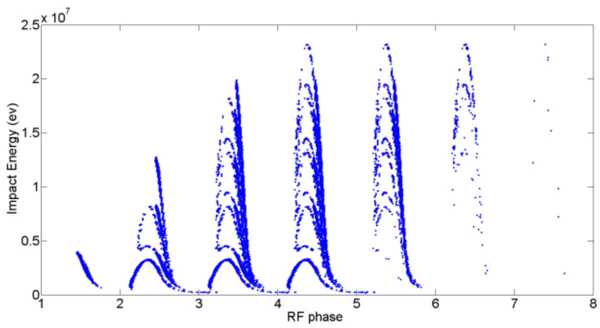

Figure 4: The captured electron time structure at downstream beam pipe.

We record the captured electrons number as a function of time and plot it in Figure 5. At the steady state, we can obtain the total electron number in this cycle and the max field emission current can be ampere level. However, this simulation presume that all surfaces emit electrons with fairly large enhancement factor. Usually, the emission current is dominated by one or two leading emission sites. Therefore, the field emission does not reflect the real case.

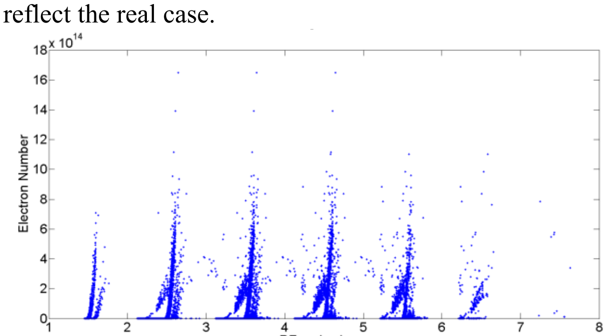

Figure 5: Numbers of the captured electrons as function of time at downstream beam pipe.

We go along the 2D cavity surfaces and plot the captured electrons (downstream) contribution from different location on SRF cavity in Figure 6. Main contributions come the iris of the center cells.

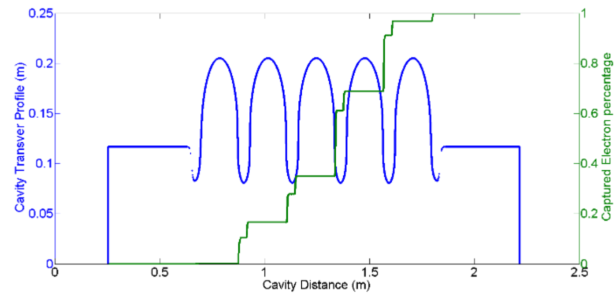

Figure 6: Different SRF cavity surfaces contributions to the captured electron at downstream end.

CYROMODULE DESIGNS

Currently, a pair of cavities would be installed in the cyromodule in this design. The cavity separation length should be determined by the fundamental mode decay length and dark current characterization. Studies show that different cavity separation length can change the distribution of the escaped electron percentage. In our eRHIC current setup, a set of combiners and splitter magnets are added before and after the Linac. Each cavity has its own RF supplied, thus the input RF phase can be controlled independently. In this case, one cannot change the downstream capture electron numbers. Once the emitted electrons are captured by RF field and escape the first cavity, their speed are very close to speed of light. The successive cavities could not reduce their energy. On the other hand, one can avoid electron back-bombardment by varying the cavity separation length. [3] In addition, we will give the captured electron emittance for further tracking the halo development in the ERL ring. The cyromodule design is shown in figure 6. The fundamental power couplers are installed in the opposite direction to facilitate RF power delivery.

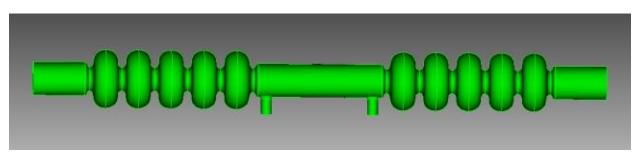

Figure 6: Potential cyromodule design.

In this study, we will vary the cavity separation length by a quarter of the fundamental wavelength (λ). The measured distant is from the first iris between both cavities. It states at 4. 5λ since the cavity length is already 4.228 λ and extra space is needed for the absorbers. The RF phase delay of both cavities will facilitate the forward electrons see the max energy gain. The distance is measured in Figure 7.

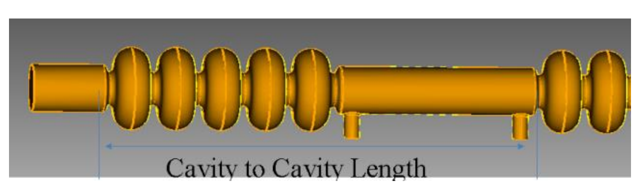

Figure 7: Scheme of changing the cavity separation length.

We emit multiple electrons within RF cycles and track them until we reach a steady state. Within that steady state, we calculate the capture electron percentages at upstream and downstream pipes. We plot the impact energy as a function of impact location in Figure 8, the cavity separation distance is from 4.5 λ to 5.25 λ.

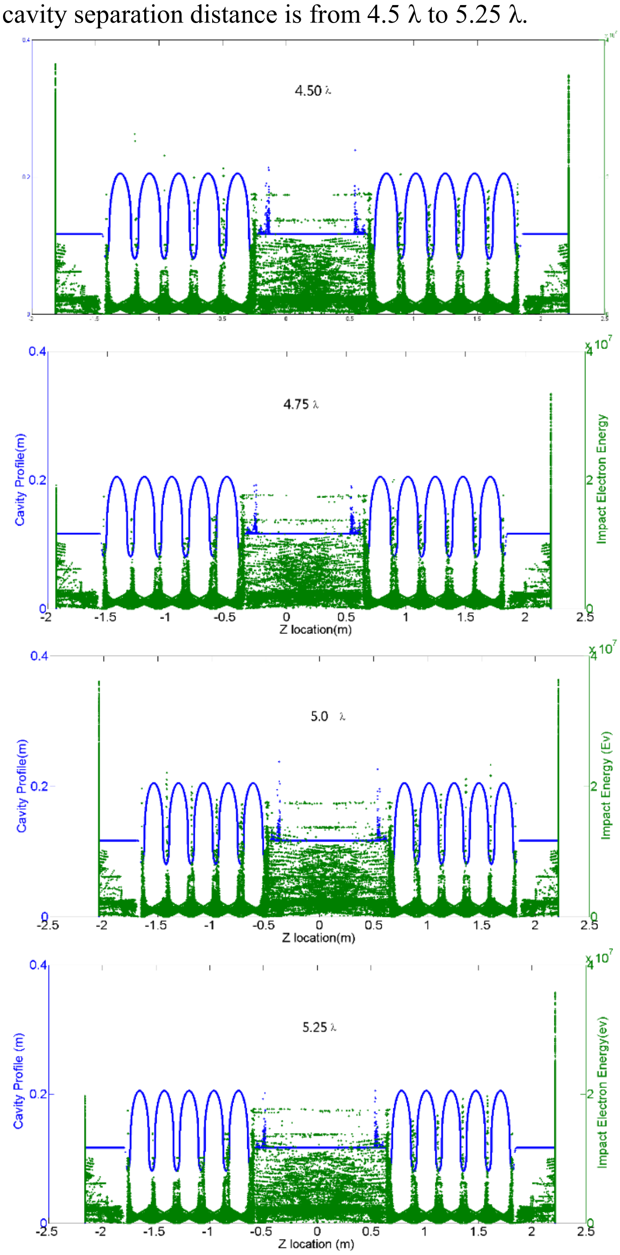

Figure 8. The field emission setup with different cavity separation length. A:4.5 λ B:4.75 λ C:5.0 λ D:5.25 λ.

One can found the max energy of captured electrons at downstream beam pipe is always the max accelerating field which is twice of the single cavity accelerating field. However, the captured electrons at the upstream pipe can be as low half of the downstream. Those capture electrons come from the upstream cavity. It suggests that the emission from the right-side cavity cannot pass the left-side cavity to escape the upstream beam pipe because the RF phase of the left cavity is not accelerating them but deaccelerating them. Those electrons will be defocus and finally ends up at SRF cavities wall and contribute to cryogenic loss. We also record the number of the captured electrons on different locations and sum them up in the table 1. By varying the distance, the distribution of the captured electrons also changes. In this study, we found the optimal cavity length is 4.75 λ.

Table 1: Captured electrons at different locations.

Distance (λ)	upstream	downstrea m	SRF wall
4.5	1.8%	2.0%	96.2%
4.75	1.6%	1.7%	96.6%
5	3.5%	1.9%	94.6%
5.25	1.4%	1.6%	97.0%

DISCUSSION

The captured electron distance vs x momentum distribution is plotted in Figure 9. The electrons are collimated by the cavity wall and beam pipe. The butterfly shape suggests that the field emission current is over focus. This emittance will be further tracked by the ring lattice to study if a beam halo can be developed.

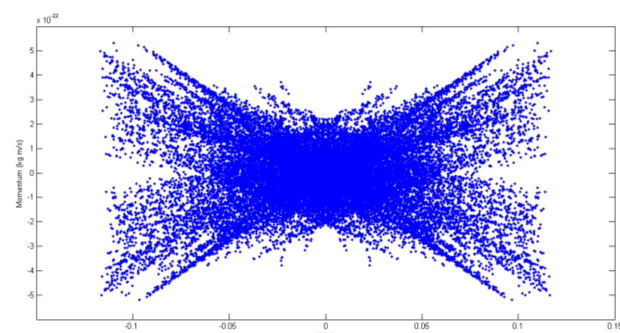

Figure 9: The captured field emission electrons in the phase diagram at downstream beam pipe.

CONCLUSION

In this study, we found the 650Mhz cavities could have severe field emission problems than the L band cavity. This study gives a max field emission current, and dark current emittance. We optimize the cavity separation length to minimize upstream. In this study, we also offer captured field emission electrons characteristics for beam halo tracking and machine protection.

ACKNOWLEDGMENT

The authors would like to thank Mike Blaskiewicz, and Alex Zaltsman in BNL, L, Ge and Z, Li at SLAC, H. Wang, at JLAB, for useful discussions.

REFERENCES

[1] Low Risk eRHIC design baseline report 2016.
[2] C. Reece. arXiv:1606.03317v3
[3] Private communication with Z.Li.