SIMULATIONS OF DARK CURRENT FROM THE bERLinPro BOOSTER MODULE*

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Abstract

Dark current emitted from the surface of high-field RF cavities can contribute to radiation levels and cryo budget and can cause damage to sensitive accelerator components such as the photocathode. The superconducting niobium cavities in the booster module of bERLinPro will have surface fields strong enough to produce significant dark current from field emission, so simulations were made using Astra to track the propagation of emitted electrons from the surfaces of the cavities to examine the effects of dark current in the bERLinPro injector. Results of these simulations, including optimization of the layout to reduce propagation of electrons to the cathode and an estimation of power from dark current deposited throughout the injector, are presented.

INTRODUCTION

bERLinPro is a 100 mA, 50 MeV single-pass ERL currently in development at Helmholtz-Zentrum Berlin [1]. Figure 1 shows the bERLinPro booster module, which is composed of three 2-cell,1.3 GHz niobium superconducting radio frequency (SRF) cavities [2]. Two of these cavities will have surface fields of nearly 17 MV/m, making dark current (DC) from field emission a potential concern.

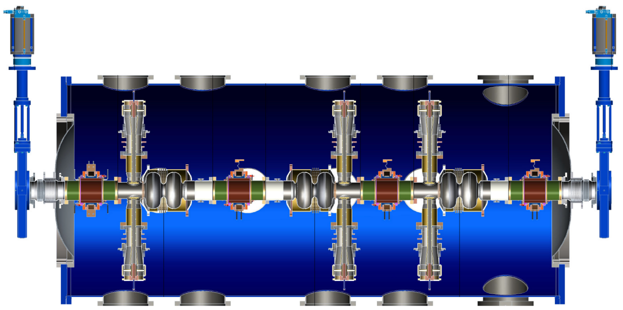

Figure 1: Layout of the booster module, composed of three 2-cell niobium SRF cavities.

The tracking code Astra [3] was used to optimize the booster layout to minimize upstream propagation of dark current from the second and third booster cavities to the cathode. Distributions of dark current electrons were generated on the cavity surfaces based on the Fowler-Nordheim equation, and upper limits for the magnitude of dark current exiting each cavity were estimated based on limits from the cryo system for power that can be deposited into the cavities.

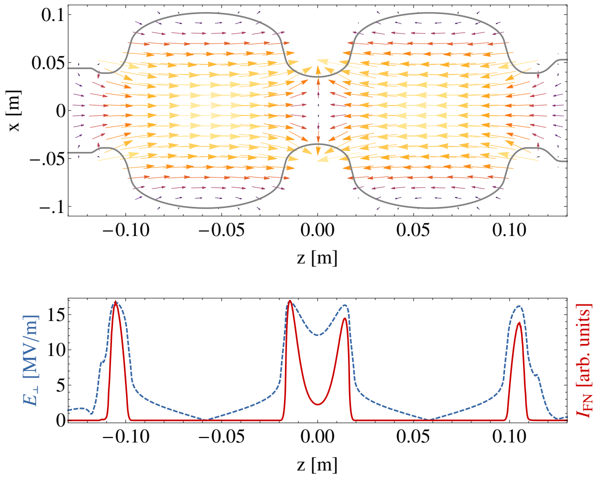

Figure 2: Top: Electrical field in the x-z plane of a booster cavity. Bottom: Magnitude of electric field normal to the cavity surface (dashed blue line), and corresponding Fowler-Nordheim current density (red line).

Dark current from the first booster cavity will be negligible because the cavity will have much lower surface fields. Secondary electron emission was not considered in these studies.

DARK CURRENT DISTRIBUTION

The strong electric fields on the cavity surface cause electrons to be emitted with a current density given by the Fowler-Nordheim equation,

$$I_{FN}(E_\perp) = \alpha_0 \left(\beta E_\perp\right)^2 \exp\left(-\frac{\alpha_1}{\beta E_\perp}\right) \qquad (1)$$

where α_0 and α_1 are constants determined by the cavity material ($\alpha_0 = 3.85 \times 10^7\ A/V^2$ and $\alpha_1 = 5.46 \times 10^{10}\ V/m$ for niobium) and β is a field enhancement factor which characterizes the geometry of electron emission sites on the cavity surface [4]. To find the total current from the cavity surface due to field emission, this current density would be multiplied by the effective area of the emitters, A_{FN}. In general A_{FN} and β would be determined experimentally for a particular cavity, but since measurements are not yet possible, for the purpose of these studies we chose a rather high value of $\beta = 1000$.

The electric field in the booster cavities and the corresponding Fowler-Nordheim current density are shown in Fig. 2. This current density is used to generate an initial distribution of 100,000 dark current electrons randomly distributed in longitudinal position z and emission time t. We will estimate an upper limit for the total magnitude of dark

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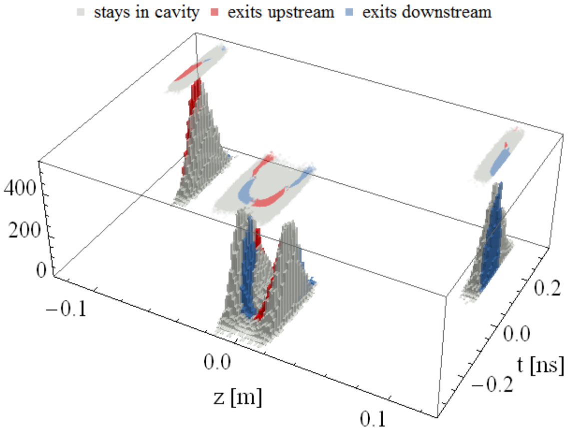

Figure 3: Initial distribution of 100,000 DC electrons distributed in longitudinal position z and emission time t according to the Fowler-Nordheim current density (Eq. 1). The particles in gray remain in the cavity, in red exit upstream, and in blue exit downstream.

current that can be emitted from the cavity based on limits for how much power can be lost into the cavities.

The initial dark current distribution is shown in Fig. 3, with particles that ultimately escape the cavity heading upstream (~13.5%) shown in red and those that escape heading downstream (~13.5%) shown in blue. Note, however, that a continuous distribution of dark current along the cavity surface is an unrealistic approximation; in the real cavity the dark current will originate from a relatively small number of emitters due to imperfections on the cavity surface, and each emitter will have its own effective area A_{FN} and field enhancement factor β.

SIMULATION RESULTS

Estimation of Upper Limit for Dark Current

The total number of electrons in the initial dark current distribution was chosen arbitrarily, as the Fowler-Nordheim current density cannot be calculated in absolute terms without some knowledge of the surface imperfections that will exist on the real cavities. A conservative upper limit for dark current emitted from the cavity surface can be estimated based on the limit for how much power the cryo system can handle being deposited into the cavities, which is approximately 4 W per cavity.

For the initial distribution of 100,000 electrons with the arbitrarily chosed value of $\beta = 1000$, about 73,000 electrons remain trapped within the cavity. Fig. 4 shows the kinetic energy distributions of electrons that remain trapped within the cavity or escape the cavity. The average kinetic energy with which the trapped electrons strike the cavity surface is about 0.25 MeV, which totals about 3.8 watts of power dumped into the cavity from dark current electrons originating in that cavity. There is also a small contribution from dark current electrons originating in the neighboring cavity. About 2000 electrons impact the neighboring cavity each RF cycle, with an average kinetic energy of 0.5 MeV, making an additional 0.2 W of power dumped into each cavity. Thus the initial dark current distribution of 100,000 electrons per cavity per RF period is just within the upper limit for how many can be emitted without resulting in excessive heating in the cavities. This corresponds to a current of less than 3 μA exiting each cavity in each direction.

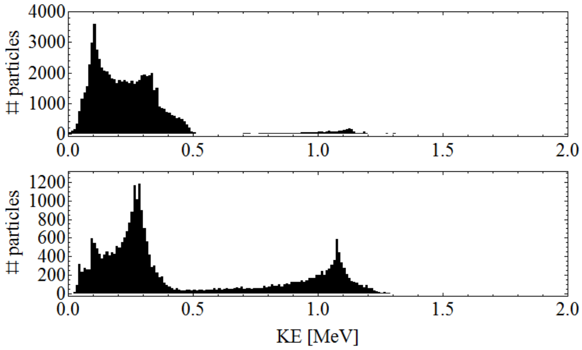

Figure 4: Energy distribution of DC electrons that remain trapped within the cavity (top) and those that escape the cavity (bottom).

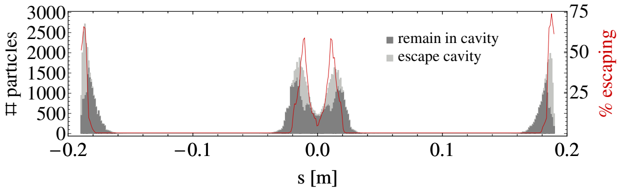

Figure 5: Number of dark current electrons emitted from a given increment of cavity surface s which remain in or escape the cavity

This is only a rough approximation for the upper limit of dark current emitted from the cavity; in the real cavities, the fraction of electrons from a given emitter which escape the cavity will vary depending on the longitudinal location of the emitters. Figure 5 shows how many of the electrons emitted from a given segment of the cavity surface escape or remain trapped in the cavity. If the emitters are located near the outer irises or about a centimeter away from the inner iris, a greater portion of the emitted electrons will escape the cavity.

Layout Optimization

The effects of the booster layout on dark current propagation upstream to the cathode were investigated by incrementally adjusting the distances between cavities in the Astra tracking simulations. The standard optics are used for the initial layout and for the settings of all lattice elements.

Figure 6 shows how many of the initial DC electrons (100,000 per cavity) reach the cathode plug as a function of cavity spacing, as well as the total power on the plug. In each row a different distance parameter was varied: the distance between the cathode and the first booster cavity (z_{01}),

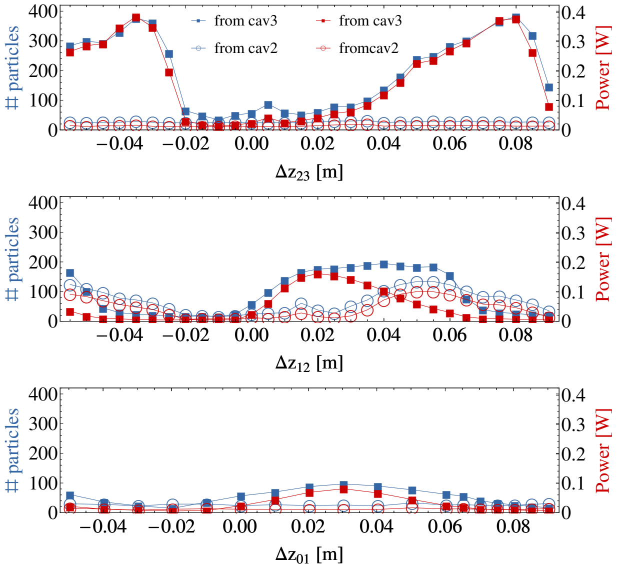

Figure 6: Dark current which reaches the cathode plug as a function of the distance between the second and third cavities (top), the first and second cavities (middle), and the cathode and the first cavity (bottom). The left axis shows the number of electrons reaching the cathode plug out of the initial 100,000 from each cavity per RF period (blue), and the right axis shows the total power on the plug (red).

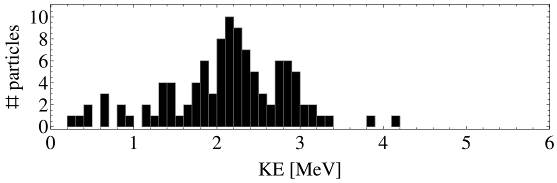

Figure 7: Kinetic energy of DC electrons that reach the cathode plug.

between the first and second cavities (z_{12}), or between the second and third cavities (z_{23}). The default layout is already well-optimized and little improvement could be expected from further adjustments to the cavity separations.

A total of about 90 particles, with less than 50 mW total power, reach the cathode plug. The distribution of kinetic energy among the electrons striking the cathode is shown in Fig. 7. With the default layout, no electrons with the highest possible kinetic energy (~6 MeV) reach the cathode and the total power of dark current electrons striking the cathode is less than 50 mW.

Note the periodic structure of the dependence of DC to cathode on z_{23}, the distance between cavities 2 and 3, with maxima separated by about 11 cm, or $\lambda/2$ for the cavity frequency f=1.3 GHz. The factor of two is due to the fact that the relative phasing between cavities changes to ensure that the arrival phase of a particle traveling downstream from cavity 2 to cavity 3 remains unchanged. As a result, a particle traveling upstream from cavity 3 to cavity 2 sees a larger change in the phase of arrival at cavity 2, caused both by the changed time of flight and also by the changed relative phasing of the cavities.

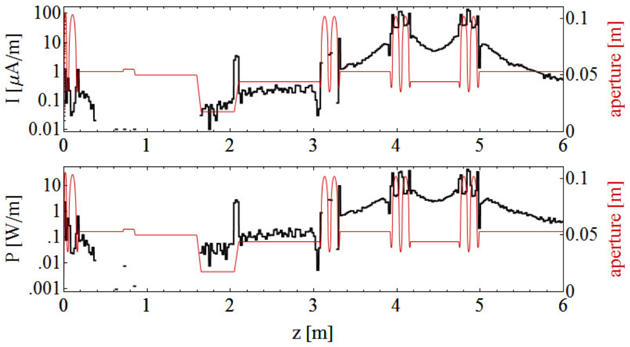

Figure 8: Linear density of current (top) and power (bottom) lost throughout injector due to dark current emitted from booster cavities 2 and 3. The power lost outside of the cavities is well below acceptable loss limits for the injector.

The total currrent and power deposited in the injector from the initial distribution of dark current electrons are shown in Fig. 8. Even with these conservative upper limits for total dark current emitted from the cavity surfaces, the power lost outside of the cavities is well below acceptable limits.

CONCLUSION

Tracking simulations show that the layout of the booster module is well optimized to minimize the propagation of field emission dark current from the booster cavities upstream to the cathode. Approximately 27% of the dark current electrons generated in each cavity will escape the cavity, though this figure will depend on the location of the emitters in the real cavities. A conservative estimation for the upper limit of dark current that can be generated in the cavity, based on the fact that the cavity cooling system can dissipate about 4 W of heat, suggests that a maximum of nearly $3\mu\ A$ of dark current could exit each cavity in each direction. The maximum total power of dark current electrons impacting the cathode is expected to be less than 50 mW.

ACKNOWLEDGEMENT

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