SIMULATION OF CATHODE BACK-BOMBARDMENT IN A 100 MHz THERMIONIC RF GUN*

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Abstract

A 100 MHz thermionic rf gun is under consideration as the electron source for the X-ray Free Electron Laser Oscillator[1]. Because the source must operate continuously, back-bombardment of the cathode is a serious concern. We present results of simulations of back-bombardment, as well as strategies for reducing the back-bombardment power on the cathode.

INTRODUCTION

In this paper, we present the results of back-bombardment investigations for the 100 MHz XFEL-O rf gun. The XFEL-O injector design[2] uses a thermionic rf gun in order to achieve very low normalized emittance ($\sim 0.1\mu$m) for low charge ($\sim$ 50 pC) in relatively long bunches ($\sim$ 2 ps rms after compression).

The gun cavity [3] is based on the LBNL design [4]. Figure 1 shows detail of the cathode and beam pipe region. Because the cathode is thermionic, it emits during half of the rf cycle. Many electrons emitted late in the cycle acquire insufficient energy to exit the gun before the field reverses sign and back-accelerates them toward the cathode. These electrons may impact the cathode or the structure around it, a phenomenon known as back-bombardment (BB).

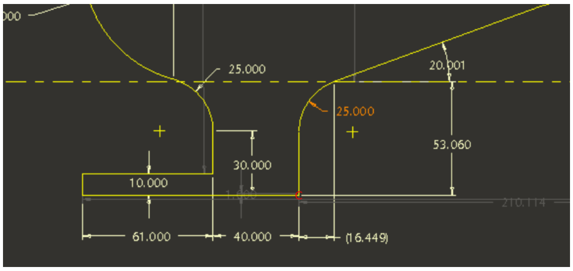

Figure 1: Detail of gun cavity design (G. Waldschmidt, ANL/APS). The cathode position is marked by the red "C."

BB was observed in the single-cell rf gun built at Stanford University, [5], where deflecting magnets were used for mitigation. The two-cell rf gun built at the Stanford Synchrotron Radiation Laboratory [6, 7] also exhibited BB. However, it was not serious, as only a $\sim 2\mu$s rf pulse was for operations, due to the choice of field ratio between the cells. For an rf pulse of $\sim 4\mu$s, BB power was sufficient to allow turning off the cathode filament. The gun would deliver current in that condition indefinitely. When the pulse was extended beyond $\sim 5\mu$s, the beam current would rapidly rise during each macropulse, resulting in significant cathode damage. Because the application only required a $\sim 2\mu$s rf pulse, the use of deflecting magnets was not needed for this gun, nor for application of a similar gun at the Advanced Photon Source [8, 9]. In some guns, current variation due to BB occurs throughout the rf pulse. For this case, it was proposed [10] to use a modulated CW laser as a supplemental cathode heater. The modulation would be such as to maintain constant total cathode heating power.

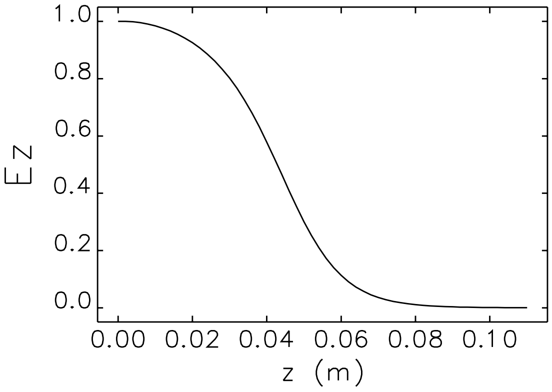

Figure 2: On-axis normalized electric field used for the gun simulation. The peak electric field is 23.5 MV/m. (Data courtesy P. Piot.)

In a CW thermionic rf gun, like the proposed for XFEL-O gun, BB will be a significant concern. We have investigated [11] nanosecond pulsed laser heating of the cathode at a few MHz rate. While this essentially eliminates BB, it requires considerable average laser power, such that the cathode would need to be cooled. An alternative is to gate the cathode with a high-voltage pulser, as discussed in [12]. In the present work, we return to the original solution, namely, use of deflecting magnets.

BACK-BOMBARDMENT SIMULATION

We simulated back-bombardment with the 2.5-dimensional fully electromagnetic program `spiffe` [13], in part because of the program's excellent data output. Instead of simulating the gun cavity, we used the on-axis field profile $E_z(z)$, shown in Fig. 2. Since `spiffe` uses a third-order expansion in r to obtain the off-axis electric and magnetic fields, and since the 0.3-mm-radius cathode is small compared to the relevant gun dimensions, this time-saving approximation is reasonable.

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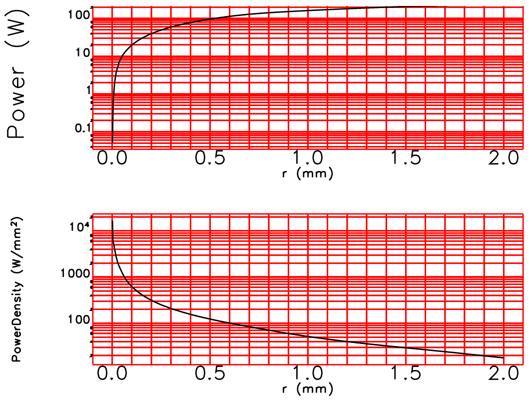

Figure 3: Histograms of back-bombarding power and power density at the cathode position. The cathode radius is 0.3 mm.

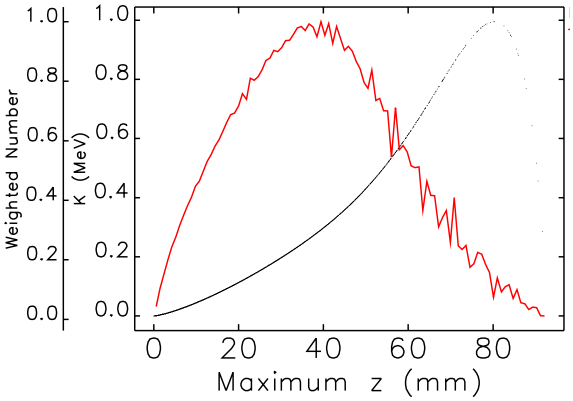

Figure 4: The points (black) show kinetic energy at cathode impact vs distance z_{max} traveled from the cathode before being turned around. The histogram (red) shows the relative number of electrons impacting the cathode weighted with their kinetic energies.

We placed a `spiffe` "screen" diagnostic at the gun exit (z=11 cm) and another in front of the cathode (z=0.01 cm) to detect backward-propagating beam. The required peak current is 80 mA [2], which determines the current density for the 0.3-cm-radius cathode. The beam power is $P = \frac{m_e c^2}{e T_{\rm rf}} \sum_{i=1}^{N} q_i(\gamma_i - 1)$, where e is the electron charge, m_e the electron rest mass, $T_{\rm rf}$ is the rf period, and γ_i the relativistic factor for the i^{th} macro-particle, which has charge q_i. The sum is over all the macro-particles crossing the relevant surface during a single rf period. For the cathode BB power, we simply restrict the sum to particles with radii $r_i < 0.3mm$.

The computed total beam power exiting the gun is 26 kW. The BB power is 230 W, which is very high, of which 60 W hits the cathode. Further, the power is concentrated at the center of the cathode, as Fig. 3 shows, giving a peak power density of $\sim$10 kW/mm^2. If we pulse the gun with a laser as mentioned above to gate the emission off 99% of the time, the backbombardment power drops to about 0.6 W, which is negligible. However, as discussed in [11], the average power due to the laser is potentially larger than the BB power. We could also use a deflecting magnet around the gun body, as discussed in the next section.

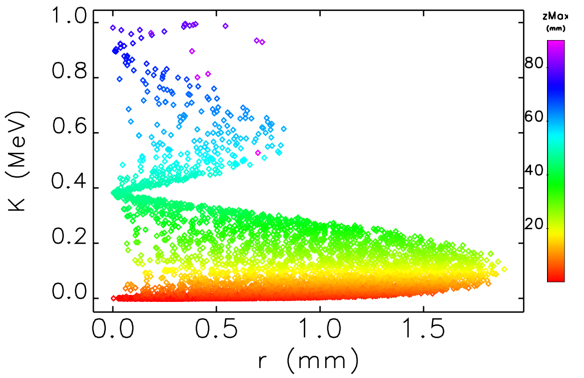

Figure 5: Radius and kinetic energy at which electrons hit the cathode, color-coded by z_{max}.

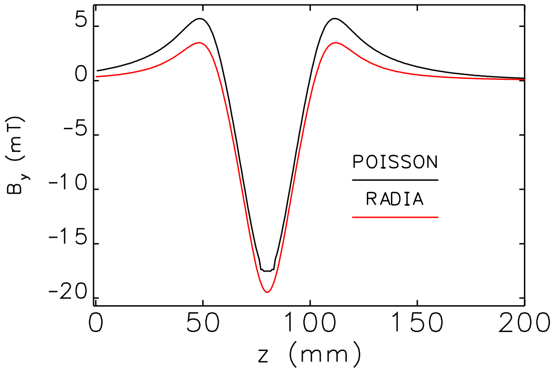

Figure 6: On-axis field of idealized 2D and 3D wigglers.

USE OF A THREE-POLE WIGGLER TO REDUCE BACK-BOMBARDMENT

If we impose a dipole field on the gun, accelerating electrons are deflected by this field, but the deflection is "damped" by acceleration. Once the beam exits the gun, its trajectory can be corrected by additional dipole magnets. There will be some increase in the emittance, since the electrons do not all experience the same acceleration. Back accelerated electrons see a relatively large net deflec-

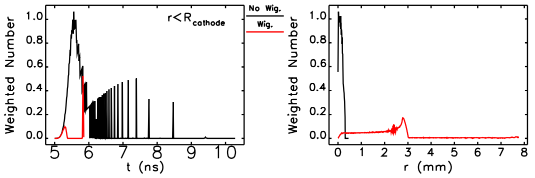

Figure 7: Comparison of K*q-weighted histograms with and without the wiggler.

tion because they never see the correcting fields.

Because of the gun's size, immersing the entire gun in a magnetic field is perhaps impractical, and might degrade the ultra-small emittance. Instead, we explored putting a three-pole electromagnetic wiggler inside the anode structure of the gun (seen on the left-hand side of Fig. 1). This device has $\int Bdl = 0$, to ensure small net deflection of particles that make it out of the gun. Since the device is electromagnetic, one could tune the strength of the three poles to provide zero net deflection and offset for the electrons of interest (i.e., those near the maximum energy).

In order to effectively suppress BB, the field must extend into the rf gap. Figure 4, shows the BB electrons' kinetic energies at impact vs z_{max}, the maximum distance traveled from the cathode. In general the most energetic electrons have traveled the greatest distance from the cathode before being turned around. These electrons travel the longest distance back to the cathode and hence gain significant energy. The figure also shows an energy-weighted histogram of the distance traveled, showing that most of the energy delivered to the cathode comes from electrons with $10mm \leq z_{max} \leq 60mm$. Hence, the deflecting field should be significant over this range.

Figure 5 shows the radius at impact vs the kinetic energy at impact. We see that some backstreaming electrons experience a net focusing force that results in formation of a small spot of energetic electrons hitting the cathode. This results in high power density at the center of the cathode, as also seen in Fig. 3.

Since `spiffe` assumes cylindrical symmetry, it cannot simulate deflecting fields. As a first step in simulating the deflection system, we used the simple program `rfgun` along with a wiggler designed using `POISSON` [14]. Figure 6 shows the wiggler field, which is designed to be as large as possible subject to $1A/mm^2$ current density. As seen in Figure 7, the wiggler significantly alters the number of particles striking the cathode by steering them well off-axis. The predicted BB power is reduced 20-fold.

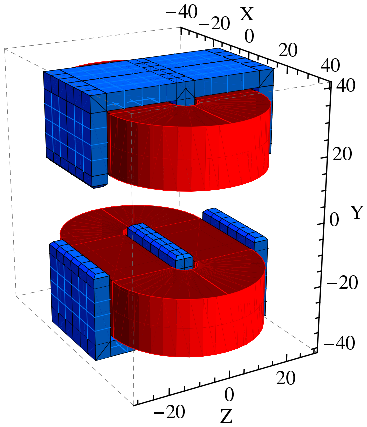

Figure 8: Radia 3D drawing of 3-pole deflecting magnet.

Table 1: Comparison of BB Power Simulated by GPT

	w/o magnet	**RADIA fields**
Total BB Power	227 W	259 W
On-Cathode BB Power	50 W	9 W

Since `rfgun` does not include space charge, and since the wiggler model is not realistic (being infinitely wide in the x direction), we continued our studies using GPT [15] and a 3D wiggler modeled with RADIA [16], shown in Fig. 8 and with on-axis fields as shown in Fig. 6. These simulations indicate that the BB power is reduced to less than 10 W, which is not as large an effect as predicted by the `rfgun` simulations, but still significant. One reason, confirmed by an `rfgun` simulation with the on-axis fields from RADIA, is that the fields predicted by RADIA fall off more rapidly with longitudinal position than those predicted by POISSON. Hence, there is less field in the rf gap, resulting in a two-fold reduction in effectiveness. The 3D simulations also predict a more than 2.5-fold increase in the horizontal emittance, which is results from a ten-fold increase in $\int Bdl$ and the transverse non-uniformity of the wiggler field. Future work should concentrate on designing a wiggler with better properties, including geometry that conforms to the cylindrical region available inside the anode.

CONCLUSION

We have explored the beam dynamics of back-bombardment in a 100 MHz thermionic rf gun. Because this gun must operate CW for driving the XFEL oscillator, the average cathode back-bombardment power is 60 W, with $\sim$10 kW/mm^2 power density. Use of an embedded three-pole wiggler was found to reduce back-bombardment of the cathode to below 10 W, while spreading out the beam. The impact on emittance is significant, but may be reduced by improved magnet design.

REFERENCES

[1] K. J. Kim *et al.*, Phys. Rev. Lett. 100, 244802 (2008).

[2] P. N. Ostroumov *et al.*, Proc. LINAC08, 676-678 (2008).

[3] G. Waldschmidt, private communication.

[4] J. Staples *et al.*, Proc. PAC07, 2990-2992 (2007).

[5] G. A. Westenskow and J. M. J. Madey, HEPL Tech. Note, TN-86-1 (1986).

[6] M. Borland *et al.*, Proc. LINAC90, 761-763.

[7] M. Borland, SLAC-Report-402, 1991.

[8] M. Borland, Proc. PAC93, 3015-3017 (1993).

[9] J. Lewellen *et al.*, Proc. Linac98, 863-865 (1998).

[10] Y. Huang *et al.*, Proc. PAC91, 2017-2019 (1991).

[11] M. Borland *et al.*, these proceedings.

[12] X. Dong *et al.*, these proceedings.

[13] `http://www.aps.anl.gov/asd/oag/manuals/spiffe_V3.2/spiffe.html`

[14] Los Alamos National Laboratory.

[15] Pulsar Physics, `http://www.pulsar.nl/gpt`

[16] O. Chubar *et al.*, J. Synchrotron Rad. 5, 481-484 (1998).