A TWO FREQUENCY GUN FOR HIGH CURRENT THERMIONIC CATHODE ELECTRON INJECTOR SYSTEMS

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Abstract

This paper discusses work done at Colorado State University (CSU) on designing a radio frequency, thermionic cathode electron gun for high-current injection systems for free electron lasers. Some background and a brief overview of other facilities using this type of injector is provided followed by the basic theory of back-bombardment and why it is a problem for such high-current injectors. We then discuss the theory of how a second frequency in the gun could mitigate this back-bombardment effect. Scaling from a previous design to the relevant CSU frequencies and using beam simulations we show results comparable with previous work done in this field [1]. We found that for a 100-pC bunch charge operating at 10MV/m gradient the harmonic field produced a 63% reduction in the back-bombardment power.

INTRODUCTION

Production of 1) high-brightness, 2) low-emittance, and 3) high-average current beams is necessary for high average power free-electron lasers (FELs) and with regards to the first two the use of photocathode RF guns dominate. However, achieving high-average currents in the photocathode mode is complicated by the need of robust, high-quantum efficiency cathodes and complex laser systems. A simple thermionic cathode RF gun system can achieve quite high average currents and, properly designed, can achieve the high-brightness required for many FEL applications in the IR and longer wavelengths [2,3,4,5]; furthermore, the cathodes tend to be robust and long-lived (months to years).

While the use of thermionic cathodes can drastically increase the cathode lifetime, use of such cathodes presents two major complications. The first and foremost is how to prevent the potentially destructive electron back-bombardment, while of secondary concern is how to operate the accelerator in a pulsed mode, which is useful for characterizing the machine.

This paper does not address pulsed-power operation; however, previous work has analysed the possibility of both laser-gated thermionic emission or cathode grids to gate the emission [6]. Instead here we focus on a method to mitigate the electron back-bombardment heating effect.

BACK-BOMBARDMENT IN THERMIONIC RF GUNS

A thermionic cathode when held at a chosen elevated temperature will continuously emit electrons at a rate dependent on the cathode temperature. If the field on the cathode is positive there will be no emission because the field attracts the electrons back to the cathode. When the field is negative the emission from the cathode will be continuous. Some electrons, which are emitted late in the RF cycle, will not gain enough energy to exit the gun and will be accelerated back towards the cathode. These back-bombarded electrons transfer their energy to the cathode surface in the form of heat and subsequently can raise the cathode temperature. This effect is referred to as back-bombardment and is a negative feedback mechanism: higher temperatures produce more electrons, which in turn increase the back-bombardment. If left unchecked, cathode damage may occur.

Using a simple Newtonian model, we computed the trajectories of a single electron subjected to a time varying RF field. Figure 1 shows, as a function of injection phase, the resulting final position of these particles. A time domain overlay of the RF fields is also shown.

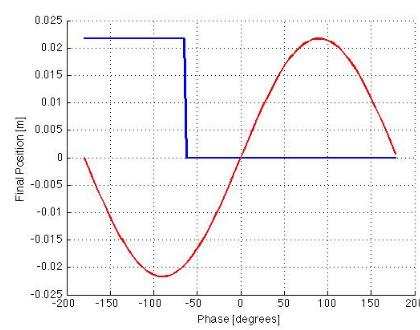

Figure 1: The resultant back-bombardment phase profile for a gap of 2cm and a RF frequency of 1.3GHz. Using a simple Newtonian model.

As stated previously, when the field is positive there is no emission so even though these particles have a final position of zero, they also never gain any energy. However for this model, there is a range of phases from roughly -63 to 0 degrees, where emission occurs but the particles ultimately are accelerated backwards by the rapidly changing field and strike the cathode. This corresponds to about 1/3rd of the region where emission is favourable and back-bombardment occurs.

THEORY OF BACK-BOMBARDMENT MITIGATION

In order to mitigate the back-bombardment effect we must consider what ideal waveform will completely eliminate this effect. A waveform that emits over some time, then holds zero long enough for the particles to

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leave the cavity before turning negative, should eliminate back-bombardment. This waveform and its resulting back-bombardment profile, similar to that of figure 1, are presented in figure 2.

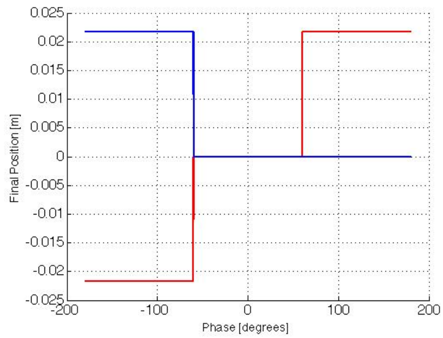

Figure 2: Ideal waveform (red) for complete back-bombardment mitigation with an overlay of its emission phase profile (blue).

This ideal waveform has practical limitations, so we must consider an approximation. We can express this periodic waveform through the use of a Fourier series. To eliminate possible adverse effects due to spurious overshoot caused by an incomplete set of harmonics we consider the first order approximation seen in equation 1.

$$E_z(t) = E_0 \sin(\omega t - \pi) + \frac{E_0}{2}\sin(2\omega t) \qquad (1)$$

The result of the back-bombardment phase profile, similar to those seen in figures 1 and 2, is presented in figure 3 with the overlay of our approximated ideal RF waveform.

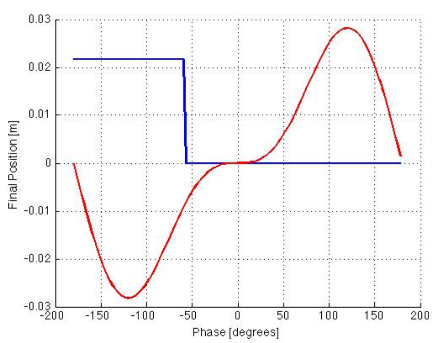

Figure 3: Phase profile for the two-frequency case using a simple Newtonian model (blue) with the temporal field envelope overlay (red).

Figure 4 compares the result of figure 1 and figure 3. This shows that we should see a decrease in the back-bombardment by the introduction of the first harmonic mode in the RF gun. This however was not optimized in relative field amplitude strength and relative phase or for other effects such as space charge. We need to consider a more general parameter space and do a proper scan over this space. Equation 2 represents a more general field profile where the harmonic phase and field ratio are given as variables.

$$E_z(t) = E_0(\sin(\omega t) + H\sin(2\omega t + \phi)) \qquad (2)$$

To better understand how the back-bombardment may vary, we performed a scan of these parameters on a 1D model for the back-bombardment.

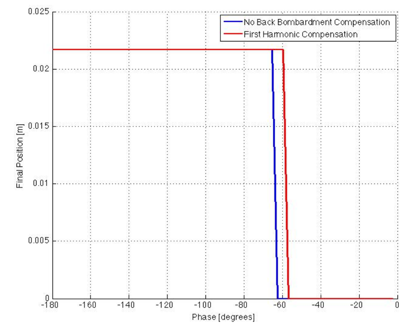

Figure 4: Comparison of the output phase profiles for the two-frequency case and the single frequency case.

Figure 5 shows the back-bombardment power in watts as a function of the harmonic field ratio and relative RF phase for the waveform defined by equation 2. The back-bombarded particle's energy is computed when it strikes the cathode, which is used to compute the energy deposited per RF cycle and consequently the back-bombardment power.

Our expected local minimum near 0.5 HFR and 180-degree phase offset is present, however the true local minimum occurs at 0.75 HFR and a 240-degree phase shift. This theoretical model predicts approximately a 40% reduction in the back-bombardment.

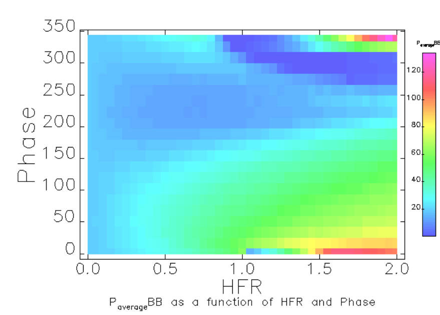

Figure 5: Theoretical result for the back-bombardment power as a function of the harmonic field ratio and the relative phase of the two RF powers.

There is also a minimum band in the upper right corner of the parameter space, since this does not appear in our simulations we believe this to be an artefact of the nonrelativistic approximation.

BEAM SIMULATIONS

The beam transport simulations were conducted using SPIFFE [7], a 2.5-D electromagnetic solver that includes space charge effects.

Without Space Charge

To compare our theoretical model with the more complete and realistic relativistic simulation we begin by running the same parameter scan as before with space charge calculations turned off. The gradient of the cavity was 10MV/m. What we see is a general trend that corresponds with the basic non-relativistic approximation, though with some specific variances due to these approximations.

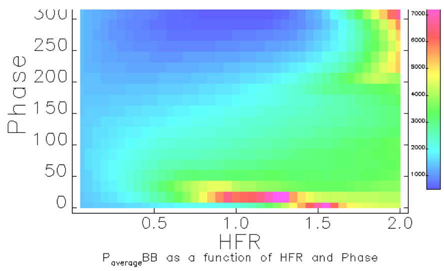

Figure 6: Back-bombardment simulation power as a function of harmonic field and the relative RF phase. The minimum is at 310 degrees and 1.1 HFR

With Space Charge

Having satisfied ourselves that the theoretical and non-space-charge simulations generally agree we turn on the space charge and execute a parameter scan over the same space as before. In this case we are assuming a modest amount of charge (100pC) emitted uniformly during a cycle. We see that the global minimum is roughly in the same location as in the non space charge region. This is indicative that in this modest charge case the space charge is not significantly affecting the ability of the harmonic mode to reduce the back-bombardment.

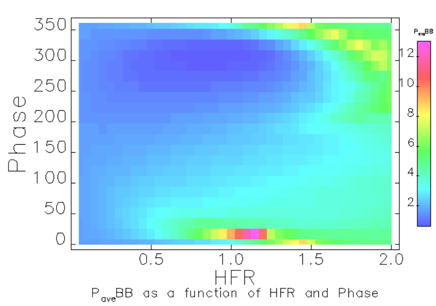

Figure 7: Back-bombardment as a function of the harmonic field ratio and the relative RF phase.

The back-bombardment power reaches a minimum at a relative phase of 310 degrees and a harmonic field ratio of 0.85. With no harmonic compensation the average back-bombardment power is 1.6kW. After introducing compensation the average back-bombardment power is reduced to 617W, about 37% of the baseline.

It should also be noted that while the harmonic field can mitigate the back-bombardment, improper tuning could increase it, which would greatly compound the cathode heating effects.

CONCLUSIONS

We have shown that the technique of using a harmonic field to reduce back-bombardment in thermionic guns can reduce the average back-bombardment power by about 63%.

AKNOWLEDGEMENTS

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