ION BOMBARDMENT IN RF PHOTOGUNS

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Abstract

A linac-ring eRHIC design requires a high-intensity CW source of polarized electrons. An SRF gun is viable option that can deliver the required beam. Numerical simulations presented elsewhere have shown that ion bombardment can occur in an RF gun, possibly limiting lifetime of a NEA GaAs cathode. In this paper, we analytically solve the equations of motion of ions in an RF gun using the ponderomotive potential of the RF field. We apply the method to the BNL 1/2-cell SRF photogun and demonstrate that a significant portion of ions produced in the gun can reach the cathode if no special precautions are taken. Also, the paper discusses possible mitigation techniques that can reduce the rate of ion bombardment.

INTRODUCTION

Ion backbombardment is the major cause of degradation of the quantum efficiency of GaAs cathodes in DC guns. Numerical simulations described in [1],[2] revealed that ion backbombardment also can occur in RF guns. Although numerical simulations are useful for a specific gun, they are hard to extrapolate to other guns if the scaling laws are not known. In this paper, we use the ponderomotive potential of the RF field [3] to analyze the motion of ions in an RF gun. We briefly describe the method and examine the ion motion in the BNL 1/2-cell SRF gun.

MOTION OF IONS IN A RAPIDLY OSCILLATING RF FIELD

The motion of an ion in an RF field can be described as a superposition of a fast oscillating term, $\mathbf{a}$, and a term describing the ion motion averaged over the fast oscillations, $\mathbf{x}(t) = \overline{\mathbf{r}(t)}$: $\mathbf{r} = \mathbf{x} + \mathbf{a}$. Assuming the RF electric field can be written as $\mathbf{E} = \vec{\mathcal{E}}(\mathbf{r})\cos(\omega t + \psi)$ where $\omega t + \psi$ is the RF phase, the fast oscillating term is given by

$$\mathbf{a} = -\frac{\lambda^2}{4\pi^2}\frac{q\vec{\mathcal{E}}\cos(\omega t + \psi)}{mc^2} \tag{1}$$

and the equation for the averaged motion is given by

$$\ddot{\mathbf{x}} = -\frac{\lambda^2 c^2}{16\pi^2}\left(\frac{q}{mc^2}\right)^2 \nabla\vec{\mathcal{E}}^2, \tag{2}$$

where m and q are the mass and charge of the ion, c is the speed of light, and λ is the RF wavelength. Thus, the averaged motion is determined by the effective potential energy, frequently referred to as the ponderomotive energy:

$$U_e = \frac{mc^2}{16\pi^2}\left(\frac{\lambda q\vec{\mathcal{E}}}{mc^2}\right)^2. \tag{3}$$

If an external static electromagnetic field is present, the Lagrange function of the averaged motion is

$$L = T_e - U_e - q\Phi + \frac{e}{c}\mathbf{A}\cdot\dot{\mathbf{x}}, \tag{4}$$

where Φ and $\mathbf{A}$ are the scalar and vector potentials of the external field, respectively, and T_e is the effective kinetic energy $m\dot{\mathbf{x}}/2$.

The method is applicable provided that the amplitude of the fast oscillations, $|\mathbf{a}|$, is small compared to the characteristic size of the inhomogeneity of the RF field, L: $|\mathbf{a}|/L \ll 1$.

Initial Conditions

In treating the ion motion, we assume that the ions are generated only in collisions of the electron beam with the residual gas. An ion can gain its initial energy interacting with a bunch that produces the ion. However, in this paper, we assume that the charge of electron bunches is sufficiently small and neglect this interaction. Also, the ion can gain energy during the ionization process. The energy transferred in the ionization process is mostly absorbed by knocked out electrons. Therefore, the cross section of collisions with a large energy transfer to an ion is much smaller than the ionization cross section. Thus, we can assume that ions originate at rest and find the initial effective velocity $\dot{\mathbf{x}}_0$:

$$\dot{\mathbf{x}}_0 = -\frac{\lambda c}{2\pi}\frac{q\vec{\mathcal{E}}\sin(\phi_0)}{mc^2}, \tag{5}$$

where ϕ_0 is the ionization RF phase. The associated initial effective kinetic energy is given by:

$$T_{e0} = \frac{mc^2}{8\pi^2}\left(\frac{\lambda q\vec{\mathcal{E}}}{mc^2}\right)^2 \sin^2(\phi_0) = 2U_e\sin^2(\phi_0). \tag{6}$$

BNL 1/2-CELL SRF GUN

Brookhaven National Laboratory and Advanced Energy Systems, Inc. are jointly developing a 1/2-cell superconducting radio-frequency (SRF) photogun [4]. Fig. 1 shows the SuperFish model of the gun. Table 1 shows the nominal gun parameters. We note that the gun repetition rate and current can be increased to 350 MHz and 500 mA, respectively, after an upgrade of the drive laser.

Motion on the Gun Axis

The motion of ions on the gun axis is one-dimensional. The electric field on the gun axis was calculated by SuperFish. The program Parmela was used to calculate the RF phase at which electron bunches pass a given coordinate,

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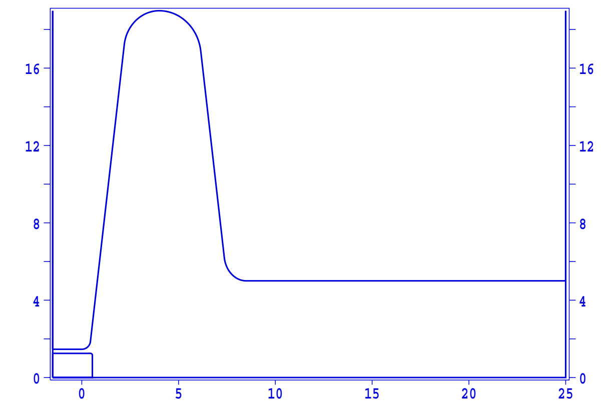

Figure 1: SuperFish model of the BNL 1/2-cell SRF gun. The horizontal axis corresponds to the gun axis.

Table 1: Parameters of the BNL 1/2-cell SRF gun with nominal values. The numbers in parentheses show values after a possible laser upgrade.

Parameter	Value
Beam Energy (MeV)	2.0
$\mathcal{E}_{\rm max}$ (MeV/m)	29
$F_{\rm RF}$ (MHz)	703.75
$F_{\rm bunch}$ (MHz)	9.38 (352)
$q_{\rm bunch}$ (nC)	0.7-5
$I_{\rm beam}$ (mA)	7-50 (500)

yielding the ionization phase ϕ_0 as a function of z. In this simulation, the initial beam phase was chosen to minimize the beam emittance. Fig. 2 shows the effective potential energy (in red) of H_2^+ ions on the gun axis. Also, Fig. 2 shows the total effective energy of H_2^+ ions as a function of the ionization coordinate. The total energy curve is divided into two branches: Ions whose velocity $\dot{\mathbf{x}}_0$ points towards the cathode (in green) and those whose velocity points out of the gun (in blue). The total effective energy of ions originating at $z < 3.4$ cm is larger than the effective potential energy at the cathode. Also, their initial velocity points towards the cathode. Thus, those ions originating at $z < 3.4$ cm will reach the cathode. All other ions produced at $z \geq 3.4$ cm will be expelled from the gun.

Off-Axis Motion

Off-axis, ions experience a deflecting force. The effective potential energy off the gun axis is given to the second order in r by

$$U_e = \frac{mc^2}{16\pi^2}\left(\frac{\lambda q}{mc^2}\right)^2 \times \left(\mathcal{E}_a^2 - \frac{\mathcal{E}_a}{2}\left(\mathcal{E}_a'' + \frac{\mathcal{E}_a}{\lambda^2}\right)r^2 + \frac{(\mathcal{E}_a')^2}{4}r^2\right), \quad (7)$$

where $\mathcal{E}_a(z)$ is the electric field on the gun axis, and $'$ denotes a derivative with respect to z. Because we assumed

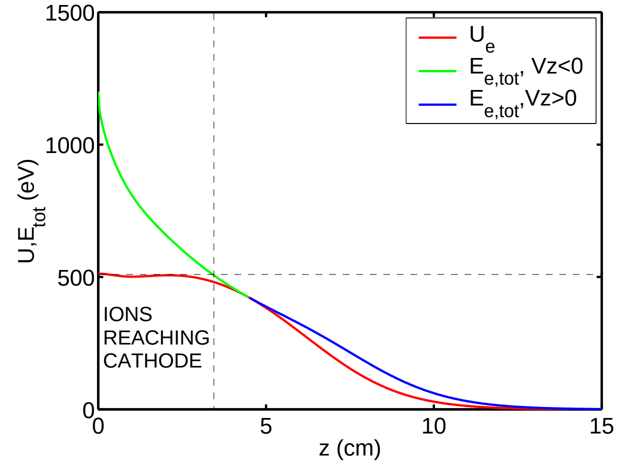

Figure 2: The effective potential energy (red) and the total effective energy (green and blue curves) of H_2^+ ions in the BNL 1/2-cell SRF Gun. The green and blue curves, respectively, show the total energy of ions with the effective velocity $\dot{\mathbf{x}}_0$ pointing towards the cathode and away from the cathode.

that ions originate at rest, we can neglect the angular momentum and write the equation for the average ion radius as

$$m\ddot{r} = -\partial U_e/\partial r. \quad (8)$$

This equation has to be solved simultaneously with the Lagrange equation for z. However, because we are interested only in ion trajectories with a small deviation from the gun axis, we can assume that the axial motion does not depend on r and use the value of $\dot{x}_z$ on the gun axis.

Generally, Eq. (8) has to be solved numerically. Its solution also can be found by iterations. If the trajectory radius changes little, we can limit the solution to the first iteration and solve the problem analytically. Fig. 3 shows a deviation of ion trajectories from the initial radius calculated at the cathode and normalized to the initial radius vs. the ionization coordinate. The blue curve shows the result of numerical solution of the equation of the radial motion. The green curve depicts the first iteration obtained analytically. The first iteration obtained analytically is not small in the region $3 < z < 3.4$ and, therefore, fails to predict the motion of ions correctly for those ions originating at $3 < z < 3.4$ cm.

Validation by Tracking

To validate the results obtained by using the ponderomotive potential, we tracked ions directly in a SuperFish RF field map using the Runge-Kutta method. The simulated axial motion agreed very well with the predictions obtained using the ponderomotive potential: Ions originating between the cathode and $z \approx 3.4$ cm reached the cathode while those originating at $z > 3.4$ cm left the gun. Fig. 3 shows the result of the simulation of the radial motion

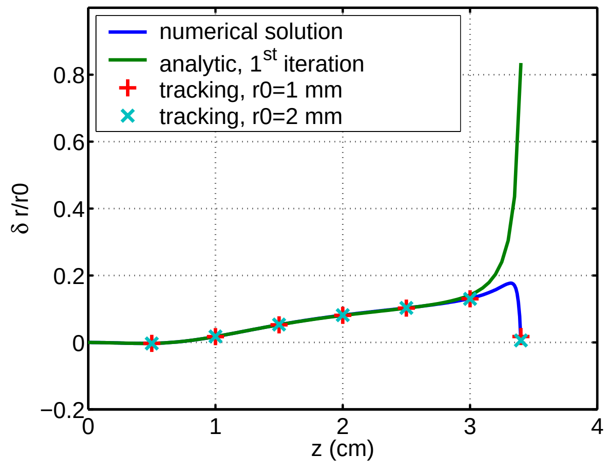

Figure 3: Normalized deviation of ion trajectories from the initial radius at the cathode as a function of the ionization coordinate. Tracking results for initial radii $r_0 = 1$ mm and $r_0 = 2$ mm practically coincide with each other, confirming the linearity of ion motion close to the gun axis.

(off-axis). There is a good agreement among all the solutions for $z < 3$ cm. The tracking result also shows a good agreement with the numerical solution of Eq. (8) for ions originating at $3 < z < 3.4$ cm.

Rate of Ion Bombardment. Comparison to a DC Gun.

The number of ions bombarding the cathode normalized to the extracted charge is given by

$$\frac{\mathrm{d}N}{\mathrm{d}Q} = \frac{n_i}{e}\int_0^D \sigma(E(z))\mathrm{d}z, \tag{9}$$

where n_i is the particle density of the residual gas, σ is the ionization cross section, and D is the distance from which ions can reach the cathode. For a residual hydrogen pressure of $5 \cdot 10^{-12}$ Torr and a distance D of 3.4 cm, equation (9) yields $(\mathrm{d}N/\mathrm{d}Q)_{\mathrm{BNL}} = 1.7 \cdot 10^6$ ions/C. We can compare this number to the number of ions produced in a high voltage DC gun. For this example, we choose the following parameters: a beam energy of 650 keV, an accelerating gap of 5 cm, and the residual gas pressure the same as that in the example of the BNL gun, viz., $5 \cdot 10^{-12}$ Torr. With these parameters, equation (9) yields $(\mathrm{d}N/\mathrm{d}Q)_{\mathrm{HVDC}} = 2.4 \cdot 10^6$ ions/C.

Ions produced in a transfer line can be trapped in the beam and travel towards a gun. However, trapped low energy ions cannot reach the cathode in the BNL gun because of the effective potential barrier produced by the accelerating RF field. In a DC gun, the flux of trapped ions can be eliminated by biasing the anode to a positive potential of a few hundred or thousand Volts as proposed in [5].

This example indicates that rates of cathode ion bombardment can be comparable in RF and DC guns. However, in reality, a cross-comparisson of the cathode lifetime between these two types of guns based on the over-all rate of ion bombardment can be difficult. First, the ion energy spectra in the two differ substantially. Second, DC guns are frequently operated with the laser spot shifted from the cathode center. Therefore, a detailed knowledge of the ion spectra and the efficiency of QE damage as a function of the ion energy are required to predict the cathode lifetime with a reasonable accuracy.

MITIGATION TECHNIQUES

The dependence of the initial drift velocity $\dot{\mathbf{x}}_0$ on the accelerating phase can be employed to suppress ion bombardment in a single-cell gun. Assuming the RF field is accelerating in the phase range from $-\pi/2$ to $\pi/2$, the initial drift velocity $\dot{\mathbf{x}}_0$ of all ions will point away from the cathode if the RF phase changes between 0 and $\pi/2$ during the acceleration of electron bunches. Ions with the total effective energy greater than the effective potential energy will exit the gun. Only a small portion of ions originating close to the cathode still will be able to strike the cathode because positively charged ions are accelerated towards the cathode immediately after ionization.

The phasing method described above is not applicable to a multi-cell gun because the accelerating phase cannot be limited to the range between 0 and $\pi/2$. Cathode biasing can be used in this case. Also, cathode biasing can be effective in a single-cell gun. For the BNL gun, a bias voltage of 800 V might suffice to significantly reduce the rate of ion bombardment.

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