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Ion trapping and cathode bombardment by trapped ions in DC photoguns

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ION TRAPPING AND CATHODE BOMBARDMENT BY TRAPPED IONS IN DC PHOTOGUNS *

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Abstract

DC photoguns are used to produce high-quality, high-intensity electron beams for accelerator driven applications. Ion bombardment is believed to be the major cause of degradation of the photocathode efficiency. Additionally to ions produced in the accelerating cathode-anode gap, the electron beam can ionize the residual gas in the transport line. These ions are trapped transversely within the beam and can drift back to the accelerating gap and contribute to the bombardment rate of the cathode. This paper proposes a method to reduce the flow of ions produced in the beam transport line and drifting back to the cathode-anode gap by introducing a positive potential barrier that repels the trapped ions. The reduced ion bombardment rate and increased life time of photocathodes will reduce the downtime required to service photoinjectors and associated costs.

INTRODUCTION

The successful demonstration of high power energy recovery at JLAB FEL [1], has led to a great interest in developing high average current, high brightness photo injectors for such applications as ERL based synchrotron radiation facilities [2],[3], FELs [3], electron cooling [4], and colliding beams for nuclear and high energy physics [5]. These applications require beams with an average current of tens to hundreds of milliamps and a normalized emittance of the order of several mm·mrads or less. Additionally, nuclear and high energy experiments require a high degree of polarization.

Fixed voltage (DC) photoemission guns have been successfully used to produce high-quality, high average intensity electron beams for accelerator driven applications [6], [7], [8]. Because of their proven design and ability to produce high average beam current, DC phtotoguns were selected as a technology of choice for the currently developed Cornell ERL and Daresbury 4GLS [2],[3].

Existing DC photo-injectors have demonstrated a cathode charge lifetime of several hundred Coulombs. Although this extracted charge is adequate for current applications, it becomes exceedingly small for proposed accelerator projects. Cathode back-bombardment by ions of the residual gas created in collisions with the accelerated beam is believed to be a major cause of the quantum efficiency (QE) degradation [9],[10]. While the exact details of the damage mechanisms are not clear, improving the residual vacuum, reducing beam losses, and increasing the laser spot size proved to mitigate the problem of ion back bombardment and increase the cathode charge lifetime.

Existing models of cathode ion bombardment consider only ions produced by the beam in the cathode-anode gap. In this paper, we discuss an additional source of ion bombardment that was overlooked so far: ions produced in a beam transport line behind the anode and trapped within the beam. Transversely confined in the beam, these ions can drift towards the cathode-anode gap, accelerate, and damage the cathode surface. As shown in this paper, the flux of trapped ions can significantly exceed the flux of ions produced directly in the cathode-anode gap.

ION TRAPPING IN DC PHOTOGUNS

A DC photoemission gun consists of a negatively biased photocathode and a grounded anode separated by a distance of a few centimeters. The cathode, biased to a negative potential of several tens to several hundreds of kilovolts, emits photoelectrons when illuminated by a laser. On its path, the accelerated electron beam ionizes residual gas. Ions produced in the cathode-anode gap are accelerated towards the cathode and damage its surface on impact, reducing QE. Additionally, the beam ionizes residual gas in the transport line behind the anode. These ions can be trapped by the electron beam and drift towards the cathode-anode accelerating gap.

The electric potential induced by a DC electron beam with uniform current density is (in CGS units):

$$\phi = \begin{cases} \dfrac{2I}{\beta c}\left(\dfrac{r^2}{2a^2} - \dfrac{1}{2} + \ln\left(\dfrac{a}{b}\right)\right) & 0 \le r \le a \\ \dfrac{2I}{\beta c}\ln\left(\dfrac{r}{b}\right) & a < r \le b \end{cases} \tag{1}$$

where a is the beam radius, b is the beam pipe radius, I is the beam current and βc is the beam velocity. For a beam pipe radius of 2.5 cm, beam radius, a, of 2.0 mm, beam energy of 100 keV, and a beam current of 5 mA, equation (1) yields the potential well depth of 1.7 V. Because the energy transferred in the ionization process is mostly absorbed by a knocked out electron, the energy of newly created ions is approximately equal to the average thermal energy of the residual gas, $4 \cdot 10^{-2}$ eV at room temperature. Equation (1) and the numerical example presented above indicate that ions will be trapped in practically any photogun if the beam current exceeds a few hundred microamps. Note that equation (1) does not include the potential of trapped ions assuming that the beam neutralization degree is small.

In the normal operational regime, DC photoguns generate a bunched electron beam obtained by modulating the

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driving laser beam. Equation (1) can be also used to analize ion trapping if the beam intensity is low. At a high beam current, trapped ions can become unstable in a bunched beam. The standard matrix stability analysis that treats interaction of ions with electron bunches as a sequence of thin lenses yields the stability criterion for singly ionized ions of the atomic weight A:

$$\frac{I}{f_b^2} < \frac{2Aa^2e}{r_p\beta c}, \tag{2}$$

where r_p is the classical proton radius, e is the elementary charge, I is the average beam current, f_b is the bunch repetition rate, and a is the radius of electron bunches. H_2^+ ions will be stable in a bunched electron beam with an energy of 100 keV, bunch radius of 2 mm, and bunch rep rate of 10 MHz if the beam current is below 1 A. Using this numerical example, one can write the beam current at which H_2^+ ions become unstable as

$$I = \frac{0.55}{\beta}\left(\frac{a}{2\text{mm}}\right)^2\left(\frac{f}{10\text{MHz}}\right)^2 \cdot 1\text{A}. \tag{3}$$

In a typical electron gun, the beam freely diverges in the transfer line until it is focused by a solenoid. Becasue the potential given by (1) depends on the beam size, it also changes along the transfer line. According to (1), the longitudinal force experienced by trapped ions is directed towards a smaller beam size, that is, towards the cathode-anode gap. Therefore, the portion of total number of trapped ions reaching the cathode is between 1/2 and unity, depending on parameters of the accelerated beam.

Flux of trapped ions

The number of ions produced in the accelerating gap and the number of ions produced in a transfer line behind the anode, normalized to extracted charge Q, are given by

$$\left(\frac{dN}{dQ}\right)_{gap} = \frac{n}{e}\frac{L_{gap}}{E_{max}}\int\sigma(E)dE \tag{4}$$

$$\left(\frac{dN}{dQ}\right)_{trapped} = \frac{n}{e}L_d\sigma(E_{max}) \tag{5}$$

respectively, where n is the residual gas molecular density, e is the elementary charge, $\sigma(E)$ is the ionization cross section as a function of energy, E_{max} is the beam energy after acceleration, L_{gap} is the length of the accelerating cathode-anode gap, and L_d is the length of a free drift after the anode. Figure 1 shows the H_2 ionization cross section as a function of the electron beam energy [11].

Using equations (4-5) and assuming a maximum electron beam energy of 650 keV, a length of the accelerating cathode-anode gap, L_{gap}, equal to 2 inches, residual gas pressure of $5 \cdot 10^{-12}$, and a distance to the first dipole corrector L_d of approximately 50 cm, one can estimate the flux of ions in proposed high intensity DC guns:

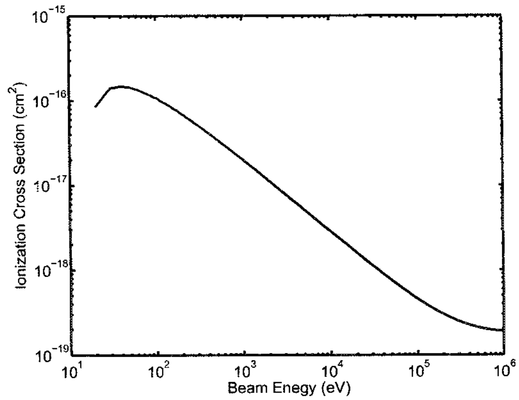

Figure 1: H_2 ionization cross section as a function of the electron beam energy

$$\left(\frac{dN}{dQ}\right)_{gap} = 2.4 \cdot 10^6 \text{ ions/C} \tag{6}$$

$$\left(\frac{dN}{dQ}\right)_{trapped} = 1.0 \cdot 10^7 \text{ ions/C}. \tag{7}$$

This numerical example shows that the flux of trapped ions can significantly exceed the flux of ions produced at the cathode-anode gap.

An amount of damage done by a single ion can depend on the ion energy. Qualitative measurements of QE degradation ([9],[10],[12]) clearly demonstrated that ions within a wide range of energies can effectively damage the cathode surface. However, no quantitative data on the damage efficiency as a function of the ion enegy exists. Therefore, this paper does not conclude on how much QE degradation is caused by trapped ions relatively to the damage done by ions originating near the cathode.

POSITIVE POTENTIAL BARRIER

An obvious solution to the problem of trapped ions is a positive potential barrier on the way of trapped ions. A positive barrier of a few volts should be sufficient to repel trapped ions. The optimum location of the potential maximum is right at the end of the accelerating gap, that is, at the anode.

Biased anode setup

A simplified POISSON [13] model of the new JLab loadlock photo gun, shown in Figure 2, has been developed to demonstrate the effect of anode biasing on the electrostatic potential. The model consists of a cathode biased to -100 kV, an isolated anode, an isolated anode support, and a flange. The actual gun is operated with the anode and its support grounded (at zero potential). To simulate a potential barrier the anode of the POISSON model was biased to 2 kV and the support was biased to 300 Volts. Figure

3 shows the electrostatic potential in the anode region produced by the described setup. The positive potential barrier is approximately 900 V.

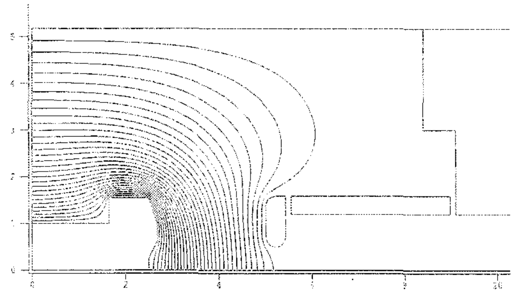

Figure 2: Simplified POISSON model of the new JLab load-lock gun. The cathode, shown in the lower left corner, is biased to -100 kV. The anode and the anode support are biased to 2 kV and 300 V respectively. The flange supporting the anode structure, shown on the right, is at 0 V.

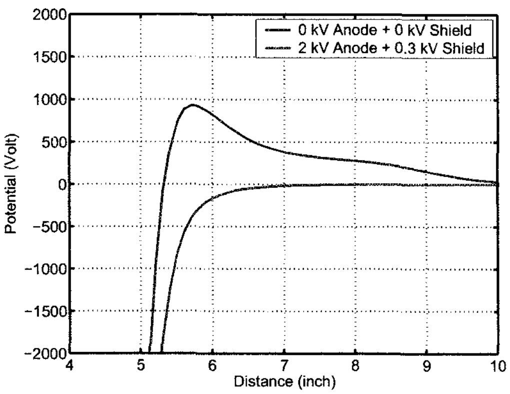

Figure 3: Electrostatic potential on the gun axis in the anode area for the actual gun design (blue) and with the biased anode and its support (red). The horizontal scale corresponds to that of Figure 4. The distance 5" corresponds to the anode face.

SIGNIFICANCE FOR FUTURE HIGH CURRENT PHOTO-INJECTORS

Accelerated to the full energy, trapped ions strike the cathode at the gun electrostatic center. If the laser spot is offset from the gun electrostatic center, trapped ions will not affect the cathode life-time. This method does not require biasing anode or any other gun geometry modification. However, this technique can be employed only if the laser spot is sufficiently small and the cathode is sufficiently large. Under the assumption that the cathode damage rate at the laser spot is proportional to the product of the beam current density and the vacuum pressure, the amount of charge that can be extracted from a fixed laser spot is proportional to the area of the spot. Thus, the time interval during which a photo gun can be operated with a fixed laser spot is proportional to the spot area divided by the beam current. To keep this interval within a reasonable limit the area of the laser spot has to be increased at a high beam current. Because future applications require approximately 100 times more average current than that produced by modern DC photoguns, an increase of the laser spot area by more than an order of magnitude is expected. The larger laser spot size can make clear separation of the laser spot and the area hit by trapped ions impossible in future high intensity DC photoguns. In this case, bombardment by trapped ions will directly limit the cathode life time. A positive potential barrier in the form of a biased anode provides a simple and effective solution to this problem.

CONCLUSIONS

Ion trapping in a transfer line can significantly increase cathode ion bombardment in a fixed-voltage photo gun. The effect of trapped ions on the cathode life-time should be more pronounced in guns where the laser spot cannot be clearly offset from the gun electrostatic center. This can be a concern for future high-intensity photo guns where a substantial increase of the laser spot area might be necessary to extend the cathode life-time. A positive potential barrier can eliminate the flux of trapped ions and is a simple and effective solution to this problem.

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