ION EFFECTS IN HIGH BRIGHTNESS ELECTRON LINAC BEAMS

S. Full*, A. Bartnik, I.V. Bazarov, J. Dobbins, B. Dunham, G.H. Hoffstaetter, K. Smith
CLASSE, Cornell University, Ithaca, New York 14853, USA

Abstract

Electron beams ionize rest gas particles which then accumulate around them, disturbing beam dynamics and causing background radiation. While this effect has been predicted in the past, linacs have hitherto not suffered from it because of their rather small beam current. The effect of ions increases with larger currents and smaller cross sections of the beam, and it has clearly been observed in Cornell's high-brightness ERL injector for the first time. This paper will show experimental evidence for ions, demonstrate strategies for their elimination, and will compare the experimental data to theories of beam-ion interactions.

INTRODUCTION

In an accelerator's vacuum chamber, any residual gas is rapidly ionized by collisions with the electron beam. At high beam currents, the resulting positive ions become trapped inside of the negatively charged beam and can cause a variety of effects including charge neutralization, coherent and incoherent tune shifts, optical errors, beam halo, beam losses, or even beam instabilities [1, 2]. Even with improvements in vacuum technology, ions can fully neutralize a beam within seconds for vacuum pressures as low as 1 nTorr. Therefore one must directly remove the trapped ions to avoid or mitigate these potential effects.

The Cornell DC photoinjector was built to serve as the injector for Cornell's proposed Energy Recovery linac (ERL). It is designed to operate with a beam energy of 5–15 MeV and beam currents up to 100 mA, corresponding to a bunch charge of 77 pC at a repetition rate of 1.3 GHz. Unlike previous linacs, the photoinjector reaches a new regime of beam parameters where ion trapping becomes a concern. Although problematic ion accumulation in linacs has been predicted in the past [1], it has rarely been observed due to low repetition rates that allow ions to drift out of the center of the beam pipe between bunches. In this paper we present some of the first observations of actual ion trapping in a high current linac. We also share the results of recent experiments in the photoinjector [3] that have validated the effectiveness of three different clearing methods: ion clearing electrodes, bunch gaps, and beam shaking.

EVIDENCE OF ION TRAPPING

Once trapped inside of the beam, the ions oscillate back and forth inside of the beam's potential with a characteristic frequency that depends on beam current, transverse beam size, and the ion's mass [3]. In general, trapping occurs when the ion oscillation frequency is significantly less than the bunch repetition rate. This makes the ion oscillation frequency a good estimate for determining whether or not ion trapping will occur within an accelerator. For the photoinjector, we both predicted and measured an ion oscillation frequency on the order of kHz [3] for millimeter beam sizes, which is significantly less than the 325 MHz or 1.3 GHz bunch repetition rates used here. Therefore, we expect there to be ion trapping in the photoinjector.

During reliability test runs at 20 mA and 350 keV, we have observed beam trips that limit stable machine operation to approximately 10-15 minutes. The beam trips were the direct result of the gun's high voltage power supply tripping off. Employing ion clearing techniques, primarily clearing electrodes and/or bunch gaps, allowed stable beam operation for at least 24 hours, leading us to conclude that ions are the cause of the trips. Note that no testing was done for more than 24 hours.

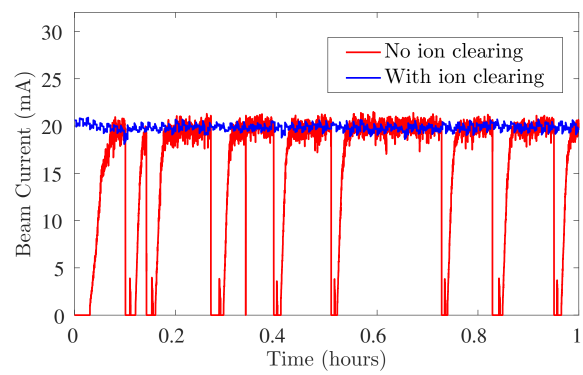

Figure 1: During certain running conditions, the photoinjector suffers from intermittent beam trips every 10–15 minutes. While employing ion clearing methods, we can obtain a stable beam current for at least 24 hours.

Although we have yet to determine the exact mechanism of these trips, we currently have two theories. The first is that trapped ions drift backwards and strike the cathode, ejecting particles that then cause arcing. This would ultimately trip off the high voltage power supply. The process of the ions striking and destroying the center of the cathode (known as ion back bombardment) is expected and dealt with during normal operation. However, in the past ion back bombardment in the photoinjector has not always been linked to these type of trips. The second theory is that dust particles become trapped inside of the beam and drift longitudinally towards the DC gun, where they eventually cause arcing that trips off the power supply. In both cases, the fact that the beam is low energy and the absence of a Superconducting RF cavity (which can impede the longitudinal motion of ions) between sections A1 and A3 (shown in Fig. 2) during these runs are likely important factors in explaining this phenomenon.

* sf345@cornell.edu

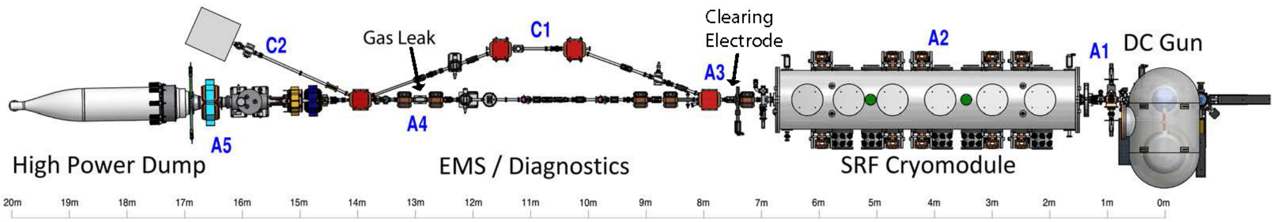

Figure 2: A schematic of the photoinjector that shows our experimental setup. Radiation measurements for the beam shaking experiments were taken using photomultiplier tubes at several locations between sections A3 and A4 (next to the beam pipe).

SIMULATING ION EFFECTS

While they are trapped, the ions tend to drift toward minima of the DC beam's electrostatic potential. For uniform cross sections of the vacuum chamber, these tend to be at the beam-size minima. Eventually, the ion distribution reaches an equilibrium state and can be treated as if it were a lens spread throughout the entire accelerator. The kicks created by the ions can be found first by assuming a certain transverse charge distribution and then calculating the electric field of that distribution. Once we know the correct shape of the field, we use General Particle Tracer (GPT) – the preferred simulation tool for the photoinjector – to track the beam through the ion column.

We modeled the ion distribution using four different transverse charge distributions: round constant charge density, elliptical constant charge density [4], round Gaussian charge density and elliptical Gaussian charge density [5]. In our simulations we found that the elliptical Gaussian charge distribution with a width proportional to the transverse beam size (σ_x or σ_y) achieved the most realistic results overall, so that is what we will focus on here. The Bassetti-Erskine electric fields for a Gaussian distribution that is uniform in the z direction are given by [5]

$$E_x - iE_y = \frac{-i\lambda}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right)w\left(\frac{\frac{x\sigma_y}{\sigma_x}+\frac{iy\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right] \quad (1)$$

where λ is the ion charge per unit length, σ_x and σ_y are the transverse beam sizes, and $w(z)$ is the complex error function, also known as the Faddeeva function.

There are several reasons why the elliptical Gaussian model is preferred. Although the beam in the photoinjector is nearly round, a round ion distribution is not sufficient, as manifested by the fact that an even slightly elliptical beam showed noticeable differences with round models. Elliptical models are therefore preferred when possible. Secondly, the electric fields for a constant charge distribution have a sharp cusp near the edge of the distribution. If you assume that the ion column has the same transverse width as the beam, the majority of the beam will experience a linear force. However, the outside edges of the beam will experience a highly non-linear force. At the edge of the ion column, this change between linear and non-linear field is very abrupt, and that ultimately causes unnaturally sharp "tears" in the beam's phase space. The gradual cusp of a Gaussian distribution smooths out this behavior and is therefore preferred.

However, it has been shown that these models do not always accurately reflect reality, and the ions tend to sharply accumulate near the center of the beam [6]. While this charge distribution and electric field are difficult to obtain analytically, a useful approximation can be obtained by simply replacing the transverse beam size $\sigma_{x/y}$ with $\sigma_{x/y}/\sqrt{2}$ in the expression for the electric field of a Gaussian distribution [6].

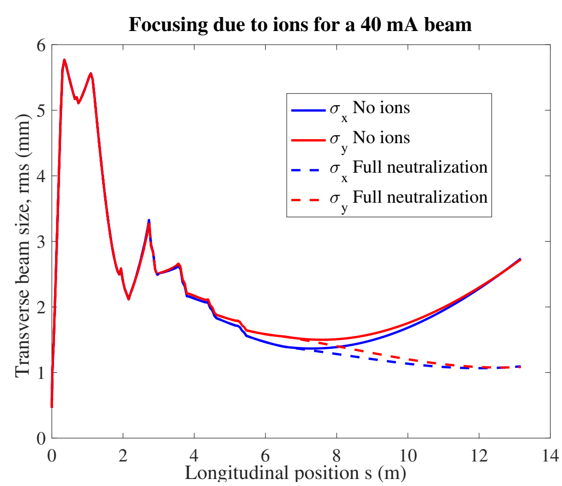

Figure 3: Simulations showing the focusing effects of an elliptical Gaussian ion distribution on a 40 mA beam. The ion column begins at s = 6.5 m, immediately after the beam has exited the last SRF cavity of the injector linac.

The primary effect of the ions is to provide an additional focusing effect on the beam, as shown in Fig. 3. This is especially noticeable at lower energies (i.e. MeV), where the ions screen the otherwise dominant space-charge forces of the beam. This additional focusing can lead to strong deviations from simulated beam optics, which may impact accelerator design, optimization and operation. An exam-

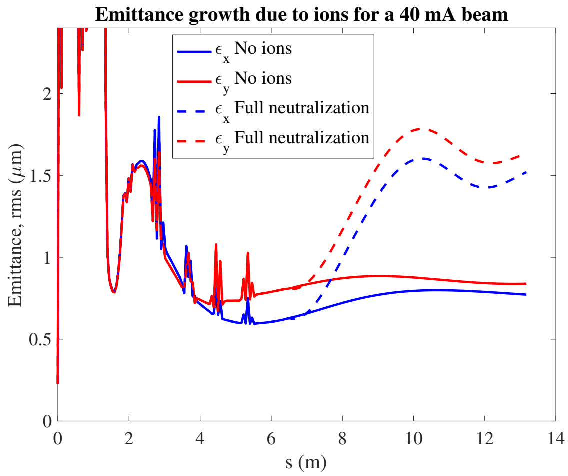

Figure 4: Simulations showing the effects of an elliptical Gaussian ion distribution on a 40 mA beam. The ion column begins at s = 6.5 m, immediately after the beam has exited the last SRF cavity of the injector linac.

ple of significant emittance growth due to ions for typical photoinjector optics settings is shown in Fig. 4.

In principle, it is possible to compensate for this additional focusing using optics. In order to accurately model the ion phenomenon, this would involve carefully tracking the locations of the trapped ions and varying the ion density λ along the length of the accelerator accordingly. But the ion distribution and its fields are nonlinear, and even if they were simulated accurately they cannot be compensated exactly by linear optics. Thus our primary concern is to focus on ion mitigation so that these problems are avoided outright.

ION MITIGATION EXPERIMENTS

Experiments were performed to test the effectiveness of three different ion clearing techniques in the Cornell ERL photoinjector: DC clearing electrodes, bunch gaps, and beam shaking [3]. During the first experiment, we installed a DC clearing electrode and used a picoammeter attached in series with the electrode to measure the amount of ions it removed as a function of clearing voltage. Our results are shown in Fig. 5. It was found that even a small applied voltage resulted in significant ion clearing, and above a certain voltage the number of cleared ions reached a maximum. The voltage necessary for maximum clearing can be predicted by considering the suppression of the transverse potential of a constant charge distribution beam [3]. The necessary voltage is given by

$$V_{electrode} \geq \frac{\lambda e}{2\pi\epsilon_0}\frac{d}{\sigma_b} \qquad (2)$$

where λ is the number of electrons per unit length, e is the elementary charge, d is the clearing electrode separation, and σ_b is the rms transverse beam size. For the photoinjector, the required voltage was rather small (28 V) compared to much higher energy accelerators which may require upwards of 1 kV due to much smaller transverse beam sizes [7, 8]. It is important to consider the correct voltage, as clearing electrodes that can support applied voltages above approximately 1-2 kV require special design considerations.

From an ion mitigation standpoint, clearing electrodes appear to remain the most straightforward option. A single electrode seems to clear most of the trapped ions in the photoinjector, especially because the region of interest is rather short (only about 5 m). A larger accelerator would require the deployment of clearing electrodes near most beam size minima and other pockets of high ion concentration. This may become difficult or expensive to implement in machines with low beta functions (on the order of m). In this case, simulations must be done to determine the optimal placement of clearing electrodes [2].

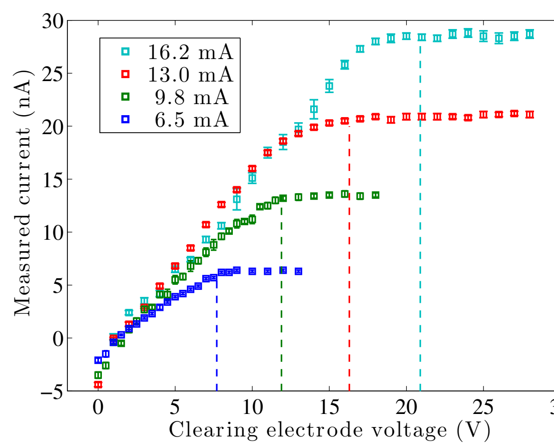

Figure 5: A picoammeter was used to measure the ion current striking the clearing electrode for different applied voltages and at different beam currents. The vertical dotted lines mark the minimum voltage required for full ion clearing, as predicted using eqn. 2.

In the second experiment, we introduced bunch gaps and determined the amount of clearing for different combinations of bunch gap duration and frequency, as shown in Fig. 6. We used our clearing electrode as a primary means of measuring the amount of clearing. When employing bunch gaps, a fraction of the trapped ions drift transversely out of the beam during the gaps and into the vacuum chamber walls. The remaining trapped ions travel longitudinally down the beam pipe towards our clearing electrode and are measured by the picoammeter. We applied a large enough voltage (28 V) to the clearing electrode to ensure maximum ion clearing. Thus we are measuring the amount of ions that remain trapped in the beam after clearing via bunch gaps.

We found that the amount of clearing depended only on the total time the beam was turned off, and was independent of the bunch gap duration and frequency [3]. This allows flexibility when implementing this scheme. Although this method is unattractive for ERLs due to issues with beam loading [1], it may be more feasible in other types of linacs.

Finally, we used an electrode to shake the beam sinusoidally and resonantly clear out any trapped ions. In ad-

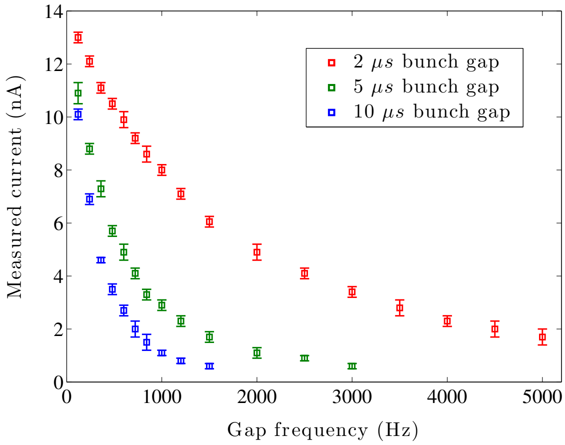

Figure 6: The number of trapped ions that reach the clearing electrode are reduced by increasing the frequency and duration of bunch gaps. The beam current was held fixed at 10 mA while taking this data.

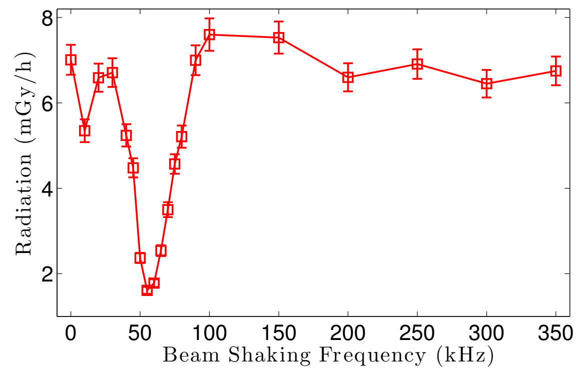

Figure 7: Shaking the beam at frequencies near the ion oscillation frequency eliminates the excess radiation caused by beam-ion interactions.

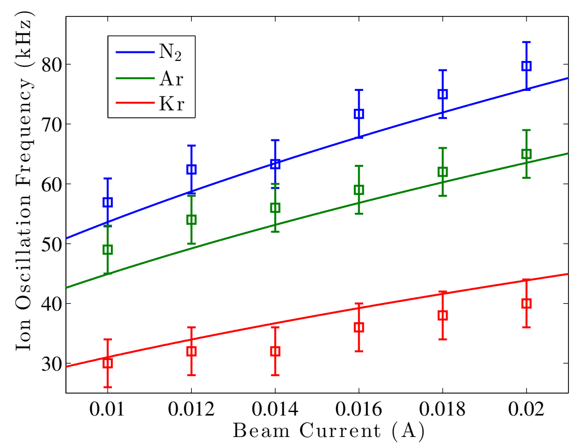

Figure 8: Resonance frequencies for various beam currents and ion species. The circles represent data points, while the lines indicate theoretical predictions [3].

dition to their longitudinal drifting, the ions oscillate transversely in the beam's potential well. One can imagine that the ion cloud and electron beam form a coupled oscillator. By driving the beam at the trapped ions' oscillation frequency, a resonance is induced that kicks the ions out of the center of the beam.

Because our clearing electrode was being used to shake the beam, we could not measure the residual ion density using the picoammeter and electrode. We were instead forced to rely solely on indirect measurements of beam-ion generated bremmstrahlung. When the ions are cleared from the center of the beam pipe at resonance, the excess radiation caused by beam-ion collisions should vanish. Thus, by measuring this radiation as a function of beam shaking frequency and noting the frequencies where the radiation vanishes, as shown in Fig. 7, we are able to determine the oscillation frequencies of the ions. By using a simple linear model, we have predicted that the ion oscillation frequency is given by [3]

$$\omega_i = \sqrt{\frac{2r_p c}{e}\frac{I}{A\sigma_b^2}} \tag{3}$$

where I is the beam current, A is the atomic mass of the trapped ion species, c is the speed of light and r_p is the classical proton radius. Our predicted values for the ion oscillation frequency agree very well with our measurements, as shown in Fig. 8. This gives us confidence that the ion oscillation frequency is a good metric to determine whether or not an accelerator will experience trapping, as mentioned earlier.

Beam shaking is attractive for large accelerators where clearing electrodes may be cost prohibitive. This is because the method only requires installing one or two electrodes to shake the beam, as opposed to installing many electrodes throughout the accelerator. The question remains whether or not the shaking amplitude is tolerable, as transversely shaking the beam can lead to undesirable effects such as emittance dilution. However, in practice, shaking appears to work for amplitudes that are much smaller than the transverse beam size, which may lessen these drawbacks.

In the future, we would like to continue these experiments with a new beam profile monitor capable of operating at high beam current [9]. This will allow us to determine transverse beam sizes and supplement our results. In addition, these measurements will be our first glimpse of any beam changes due to ions at high current in the photoinjector. We will then be able to compare our simulation results to actual experimental data for the first time.

ACKNOWLEDGMENTS

This work was supported by financial assistance from the U.S. Department of Energy (Grant No. DE-SC0012493) and the National Science Foundation (Award No. NSF-DMR 0807731). Travel grants to the conference were provided by the LINAC 2016 organizing committee and the Cornell physics department. The Cornell funding was provided by a generous donation from the family of the late Cornell professor, Albert Silverman.

REFERENCES

[1] G. H. Hoffstaetter and M. Liepe, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, *Detectors and Associated Equipment 5***57**, 205 (2006).

[2] G. H. Hoffstaetter and C. Spethmann, *Phys. Rev. ST Accel. Beams 1***1**, 014001 (2008).

[3] S. Full, *et al.*, *Phys. Rev. Accel. Beams 1*9, 034201 (2016)

[4] G. Parzen, "Electric fields of a uniformly charged elliptical beam", BNL/SNS Technical Note NO. 098 (2001)

[5] E. Keil, "Beam-beam dynamics", CERN Accelerator School, Rhodes, CERN 95-06 (1995), p. 539.

[6] L. Wang, Y. Cai, T. O. Raubenheimer and H. Fukuma, *Phys. Rev. ST Accel. Beams* **14**, 084401 (2011).

[7] A. Poncet, "Ion trapping, clearing, beam-ion interactions", CERN European Organization for Nuclear Research-Reports-CERN, 165 (1999).

[8] J.Feikes *et al.*, Observation of Ion Induced Effects and their Impact on the Performance of the MLS Electron Storage Ring, in *Proc. PAC 2009*, Vancouver (Canada).

[9] T. Moore *et al.*, *Phys. Rev. ST Accel. Beams* **17**, 022801 (2014).