TRAPPED ION EFFECTS AND MITIGATION DURING HIGH CURRENT OPERATION IN THE CORNELL DC PHOTOINJECTOR

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Abstract

The Cornell high intensity photoinjector reaches a new regime of linac beam parameters where high continuous-wave electron beam currents lead to ion trapping. Above 10 mA, we have observed beam trips that limit stable machine operation to approximately 10–15 minutes. By applying known ion clearing methods, the machine lifetime increases to at least 24 hours of continuous operation, suggesting that trapped ions are the most likely cause of the trips. In this paper we share some of our observations ion trapping in the photoinjector, as well as experimental tests of three common ion mitigation methods: clearing electrodes, beam shaking and bunch gaps.

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

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.

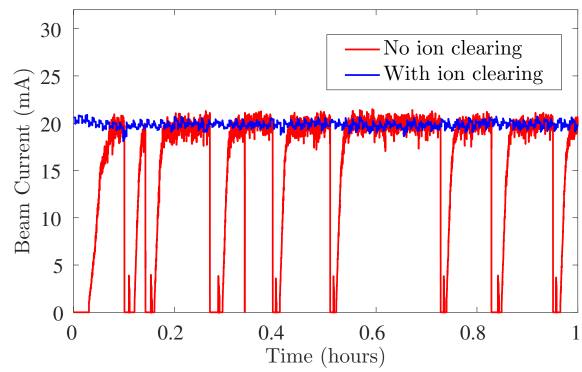

Figure 1: During certain running conditions, the photoinjector suffers from intermittent beam trips every 10–15 minutes. While employing ion clearing methods, we can obtain a stable beam current for at least 24 hours.

At this time we have yet to determine the exact mechanism of these trips, but we believe it involves arcing that is caused by charged particles. Although we know that charged particles routinely hit our cathode, and we have other evidence of light trapped ions in the beam, we have not yet determined what type of charged particle is responsible for the gun tripping off. It could be these same trapped ions, or it could be much heavier charged dust particles. Further tests in the future are being designed to better determine what type of particles they are.

ION MITIGATION EXPERIMENTS

Instead of measuring the effects of ions on the beam in order to determine the severity of ion trapping, we instead directly studied the trapped ions. We chose to do this because the Cornell photoinjector is a relatively short accelerator, so any changes in beam dynamics due to ions may be difficult to observe directly. Another contributing factor is that most traditional beam diagnostics are not viable in the photoinjector's parameter regime [3].

Instead we used two primary indicators of accumulated ions. The first was a direct measurement of the trapped ion density using our clearing electrode. By applying a DC voltage to the clearing electrode, the ions are drawn out of the center of the beam pipe, strike the clearing electrode and are measured by a picoammeter connected in series with the electrode. We also used our radiation monitors

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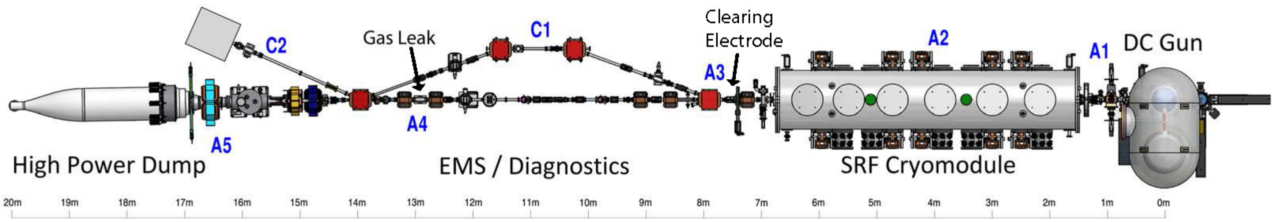

Figure 2: A schematic of the photoinjector that shows our experimental setup. Radiation measurements were taken using photomultiplier tubes at several locations between sections A3 and A4 (next to the beam pipe).

as a secondary, indirect way of observing the trapped ion density. The high power of the ERL photoinjector's beam generates large amounts of radiation, primarily created by beam losses and beam halo striking the beam pipe. When the beam current was increased above 10 mA after injecting gas into the beam pipe, measured radiation levels rose sharply above normal background levels. Before leaking gas, no such excess radition was previously observed in the 10–20 mA range, indicating that this extra radiation (presumably bremsstrahlung) was caused entirely by beam-gas interactions. All clearing methods significantly reduce this radiation, usually returning it to background levels.

Ion Clearing Electrodes

The photoinjector uses a specially created ion clearing electrode [3]. Its location in the beam line during the experiments is shown in Fig. 2. The top electrode was attached to a voltage supply, while the other was attached to ground. A picoammeter was attached in series with the voltage supply in order to measure the trapped ion current that was removed by the electrode.

During these experiments we leaked N_2 gas into the beam vacuum chamber to raise the background pressure from a nominal value of less than 1 nTorr to 117 nTorr. This ensured that we knew the dominant ion species present during the experiments. After they are created via collision ionization, the ions drift longitudinally towards beam size minima. This was taken into consideration when choosing beam optics for the experiment. For the following experiments we used a 5 MeV beam and varied the beam current from 1–20 mA by changing bunch charge.

We varied the applied voltage on the clearing electrode from between 0 V and 28 V to test its effectiveness at clearing ions. We looked at two signatures: the ion current striking the clearing electrode, and the background radiation observed by nearby radiation monitors. Our ion current data, taken for various beam currents between 5 mA and 20 mA, is shown in Fig. 3. The beam current was varied by changing bunch charge (from 5 pC to 12.5 pC) at a constant repetition rate of 1.3 GHz. Further discussion and analysis of this experiment can be found in a recent publication [3].

Bunch Gaps

While storage rings can create gaps simply by leaving a fraction of the ring empty at any given time, CW linacs

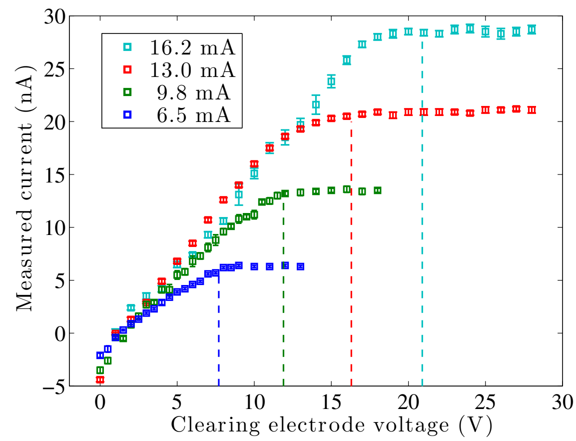

Figure 3: A picoammeter was used to measure the ion current striking the clearing electrode for different applied voltages. The vertical dotted lines mark the minimum voltage required for full ion clearing, as predicted using a simple model [3].

require the introduction of a short bunch gap every few milliseconds. 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. Data for an average beam current of 10 mA was taken for various bunch gap lengths and frequencies, and is shown in Fig. 4 and 5. The radiation data in Fig. 5 shows that the trapped ions are removed even without the clearing electrode turned on, confirming that the bunch gaps are the dominant clearing mechanism.

Beam Shaking

In addition 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

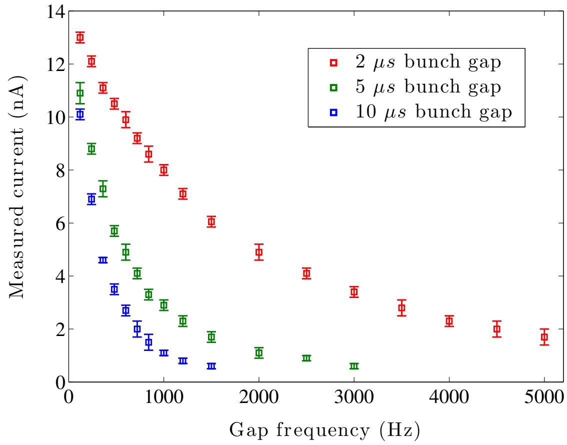

Figure 4: The number of trapped ions that reach the clearing electrode are reduced by increasing the frequency and duration of bunch gaps. The beam current was held fixed at 10 mA while taking this data.

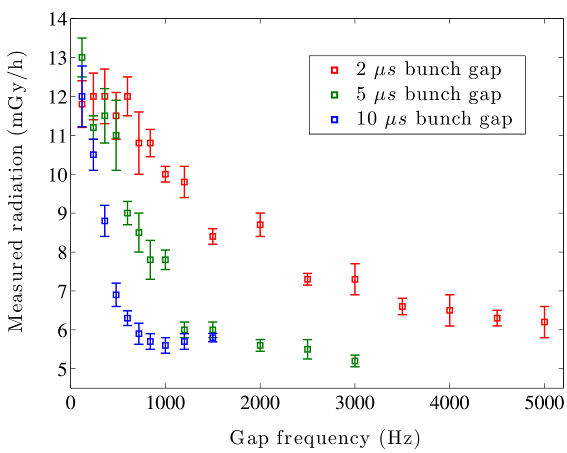

Figure 5: The number of trapped ions that reach the clearing electrode are reduced by increasing the frequency and duration of bunch gaps. The beam current was held fixed at 10 mA for this data, and the clearing electrode was turned off.

of the center of the beam. This characteristic frequency depends on the ion species, beam size, beam current.

During this experiment a sinusoidally varying voltage was applied to the clearing electrode in order to shake the beam vertically. Because our clearing electrode was being used to shake the beam, we could not measure the residual ion density using the picoammeter and clearing electrode. We were instead forced to rely solely on our indirect radiation measurements. When the ions are cleared from the center of the beam pipe at resonance, the excess radiation caused by beam-ion collisions vanishes, as shown in Fig. 6. Thus, by measuring this radiation as a function of beam shaking frequency and noting the frequencies where the radiation vanishes, we are able to determine the frequencies needed to clear any given ion species. This experiment was performed for several species of gas, as shown in Fig. 7, and the data agreed well with theoretical predictions of the ion oscillation frequency [3].

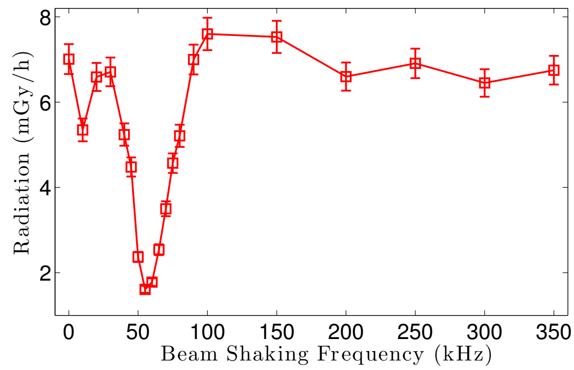

Figure 6: Shaking the beam at frequencies near the ion oscillation frequency eliminates the excess radiation caused by beam-ion interactions.

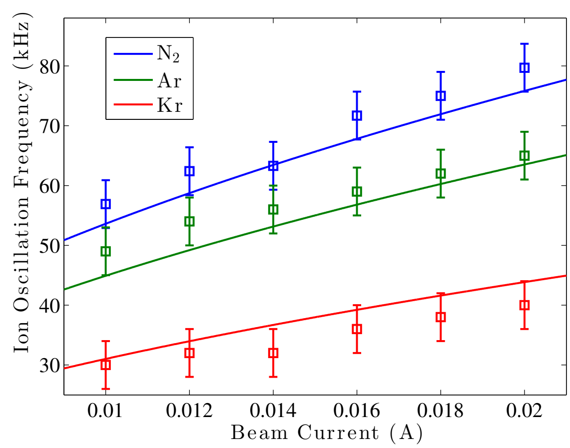

Figure 7: Resonance frequencies for various beam currents and ion species. The circles represent data points, while the lines indicate theoretical predictions [3].

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