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ION EFFECTS IN THE CORNELL ERL HIGH INTENSITY PHOTOINJECTOR*

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Abstract

We present our first measurements of trapped ions in the Cornell energy recovery linac (ERL) photoinjector. During high intensity operation, ions become trapped inside of the electric potential generated by the electron beam and oscillate transversely with a characteristic frequency. At high beam currents, electron beam-ion interactions result in excessive radiation, primarily due to beam losses and bremsstrahlung. However, by shaking the beam at the trapped ion's oscillation frequency, we are able to drive a resonance that severely reduces or eliminates this radiation. This both confirms the viability of beam shaking as an ion mitigation strategy inside high intensity injectors, and allows us to measure the trapped ion oscillation frequencies indirectly. Experimental data for a beam energy of 5 MeV, a bunch repetition rate of 1.3 GHz, and beam currents up to 20 mA, as well as simulations to describe our data and the beam shaking principle are presented.

INTRODUCTION

The residual gas in an accelerator beam vacuum chamber is readily ionized by collisions with an electron beam. The resulting ions can become trapped inside the beam at sufficiently high beam currents, such as those found in energy recovery linacs (ERLs). These trapped ions can cause a variety of undesirable effects including change of operational conditions due to charge neutralization, optical errors, beam halo, particle losses, or even beam instabilities [1]. In an ERL, where beam loss must be minimal and beam stability is paramount, these detrimental effects must be avoided.

In this paper, we will first model a trapped ion's transverse oscillations inside of the beam. We then illustrate how we have used beam shaking, a proven ion mitigation technique [2], to measure the trapped ion's oscillation frequency. Finally, we will present a full space charge simulation code that models the transverse dynamics of the trapped ions during beam shaking. We will show that our data agrees with scaling laws predicted by theory and simulations for beam current and ion mass, but not for beam size.

TRAPPED ION OSCILLATIONS

In order to calculate the frequency of trapped ion transverse oscillations inside an electron beam, we must first calculate the force acting on the ions. The Coulomb force generated by an infinitely long, rotationally symmetric Gaussian beam is given by [3]

$$F(r) = \frac{\lambda e^2}{2\pi\epsilon_0 r}\left[1 - exp\Big(-\frac{r^2}{2\sigma_b^2}\Big)\right] \tag{1}$$

where r is the distance from the center of the beam, λ is the number of electrons per unit length, and σ_b is the rms width of the electron beam. According to our simulations [4], the beam in the photoinjector is very nearly round for our experimental parameters, making this an appropriate approximation for our case. By linearizing this force, we are able to treat the ion's motion inside the beam as a simple harmonic oscillator. The equation of motion in this case is then

$$\frac{d^2r}{dt^2} + \omega_i^2 r = 0 \tag{2}$$

where ω_i is the oscillation frequency of the ions. Using the linearized form of (1), it follows that this oscillation frequency is given by [5]

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

where I is the beam current, A is the atomic mass of the ion species, and r_p is the classical proton radius. The experiments described below attempt to prove the scaling laws for beam current, ion mass and beam size predicted by this formula.

BEAM SHAKING EXPERIMENTS

Experimental Setup

Experiments to detect the presence of ions in the Cornell ERL high intensity photoinjector were recently performed. The photinjector is designed to operate with a beam energy of 4-10 MeV, a beam current of 100 mA, a bunch charge of 77 pC and a 1.3 GHz repetition rate. However, because of operational constraints at the time of this experiment, we used a 5 MeV beam and only varied the beam current from 10-20 mA.

Due to the beam's high power at full beam current operation, any traditional interceptive beam diagnostics such as viewscreens, slits or wire scanners will quickly melt (with timescales typically on the order μs). Additionally, due to the beam's low energy, we are unable to use synchrotron or diffraction radiation to take measurements. Although a fast beam profile monitor has recently been developed at Cornell for use in high intensity accelerators [6], it was not available for this experiment. Thus, we had no way of directly observing the various ion effects on the beam.

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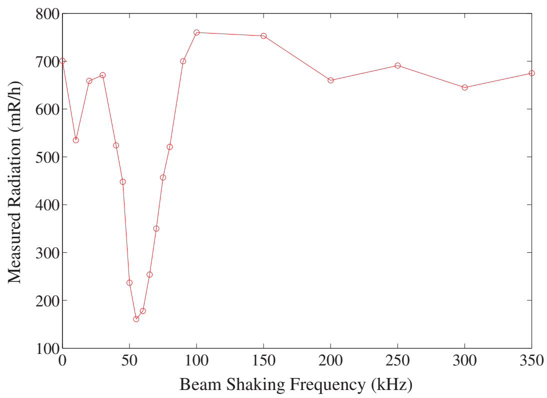

Figure 1: After leaking gas into the beam pipe, background radiation levels increase dramatically due to beam-gas collisions. Shaking the beam at frequencies near the trapped ion oscillation frequency eliminates this excess radiation.

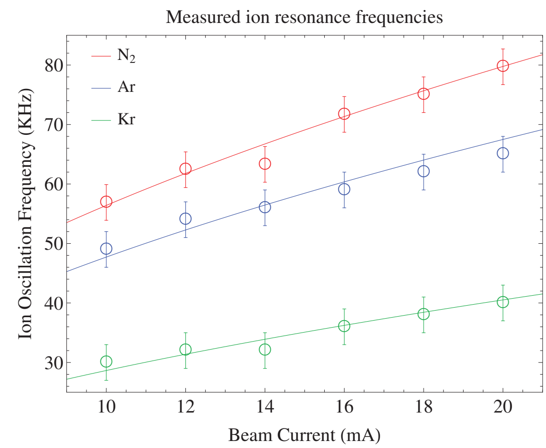

Figure 2: Resonance frequencies for various beam currents and ion species. The circles represent data points, while the lines indicate theoretical predictions given by equation (3).

Therefore, a new indirect technique was developed and employed to detect the presence of ions and measure their properties. Collisions between the electron beam and residual gas generate radiation, primarily due to bremsstrahlung and beam losses. This radiation can easily be measured using photomultiplier tubes. By using an electrode to shake the beam at the trapped ion oscillation frequency given by equation (3), one can induce a resonance that kicks the trapped ions outside of the center of the beam pipe. Therefore, when the ions are cleared from the center of the beam pipe, 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, we are able to determine the oscillation frequencies of the ions. An example of a typical measurement is shown in Fig. 1.

The experiment was performed in an approximately 8 m long straight section immediately after the beam exited the final accelerating cavity. To first demonstrate the measurement principle, a 3m section of beam pipe, starting approximately 5 m from the exit of the accelerating cavity, was injected with either N_2, Ar or Kr gas. The pressure in the beam pipe was increased to approximately 100 ntorr, as compared to typical values of approximately 1-10 ntorr measured during normal operation. When the beam current was increased above 10 mA after gas injection measured radiation levels rose sharply above normal background levels. Before leaking gas, no such excess radiation was previously observed in the 10-20 mA range, indicating that this extra radiation was caused entirely by beam-gas interactions.

An electrode, essentially in the form of a parallel plate capacitor, was used to shake the beam vertically. It was placed approximately 1 m from the exit of the accelerating cavity, and care was taken to ensure that it did not clear the ions directly. A sinusoidally time varying voltage was applied to the electrode using a function generator and high voltage amplifier. Oscillation frequencies were predicted to be in the 10-100 KHz range, so this is the primary range over which the experiment was performed. During the course of the experiment, the maximum voltage applied to the clearing electrode was adjusted as needed to completely clear the radiation at resonance, but the shaking amplitude never exceeded 0.5 mm for an approximately 2 mm beam size.

Experimental Results

In the course of our experiments we attempted to confirm the three scaling laws predicted by equation (3): resonance frequency as a function of beam current, ion mass, and beam size. Because the resonance peaks were quite broad, a polynomial fitting algorithm was used to fit the data, and the maximum value was taken as the resonance frequency. General Particle Tracker (GPT), a 3-D space charge simulation code found to be in excellent agreement with measurements taken at low beam current [4], was used to determine the rms beam size σ_b during our experiments. However, given our lack of actual beam size measurements during this experiment, and the fact that GPT has not been experimentally verified in this beam parameter range, the beam size can also be treated as a fit parameter for our data.

Figure 2 shows the measured resonance frequencies for beam currents over the range 10-20 mA, and for three different gas species. Error bars for the data points are typically $\pm$ 3 KHz, and are due to systematic shifts in resonance frequency due to changing the electrode voltage, as well as statistical fluctuations . GPT predicted a round beam size of 2 mm in the region of interest, and this was used to obtain the curves predicted by equation (3) for Nitrogen and Argon. However, the curve for Krypton required a beam size of 2.3 mm to agree with the data. Regardless, here it is shown that the resonance frequency scales as predicted with beam current and ion mass. This indicates that the resonance frequency required to clear the ions is indeed the ion oscillation frequency.

However, the resonance frequency did not scale with beam size, as predicted by theory and simulation (described below). Changing the beam size by over a factor of 2, using both a

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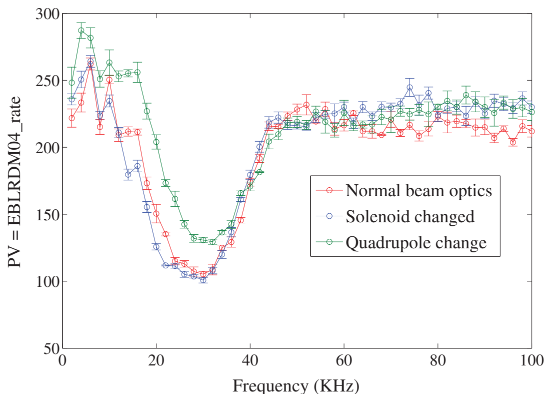

Figure 3: Radiation levels for various beam shaking frequencies. Changing the beam size by over a factor of 2 does not shift the resonance frequency, in disagreement with theory and simulation.

solenoid and quadrupole magnet, resulted in no observable change in resonance frequency, as shown in Fig. 3. This suggests that the transverse dynamics of the ions alone are insufficient for describing ion clearing via beam shaking.

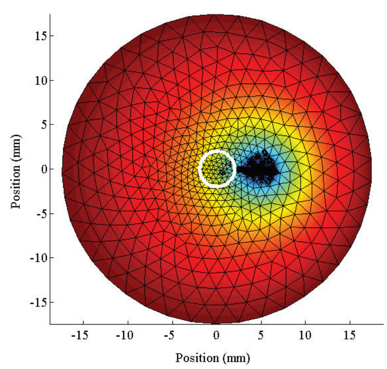

Figure 4: Simulation of the transverse ion distribution. Shaking the beam (white circle) at resonance causes the normally trapped ions (dark blue dots) to escape from the center of the beam pipe.

TRANSVERSE ION SIMULATIONS

In order to better understand the transverse dynamics of the trapped ions we have developed a 2-D space charge simulation code. The code solves the 2-D Poisson equation using a finite element method. While we used the Poisson solver to calculate the field generated by the ions, we opted to use a known analytical expression [3] for the field generated by a round Gaussian electron beam (taking into account image charges of the vacuum beam pipe chamber). The ions are generated slowly, according to the creation times calculated using the collision ionization cross section between a relativistic electron and a given ion species [1]. They are given no initial velocity, and are removed when they hit the wall of the beam pipe.

Figure 4 shows a screenshot of the simulation, and Fig. 5 illustrates the equilibrium ion density achieved both with and without beam shaking. Although it does not completely eliminate the trapped ions, our simulation shows that shaking the beam at resonance significantly reduces the equilibrium ion density. The simulation agrees with our theoretically predicted scaling laws for all three parameters: beam current, ion mass and beam size. This is in direct conflict with our experimental results, again suggesting that the transverse dynamics alone are inadequate for describing ion effects in the photoinjector.

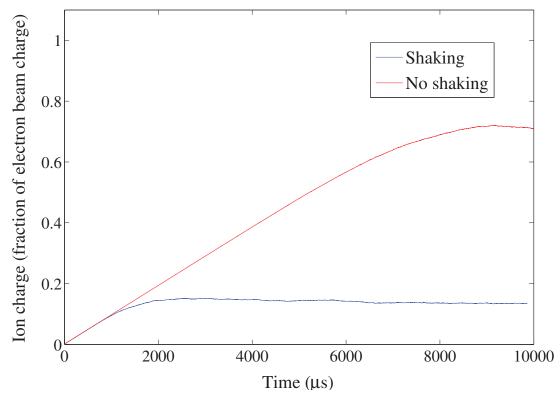

Figure 5: Equilibrium ion density as a fraction of electron beam charge. Shaking the beam results in a significant reduction of the trapped ion density.

FUTURE WORK

In the future, we plan to expand our ion simulations to include the longitudinal motion of ions, with the hopes that it will more accurately explain our data. A new fast beam profile monitor, designed for use in high intensity accelerators, should allow us to further enhance our data with actual beam size measurements. Our studies of the ions and their mitigation techniques are of critical importance to the future high intensity electron machines.

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