TRAPPING BACKSTREAMING IONS FROM AN X-RAY CONVERTER USING AN INDUCTIVE CELL

J. McCarrick, Y.-J. Chen, T. L. Houck, B. R. Poole
Lawrence Livermore National Laboratory, Livermore, California 94550 USA

Abstract

High current electron beams have been used as x-ray drivers for x-ray radiography. Typically, several thousand amperes of electron beam current at 20 MeV is focused to a millimeter spot size on a x-ray converter. Within a single pulse, the heating of the target by the electron beam will lead to rapid desorption of surface contaminants. The space charge potential of the electron beam will pull ions out of this plasma layer upstream into the beam. These backstreaming ions can act as a focusing lens which cause the beam to be overfocused at a waist upstream. The final beam spot size on the target would then be larger than intended, and the x-ray radiography resolution is reduced. We have designed a self-biased ion trap for the Experimental Test Accelerator (ETA-II) beam by using an Advanced Test Accelerator (ATA) inductive cell to prevent the backstreaming ions from moving upstream and forming a long ion focusing channel. We have studied the effects of this type of ion trap on the final focusing of the electron beam with the ETA-II beam parameters. Simulation results will be presented.

1 INTRODUCTION AND MOTIVATION

The use of electron beams in high-resolution x-ray radiography requires that a high-current beam be focused on a millimeter-sized spot for the duration of the beam pulse. The energy deposited in a small volume of target material is enough to generate a plasma of heavy target material, along with any lighter species that contaminated the target surface, such as hydrogen or carbon. Once these light ions are present, they are rapidly accelerated upstream in the strong axial electric field produced by the beam at the metallic surface of the target, in a process called "backstreaming." The presence of this excess positive charge in the beam upsets the balance of electric repulsive forces and magnetic pinching forces which determine the radius of the beam. The radial electric force is reduced, causing the magnetic forces to pinch the beam to a premature focus and then expand well past the desired spot size at the target. This reduces the achievable resolution of the radiographic image and is an undesirable effect.

Only a small quantity of positive charge is required to have an impact on the target spot size. We can compare the extraction of ions from the target plasma to the operation of an ion diode under the conditions of space-charge limited (SCL) flow. The accelerating potential is that of the beam with respect to the grounded metallic target, which has the well-known form

$$\phi_o = 30I\left(1 + 2\,ln\frac{r_w}{r_b}\right) \tag{1}$$

where r_w is the beampipe radius, r_b is the beam radius, and I is the beam current. For the ETA-II accelerator with a millimeter spot radius, 3 cm beampipe radius, and 2 kA of beam current, this potential is 468 kV. Assuming that the extracted ion current satisfies the Child Law for SCL conditions, and neglecting the small initial thermal energy of the ions compared to the beam potential, the neutralization fraction f of ion space charge to beam space charge is given by

$$f = \frac{r_b^2\left(1+2\,ln\frac{r_w}{r_b}\right)}{9d_{eff}} \tag{2}$$

where d_{eff} is the effective diode gap. Consideration of Poisson's equation in the vicinity of the target shows the potential has the approximate form [1]

$$\phi(r=0,z) \approx \phi_o\left(1-e^{-z/d}\right) \tag{3}$$

where the scale length d is approximately the beam diameter. Choosing $d_{eff} \sim 3d$ as the total acceleration gap in the ion-diode model gives a neutralization factor of 2.5%, corresponding to a number density of $\sim 10^{17}$ m^{-3}. Thus, a 25 cm channel of hydrogen ions requires a mere 2.5×10^{11} atoms, easily supplied by surface contaminants. At ETA-II parameters the asymptotic velocity for protons is $\sim 9.5 \times 10^6$ m/s, so that this channel can form in about 25 ns, about the mid-point of a pulse.

The effect of such an ion channel on the beam radius can be estimated by a simplified form of the envelope equation:

$$\frac{d^2R}{dz^2} = \frac{\varepsilon^2}{R^3} + \frac{k}{R}\left(\frac{1}{\gamma^2} - f\right) \quad (4)$$

where R=R(z) is the radius of the beam, ε is the un-normalized beam emittance, γ is the usual relativistic factor, f is the neutralization fraction, and the constant k is γ^2 times the generalized perveance of the beam. A comparison of beam envelope with and without the ion channel is shown in figure 1. This behavior is also seen in self-consistent PIC simulations which capture other effects such as emittance growth [2], and has been seen experimentally based on recent data from the ETA-II accelerator [3].

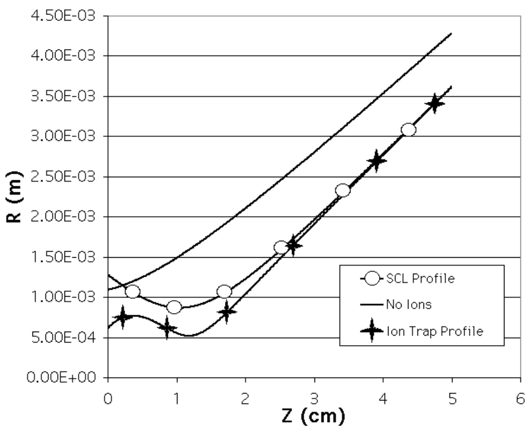

Figure 1. Beam envelope in the presence of no ions, ions with a SCL profile, and ions with the inductive trap profile.

2 APPLICATION OF AN INDUCTIVE ION TRAP

To preserve the minimum spot size of the beam throughout the pulse, it is desirable to either prevent ion emission altogether, or at least confine the ions to a sufficiently small channel such that the net effect on the beam is small. It is not feasible to bias the target with an external DC voltage due to the magnitude of the beam potential; however, it is possible to use the beam current as a "self-biasing" source. One method involves using an induction cell where the accelerating gap (or "decelerating gap", in this case) is formed between the target material and an annular electrode placed slightly upstream in the beampipe. Such a cell has been designed for ETA-II, based on an induction cell used in the Advanced Test Accelerator (ATA) [4]. A schematic of the cell is shown in figure 2.

During a beam pulse, the large inductance of the core will prevent the return current of the beam from traveling the preferred DC path A+B, forcing it instead through the shunt resistor in path A+C and causing the voltage $I_{beam}R$ to appear across the gap. This potential drop serves a dual purpose. Firstly, for a sufficiently high value of R, the sum of the cell potential and the beam potential will form a well, trapping ions in a channel of length the order of the gap size. Secondly, as charge builds up in the channel, the net electric field at the surface of the target will decrease and lower the rate of subsequent ion emission.

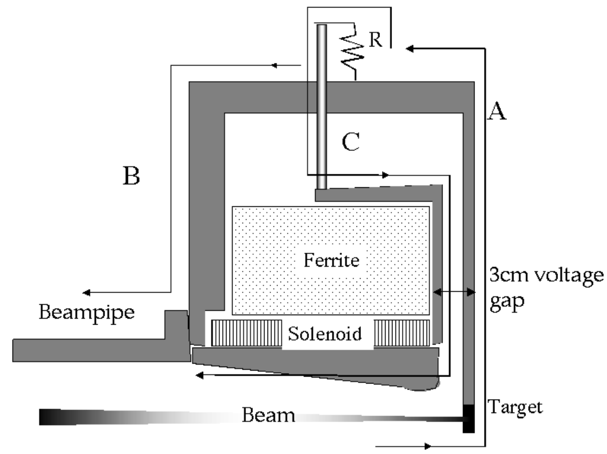

Figure 2. Schematic of Inductive-Cell Ion Trap.

There are difficulties associated with such a design. The potential provided by the cell must be of the same order as the beam potential, and the gap size must be kept as small as possible to minimize ion channel length. Such gradients could cause the electric fields in the gap to exceed the breakdown voltage. In addition, expansion of the plasma of target material could cause conducting plasma to fill the gap, causing a short. The present design has a gap size of 3 cm and a maximum desired voltage of 450 kV, producing electric fields of magnitude 150 kV/cm. By placing high-gradient insulator in the portions of the gap away from the beam, these parameters should be achievable [5].

3 NUMERICAL RESULTS

During the flattop of the current pulse, the inductive voltage across the gap should remain approximately constant, allowing it be modeled as a simple DC voltage. PIC simulations have been run on space-charge limited proton emission from the target in a 2 kA, 1mm spot radius ETA-II beam, with the ion trap operating at 400 kV. Note this value is less than the "bare" beam potential because of the ameliorating effect of the ion space charge which builds up in front of the target.

The simulation is run for 20 ns, allowing enough time for the ions to complete a full round-trip in the potential well. To reduce computation time, the electron beam particles are fixed in time, so that the effect of the ions on the beam is not simulated. The geometry along with the distribution of ions at 5ns and 20ns is shown in figure 3; note almost all of the ions have collected within the gap region, with only a small stream managing to escape the trap. Figure 4 shows the axial positions of all 50,000 particles in the simulation at 20ns; 94% of the particles are trapped within about 2.5 cm of the target.

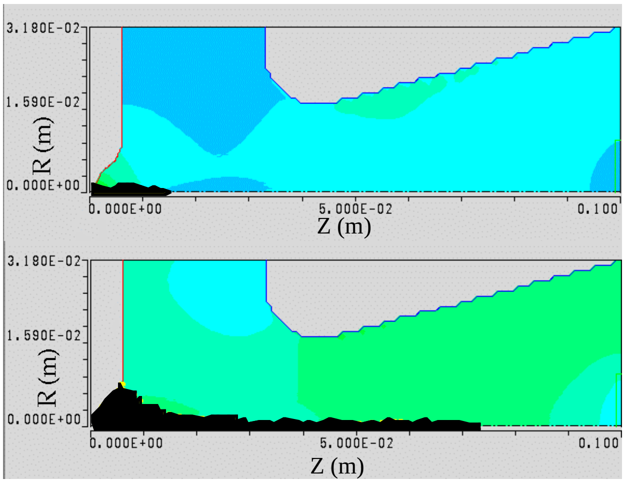

Figure 3. Inductive trap simulation geometry, showing ion distribution at 5ns (top) and 20ns (bottom) after onset of emission.

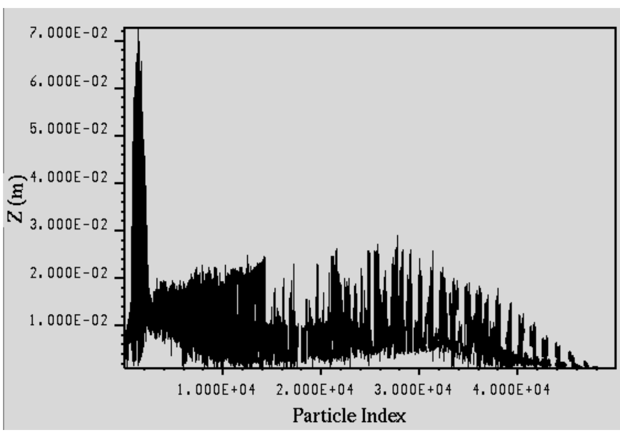

Figure 4. Axial coordinate of each particle at 20ns, showing 2.5cm trapping length.

However, figure 5 shows that ion charge density in the gap is much higher than the unconfined SCL value. The electron beam charge density is about 2 C/m^3, meaning that the neutralization "fraction" is in fact much greater than unity. Using a smooth approximation to this profile in an envelope-equation calculation yields the third curve in figure 1, showing confined oscillations of the beam envelope below the nominal profile. While these results suggest that such a tailored profile of high-density ions could prevent the growth of the beam spot, the varying divergence angle of the beam as it enters the target is not desirable for radiographic purposes. In addition, such constant-emittance envelope calculations are questionable in the presence of beam oscillations, and complete self-consistent PIC simulations including the electron beam are required.

4 CONCLUSIONS

The presence of backstreaming ions from target material in high-current electron accelerators causes undesirable growth in beam size, reducing the achievable resolution of radiographic images. We have examined the use of an inductive ion trap to confine the length of the backstreaming ion channel. PIC simulations show that an ion trap based on an ATA induction cell will confine 94% of emitted protons in the ETA-II accelerator. However, the resulting density of ions in the confinement region is much higher than the unconfined value. Preliminary envelope calculations show that this density profile confines the beam envelope to oscillations below the nominal beam radius. However, further PIC simulations which include the electron beam self-consistently must be performed to confirm this behavior. In addition, the radiographic quality of such an oscillating beam may not be acceptable.

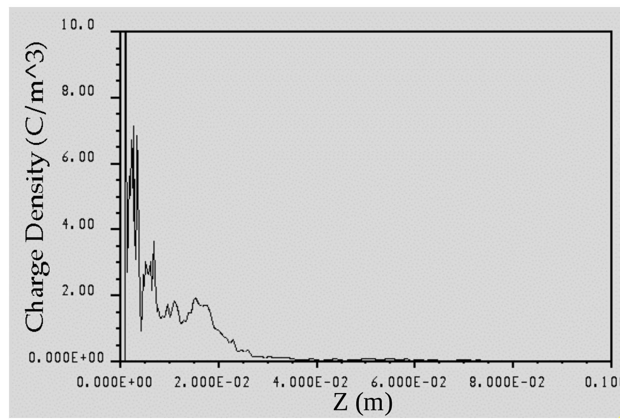

Figure 5. Ion charge density along beam axis. Beam density is 2.12 C/m^3

5 ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48

6 REFERENCES

[1] Y.-J. Chen, et. al., "Controlling Backstreaming Ions from X-ray Converter Targets with Time Varying Final Focusing Solenoidal Lens and Beam Energy Variation," this conference.

[2] P. Rambo, et. al., "EM-PIC Simulations of e-Beam Interaction with Field Emitted Ions from Bremsstrahlung Target," this conference.

[3] S. Sampayan, et. al., "Experimental Investigation of Beam Optics Issues at the Bremsstrahlung Converters for Radiographic Applications," this conference.

[4] S. Humphries. "Principles of Charged Particle Acceleration." Wiley Interscience, New York, NY 1986 p. 289

[5] S. Sampayan, et. al., "High Performance Insulator Structures for Accelerator Applications," Proceedings 1997 Particle Accelerator Conference, (IEEE), New York, NY (1997)