

CONTROLLING BACKSTREAMING IONS FROM X-RAY CONVERTER TARGETS WITH TIME VARYING FINAL FOCUSING SOLENOIDAL LENS AND BEAM ENERGY VARIATION

Yu-Jiuan Chen, George J. Caporaso, Arthur C. Paul
Lawrence Livermore National Laboratory, Livermore, California 94550 USA

Abstract

Backstreaming ions emitted from an x-ray converter hit by a tightly focused intense electron beam can form an ion focusing channel and over-focus the electron beam. As the ions move upstream in time, the net focusing strength increases. The final beam spot size on the target would then change in time and typically be larger than intended. We have developed a model to estimate the backstreaming ions' neutralization factor in a potential sheath near the target surface and away from the sheath. Performance of high resolution x-ray radiography facilities requires high current electron beams to be focused to a millimeter spot size on an x-ray converter through out the entire current pulse. We have studied the possibility of maintaining a constant final spot size for the entire pulse by using either a time varying final focusing solenoid field or beam energy variation to compensate the time varying ion focusing effects.

1 INTRODUCTION

Performance of high resolution x-ray radiography facilities requires several kiloamperes of electron beams to be focused to a millimeter spot size on an x-ray converter target through out the entire current pulse. D. Welch claimed that it would be difficult to maintain the tight focus of electron beams on a converter during the entire pulse length because of the existence of backstreaming ions[1]. He stated that a high density electron beam can heat the target surface up to 400°C and lead to rapid desorption of surface contaminants within a few nanoseconds. These desorbed gases form a plasma layer on the converter surface. Meanwhile, the charge redistribution on the target after the electron beam hits the surface creates a large potential drop and an ion diode on the target surface. The space charge field of the electron beam would pull ions out of the plasma layer into the beam. These ions trapped by the electron beam move upstream, form an ion focusing channel and over-focus the electron beam. As the ions move upstream in time, the net focusing strength increases. The final beam spot size on the target would then change in time and typically be larger than intended. The potential backstreaming ions are protons and oxygen from the water vapor on the target surface, carbon and tantalum or tungsten from the target itself. The lighter ions have a greater potential to destroy electron beam's final focus since they would travel upstream at a higher speed and form a longer ion channel. The ions from the target material itself are usually too heavy to have a large effect on the beam spot size during the beam pulse time. On the other hand, the backstreaming protons would have

the worst effects on the electron beam's final focusing if these backstreaming protons do exist. Single-pulse experiments at various radiography facilities and laboratories [2-4] (except at CESTA's PIVAIR linac [5]) have not yet been able to provide a strong evidence of existence of backstreaming protons. However, The simulated double-pulse experiments on ETA-II indicated a different backstreaming ion emission mechanism [4]. The space charge field of the electron beam would pull ions out of a pre-existing target plasma generated by the preceding pulse. The ETA-II results also indicated that the backstreaming ion emission follow a the Child-Langmuir law. In this paper, we study the possibility of maintaining a constant final spot size for an entire current pulse by using either a time varying final focusing solenoidal field or beam energy variation to compensate the time varying ion focusing effects. We have found that the required time varying rates for both the solenoidal field and the energy variation are too large to be feasible.

2 MODEL

To model the backstreaming ion effects consistently with the beam and target geometry, we should study this problem with particle simulations. Typically, the electron beam size at a converter target is about 1 mm, and the beam pipe wall radius is about several centimeters. The backstreaming ion channel can vary from a few millimeters at the beginning of an electron beam pulse to a meter at the tail of a pulse. The simulation volume has to be large enough to include the pipe wall and the entire ion channel in order to model the space charge potential and the backstreaming ion focusing effect properly. At the same time, the simulation mesh size has to be small enough to model the backstreaming ion emission in a millimeter size A-K gap. These requirements make examining time varying focusing field and energy with particle simulations very time consuming. Therefore, we study the feasibility of controlling the electron beam's spot size with a time varying final focusing solenoidal field or beam energy variation by solving the envelope equation given as

$$R'' + \frac{k_{co}^2}{4\gamma^2\beta^2} R - \frac{2I}{\gamma\beta^3 I_o R} \{1 - f_i(z) - f_T(z) - \beta^2\} - \frac{E^2}{R^3} = 0 \quad (1)$$

where R and E are the beam's edge radius and edge emittance, f_i is the backstreaming ions' charge neutralization factor, and f_T is the foil focusing effect provided by the x-ray converter. In our model, all backstreaming ions are trapped within the electron beam.

Both the electron density and the ion density are constant in radial positions within the beam radius.

2.1 Beam Potential near a Target

Let the x-ray converter target locates at $z = z_T$. At a location far away from the converter surface ($z_T - z \gg a$), the radial scale length of the beam is much less the longitudinal scale length, where a is the beam radius at the z location. Let the wall potential be zero. The space charge suppressed potential inside the beam at this location is well known and given by

$$\phi(r, z_T - z \gg a) = \phi_o + \frac{I}{\beta c a^2} r^2, \quad (2)$$

where

$$\phi_o = -\frac{I}{\beta c} \left(1 + 2 \ln \frac{b}{a} \right), \quad (3)$$

and b is the wall radius. Let's assume that the beam potential is separable in r and z such that

$$\Phi(r, z) \approx \phi(r, z_T - z \gg a) \psi(z). \quad (4)$$

Substituting Eqs. (2) and (4) into Poisson equation, we find that the beam potential is given in the form

$$\phi(r, z) \approx \phi(r, z_T - z \gg a) (1 - e^{-(z_T - z)/\lambda}), \quad (5)$$

where

$$\lambda = \frac{a}{2} \sqrt{1 + 2 \ln \frac{b}{a}} \quad (6)$$

is the scale length of the potential sheath at the target. Note that the sheath thickness is always about several times of the beam radius regardless of the wall radius since λ varies from $0.5a$ to $1.49a$ as the b/a value varies from 1 to 50. The radial, electrostatic space-charge field is given by

$$E_r(r, z) = -\frac{2I}{\beta c r} (1 - e^{-(z_T - z)/\lambda}). \quad (7)$$

Comparing Eq. (1) with Eq. (7), it is obvious that the focusing effect provided by the x-ray converter is given by

$$f_T(z) = e^{-(z_T - z)/\lambda}. \quad (8)$$

By integrate Eq. (8) over z , we find that the target's effective focusing length is λ , and the effective foil focusing factor is 1. For the case that the wall radius is 5 cm and the beam radius is 0.5 mm, the effective foil focusing length is 0.8 mm. For simplicity, we ignore the target's focusing effects.

2.2 Backstreaming Ions

According to Eq. (5), the potential drop over the distance $d=3\lambda$ from the target is 95% of ϕ_o . An ion diode is formed across this potential drop. To estimate the amount of an ion current could be extracted from this diode, we assume that the ion emission is space charge

limited. We further assume the extracted ion current follows the planar Child-Langmuir law,

$$J_i = \frac{I}{9\pi} \sqrt{\frac{2q}{M} \frac{|\phi_o|^{3/2}}{d^2}}, \quad (9)$$

where q and M is ion's charge and mass, respectively. After leaving the A-K gap, i.e., $z < z_T - d$, ions move backstream with a velocity $v_i = \sqrt{2q|\phi_o|/M}$. From Eq. (3), it is obvious that the length of the ion channel would depend on beam current, spot size, wall radius and ion species. We find that the backstreaming ions' charge neutralization factor outside the A-K gap is given by

$$f_i \approx \frac{4}{9} \left(\frac{\lambda}{d} \right)^2 \approx 5\% \quad (10)$$

as $z > z_T - v_i t$. A 5% charge neutralization factor has been observed in the PIC simulations for the backstreaming protons [6]. Note that the backstreaming ions' charge neutralization factor within an ion channel is independent of beam parameters, wall radius and ion types. A re-entry (beer-can) target configuration would help to reduce the spot size blow-up rate by reducing the beam space-charge potential, hence the length of the ion channel. However, the ion charge neutralization factor remain the same. Caporaso has shown that the backstreaming ions' charge neutralization factor is 6.4% in a beer-can model that both the electron beam and the ion beam fill a beampipe [7].

The ions' neutralization factor varies along the z location within the A-K gap region and approaches infinity. The neutralization factor averaged over the gap is

$$f_i \approx \frac{4}{3} \left(\frac{\lambda}{d} \right)^2 \approx 14.8\%. \quad (11)$$

For the case that the wall radius is 5 cm and the beam radius is 0.5 mm, the A-K gap distance d is only 2.4 mm. For a 6 kA beam, backstreaming protons would travel 1.9 cm, that is much longer than the A-K gap distance, within 1 ns. For simplicity, we assume the ion neutralization factor constant (5%) for the entire ion channel.

3 TIME VARYING SOLENOID FIELD

A potential way to compensate for the increasing backstreaming ions' focusing strength is to reduce the final focal lens strength in time. For the Advanced Hydrotest Facility's (AHF) [8] 6 kA, 20 MeV beams with 1200π mm-mr normalized edge emittance, we use a solenoid focusing field of 6350G to focus beams at a waist with a radius of 0.5 mm. Figure 1(a) shows that we need at lease to reduce the focusing field at the rate of 30 G/ns to compensate the backstreaming protons' focusing effects. We have found that varying the focusing lens' strength is not effective once the protons have traveled upstream and passed the final lens ($t > 35$ ns). Figure 1(b) indicates that at least 14 G/ns is needed to maintain the spot size for backstreaming carbon. For both cases, the required reduction rate in the final lens' strength would be hard to achieve due to the pulse power limitation.

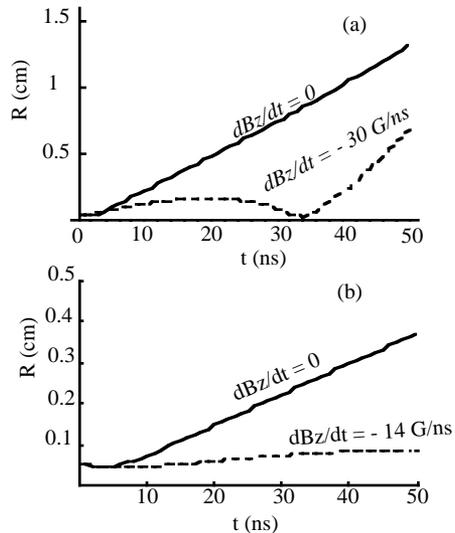


Fig.1 The time varying beam radius on a target with backstreaming (a) protons and (b) carbons and a constant (solid) and time reducing (dashed) focusing field.

4 TIME VARYING BEAM ENERGY

We now examine the feasibility of maintaining the beam spot size on a target by varying the beam energy. For simplicity, we assume that the beam energy increases linearly within a pulse, and there is no envelope variation in the pulse. For the same AHF beam, Fig. 3(a) and (b) show the compensation results for the focusing effects of backstreaming protons and carbons, respectively. Even with 150 kV/ns of energy variation rate, we can only maintain the beam spot size to a small value for about 35 ns for the backstreaming proton case (see Fig. 2(a)). For the backstreaming carbons, by varying beam energy at the rate of 40 kV/ns, we can successfully maintain the beam spot size constant (see Fig. 2(b)). For a 50 ns long, 20 MeV beam, this would require a 10% energy variation through a pulse. It would be difficult to transport a beam with such a large energy variation to the final focus region without any envelope variation.

5 CONCLUSIONS

We have developed a model to estimate the neutralization factor of backstreaming ions emitted from an x-ray converter hit by a tightly focused intense electron beam. We have found that the neutralization factor is always 5% regardless of the ion mass and charge, the electron current, beam radius and the wall radius. We have also studied two schemes, reducing the final focus lens' strength in time and increasing beam energy in time, to compensate for the increase in focusing produced by these ions. We have found that neither methods are effective in maintaining a small beam spot size if the backstreaming ions are protons. In the case of backstreaming carbons, both methods can maintain a small beam spot size. However,

the required solenoid field variation rate and the energy variation rate are quite large.

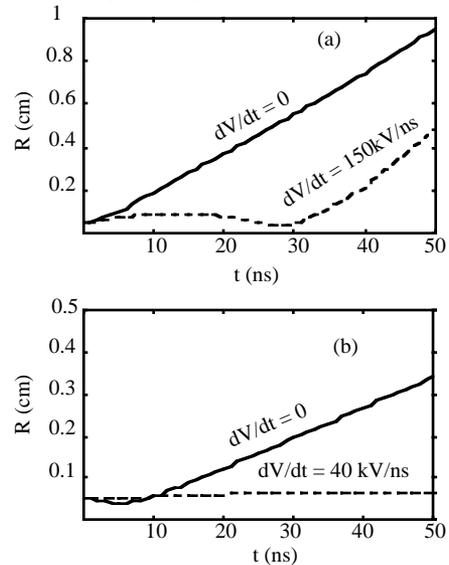


Fig. 2 The time varying beam radius on a target with backstreaming (a) protons and (b) carbons for a constant (solid) and for a time varying beam energy (dashed).

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