ELECTRON BEAM SPOT SIZE STABILIZATION FOR RADIOGRAPHIC APPLICATION

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1. Introduction

The stable propagation of a relativistic electron beam in vacuum requires balance between the electric and magnetic forces. For a charge unneutralized relativistic electron beam, the difference between its Coulomb repulsive force (radially outward) and its self magnetic force (radially inward) scales as $1/\gamma^2$, where γ is the relativistic factor. The Coulomb force always dominates slightly so the beam will diverge as it propagates in vacuum. However, if there is fractional charge and/or current neutralization of the electron beam, the dynamics of propagation can be quite different. For example, if the fractional charge neutralization is η, the net force acting on the beam scales ($\eta - 1/\gamma^2$). For a highly relativistic electron beam, a small fractional charge neutralization can cause the magnetic force to dominate, resulting in radial pinching and the subsequent divergence of the beam after the pinch point. In x-ray radiography, the electron beam generates x-rays via bremsstrahlung process in a converter target. For high dose radiography, the energy density of the electron beam is sufficiently high to cause vaporization of the target material, resulting in plasma plumes [1]. The plasma plumes are efficient sources of ions, which are drawn toward the potential well near the axis of the electron beam. Note that the formation of the potential well is due to the space charge of the electron beam. Such an ion column provides fractional neutralization of the electron beam and thus causes the beam to pinch radially inward. Furthermore, as the ion column expands in the upstream direction, the location of the pinch point also moves in the same direction. The divergence of the beam immediately after the pinch causes the beam spot on the target to grow. The temporally increasing radiographic spot size is detrimental to high-resolution radiography. This dynamical phenomenon of the electron beam has been predicted in computer simulation [2] and confirmed by experiments at the Integrated Test Stand (ITS) [3] at Los Alamos National Laboratory.

There has been considerable experimental effort to minimize and stabilize the beam spot size for ITS and the DARHT (Dual Axis Radiographic Hydro Test) facility which is currently under construction. In this paper, we present the idea of self-biasing the target to establish an electric field to control the ion column. The potential benefits of this method are its simplicity and non-intrusiveness in its implementation. For a given target material, target thickness can be chosen with respect to the electron beam energy so that the target can be charged either positive, negative, or null resulting from the balance between charge deposition and knock-on

processes due to the incident electron beam. In the case where the target is charged negatively, an electric field will develop to attract the ions toward the target foil. This can be an effective method to control the ion column, leading to the stabilization of the beam spot size.

2. Calculation of the Self Bias Potential

When an electron beam is incident on a target, a certain fraction of the charge will be deposited in the target in addition to the forward transmitted and the backward reflected components. The partition among the three components depends on beam energy, target material (atomic weight and mass density) and thickness (path length). In addition, there are low energy knock-on electrons coming off from the surfaces. Through the variation of target thickness, one can achieve a charged state of the target ranging from positive to negative depending on the balance between the charge carried away by knock-ons and the charge deposited by the electron beam. We have performed Monte Carlo electron transport calculations of the ITS electron beam and the DARHT electron beam in targets of different materials and thickness. The beam parameters for the ITS beam are 5.5 MeV, 3.8 kA, and 60 ns pulse length. To estimate the charge buildup and the resulting electric field in its vicinity, we will take the ITS 1.5-mm-thick copper target as a case study. From our Monte Carlo calculation, the fractional charge deposited on the target is 0.241. During the 10 ns rise of the ITS electron beam pulse, the electron energy is lower and fractional charge deposition will be higher. From a rough estimate of the charge buildup on the target, we find that after approximately 3.5 ns into the rise of the electron beam pulse, an electric potential of 400 kV would be developed. At that time, excess charge needs to be drained from the target to maintain this desirable bias potential for the configuration considered in the following section.

3. Electromagnetic Particle-In-Cell Simulation of Self Bias of Targets

We have carried out computer simulations using the two-dimensional fully electromagnetic code MERLIN to investigate the self-biasing phenomenon. The ITS electron beam (5.5 MeV, 3.8 kA) is injected from the left boundary through a radial collimator of 0.5 cm radius. The collimation is to reduce the magnitude of the potential well for the ions created by the space charge potential of the electron beam. The target has the properties of 0.15-cm-thick copper. When the electron beam strikes the target, the transmitted, reflected, and deposited fractions are treated according to the results of a Monte Carlo electron transport calculation. The transmitted and reflected electrons, which include the knock-ons, would have the appropriate energy and angular distributions. In general, the reflected electron charge is only a few percent of the total beam charge as indicated in our transport calculations.
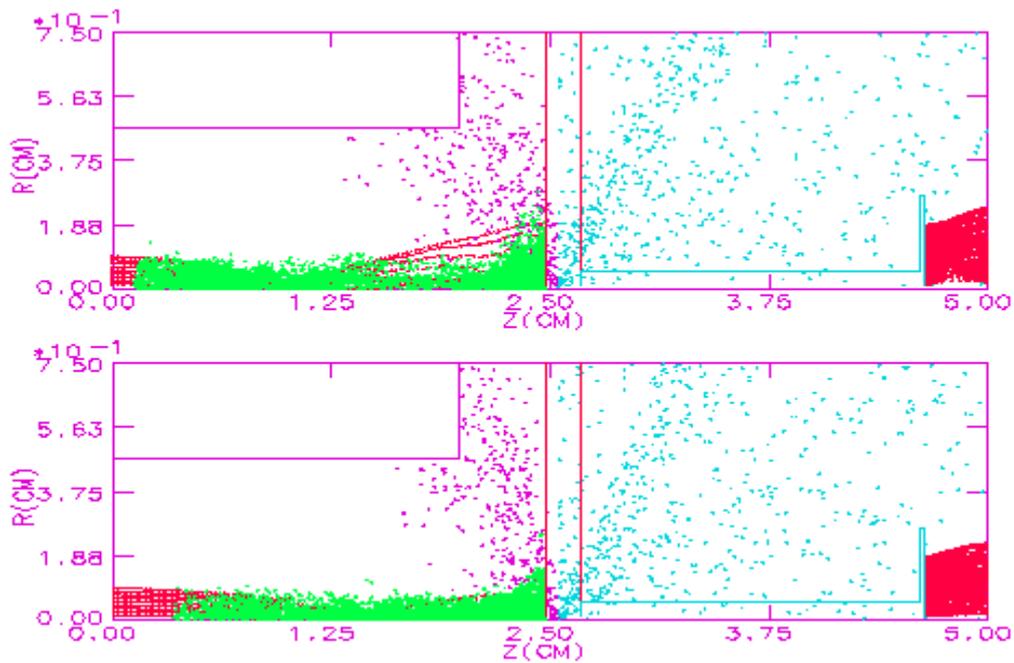
Fig. 1. The length of the ion column shrinks as the bias potential develops towards a static state value.

There is a conductor attached to the right side of the target, which forms a vacuum diode with the right hand metallic boundary. With an appropriate diode gap, a desirable amount of current can be drawn from the target to achieve the correct bias voltage between the target and ground. This configuration effectively models the electrical resistance between the target and ground. The electrons and the hydrogen ions resulted from space charge limited emission are shown in Fig. 1 at two different times in the simulation. The ion excursion length is reduced
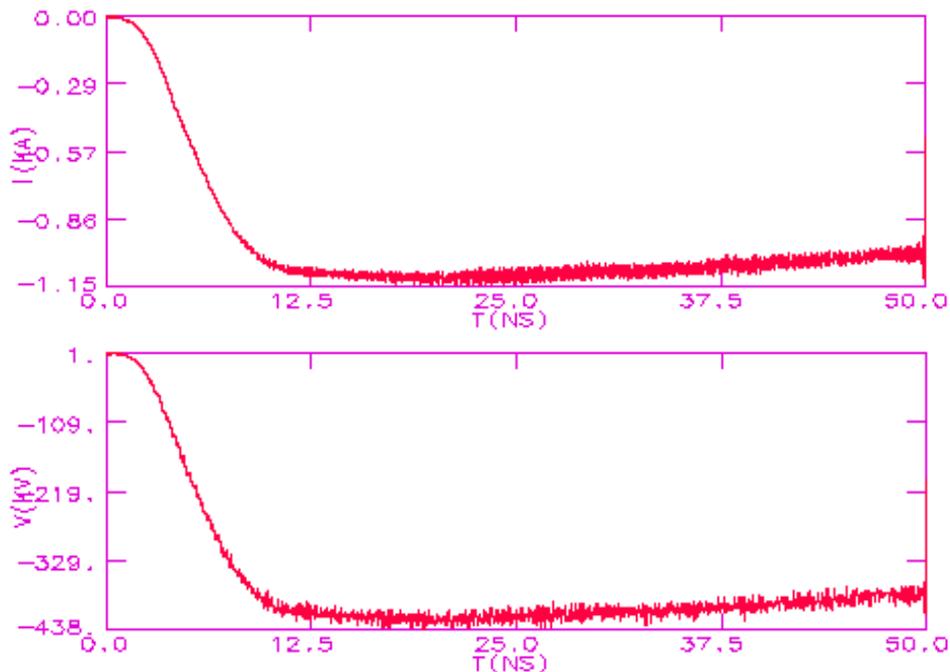

Fig. 2. Temporal profiles of the electron current flowing in the vacuum diode and the bias potential between the target and ground.

when the self-bias potential achieve the design value of 420 kV.. The time evolution of the current in the diode and the self-bias potential are shown in Fig. 2. The ITS electron beam has a rise time of about 10 ns and reaches a steady state current of 3.8 kA. The current in the vacuum diode has a similar temporal behavior as expected. It reaches a steady state of about 1.1 kA. And the potential rises to a steady state value of about 420 kV. The impedance of the diode has a steady state value about 400 ohms. This bias potential can effectively limit the length of the ion column as shown in Fig. 1, which illustrates the temporal evolution of the system. The time separation between the two frames is 3.33 ns. Finally we show the time history of the root-mean-square of the electron beam radius in Fig. 3. We note that after some initial transient beam pinching, the target biasing effect takes over and stabilizes the spot size of the electron beam on the target.
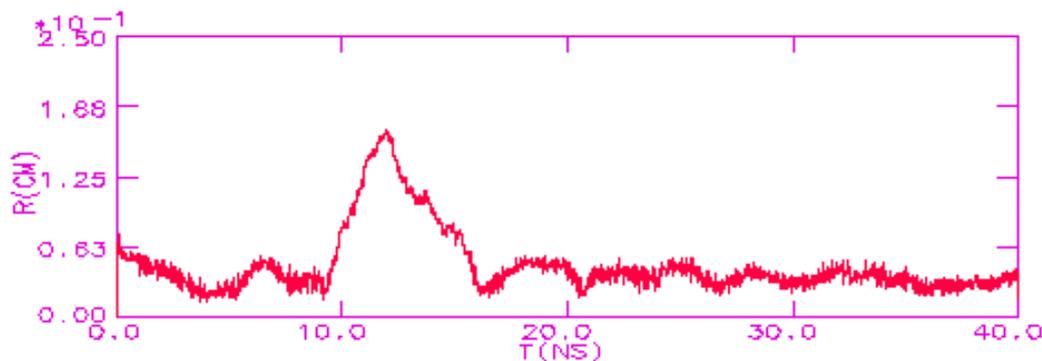

Fig. 3. The time evolution of the root-mean-square of the beam radius on the target plane shows the stabilization of the spot size due to the bias potential.

4. Conclusions

We have demonstrated through computer simulations that self-biasing the target can effectively control the ion column which causes radial pinching of the electron beam, resulting in the growth of spot size on target. This method has the unique features in simplicity and non-intrusiveness in its implementation into radiographic systems. The concept is being actively explored experimentally at the Integrated Test Stand (ITS).

References

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[3] Dave Moir: *private communication*, 1997.