DESIGN SIMULATION FOR SPOT SIZE STABILIZATION IN ITS/DARHT*

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Abstract

In high resolution flash x-ray imaging technology the electric field developed between the electron beam and the converter target is large enough to draw ions from the target surface. The ions provide fractional neutralization and cause the electron beam to focus radially inward, and the focal point subsequently moves upstream due to the expansion of the ion column. A self-bias target concept is proposed and verified via computer simulation that the electron charge deposited on the target can generate an electric potential, which can effectively limit the ion motion and thereby stabilize the growth of the spot size. A target chamber using the self bias target concept was designed and tested in the Integrated Test Stand (ITS). We have obtained good agreement between computer simulation and experiment.

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 (η - $1/\gamma^2$). 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 the bremsstrahlung process in a converter target. For high resolution radiography, the energy density of the electron beam is sufficiently intense that an electric field can develop near the converter target such that ions can be extracted from its surface. Typical ions species are from contaminants such as hydrocarbons, water vapor, oxygen, etc. Among the various species, hydrogen is the most mobile and most prone to cause radial focusing of the electron beam. In our study, we assume hydrogen ions in all of our calculations. Once the ions are created, they are drawn toward the potential well near the axis of the electron beam form by its space charge. Such an ion column provides fractional neutralization of the electron beam locally and thus causes the beam to focus 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 focal point 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 simulations[1] and confirmed by experiments at the Integrated Test Stand (ITS)[2] at Los Alamos National Laboratory

2 CONCEPT OF SELF BIAS TARGETS

In this paper, we present a novel idea of establishing an electrical potential between the target and ground that would overcome the space charge potential of the electron beam to confine the ions near the converter target. 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 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. If the target is charged negatively, an electric field will develop to attract the ions toward the converter. This can be an effective method to control the ion column, leading to the stabilization of the beam spot size. We have performed Monte Carlo electron transport calculations of the ITS electron beam and the DARHT electron beam in targets of different materials and thicknesses. The beam parameters for the ITS beam are 5.5 MeV, 3.8 kA, and 60 ns pulse length. The beam parameters for the DARHT beam are 20 MeV, 4.0 kA, and 60 ns pulse length. The target material used in the experiments was either copper or tantalum. To estimate the charge buildup and the resulting electric field in its vacinity, we will take the 1.5-mm-thick copper target as an example. 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 therefore 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 avoid electrical breakdown between the target and the surrounding grounded conductors.

2 TARGET ASSEMBLY DESIGN

One of the major concerns of the target chamber design is field breakdown resulting from the bias potential across the collimator and the target assembly. The final design of the target chamber assembly is shown in Fig. 1. The critical surfaces are shaped in such a geometry to minimize electrical field stress. The design is aimed at a bias potential of 360 kV. The minimum distance between the target and the collimator was 2.0 cm. The diameter of the collimating aperture was chosen to be 2.0 cm. The finite element code FLUX2D was used to obtain the electric field profile in the target chamber. The maximum field strengths were found to be –175 kV/cm at the target holder position and 240 kV/cm at the tip of the collimator. In addition, the code calculated the capacitance of the target chamber to be 29.2 pF. Note that the resistance of the radial liquid resistor between the Rexolite can be varied easily by changing the salt concentration.

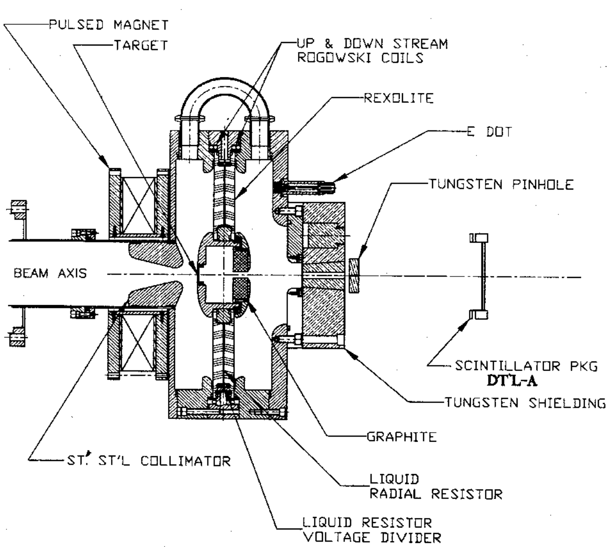

Figure 1 Experimental layout of the target chamber

3 PHYSICS DESIGN SIMULATION

The design of the target chamber was numerically simulated by using the large-scale, time-dependent, two-dimensional fully electromagnetic and relativistic particle-in-cell code MERLIN. An electron beam with the ITS parameters was injected at the left boundary and was focused on the target with a spot size of 1 mm in radius. The electron beam current was chosen to be 3.0 kA, corresponding to the experiment in which an emittance selector was inserted upstream in the beam pipe resulting in reduced current but higher beam quality. The transmitted and reflected electrons have the proper momentum and angular distributions determined by prior Monte Carlo calculations. The hydrogen ions are emitted from the target foil according to the space-charge-limited emission model. The liquid radial resistor was modeled in our simulation by a vacuum diode with its impedance determined by a properly chosen anode-cathode (AK) gap. In Fig. 2, we show the real space diagram of the target chamber assembly from our simulation. At this time, the beam current has achieved its full value of 3.0 kA. The bias potential has reached a steady state value of 360 kV after the rise time of the electron beam. We note that in Fig. 1, the axial length of the hydrogen ion column is clearly limited by the self bias potential. The ions execute vortex motion in the potential well, which limits its axial excursion. In the case where the ion column is not significantly larger than the betatron wavelength of the electron beam, the spot size on the target will not increase. The quarter betatron wavelength of the electron beam is estimated to be 3.3 cm for the parameters in our simulation. As a result, the spot size is expected to be stable. In Fig. 3, we show from our computer simulation the root-mean-square(rms) radius of the electron beam on the target plane. After the transient state due to the rise of the beam current (i.e., the development of the bias potential), the rms radius achieves a steady state value of about 0.5 mm. Note that the root-mean-square value is weighed by the beam current.

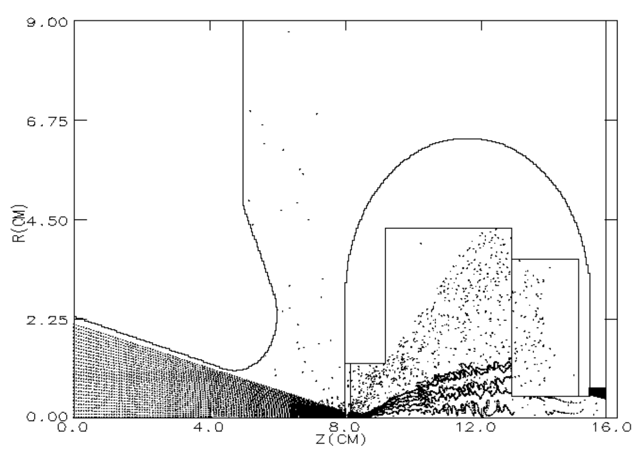

Figure 2 Physics simulation of the target chamber

4 EXPERIMENTAL COMPARISON

Experiments to validate the concept of a self bias target and the design of the target chamber were carried out at the ITS. Emittance selectors were used in the beam pipe to increase the quality of the electron beam and reduce the beam halo phenomenon. The experiment reported here had a beam current of 3.0 kA and a voltage of 5.6 MV. The radiographic spot size was monitored as a function of time. Its measured radius versus time is shown in Fig. 4. It is clear that after some transient behavior consistent with the development of bias potential, the spot size is stabilized. Besides the difference in a scaling factor due to normalization, the comparison with the simulation result in Fig. 3 is found to be quite favorable.

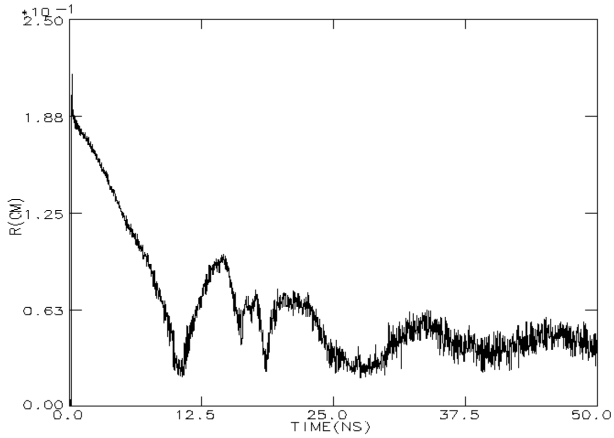

Figure 3 The rms radius of the electron beam at the target plane from the simulation

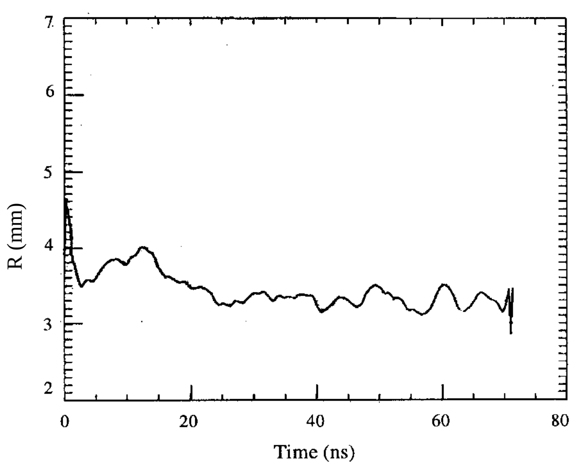

Figure 4 The radius of the radiographic spot obtained from the experiment

5 CONCLUSIONS

We found good agreement between experiment and simulation of the target chamber. The self bias potential between the target and the collimator is shown to be able to maintain the radiographic spot size in high dose radiography.

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REFERENCES

1. Thomas J. T. Kwan, John C. Goldstein, and Barbara G. DeVolder, Los Alamos National Laboratory Research Note XPA-RN(U)97-021, June 1997.
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