SIMULATIONS, EXPERIMENTS, AND ANALYSIS OF BEAM TARGET INTERACTION

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Abstract

The onset of the growth of the electron beam spot due to partial charge neutralization by ions extracted from the target plasma has been predicted by theory and simulation. The concept of an electrically self-biased target was developed to control the length of the ion column and experiments were fielded on the Integrated Test Stand (ITS) for the Dual Axis Radiographic Hydro Test (DARHT) facility at Los Alamos National Laboratory. The experimental results confirmed the stability of the spot size when the target is self-biased at a potential of 350 kV. Our analyses and quantitative comparison between computer simulations and experiments show that the ions generated by the electron beam were from target materials and that the delay for onset of the spot growth was governed by the time needed for the ionization of target material and formation of the ion column with sufficient length.

1 INTRODUCTION

The Dual Axis Radiographic Hydro Test (DARHT) machine uses an intense electron beam of 4 kA and 20 MeV to produce high dose radiation with small spot size for radiography of dense dynamic objects. However, this combination of high current in a small area leads to undesirable effects such as intense local energy deposition from the high intensity electron beam causing vaporization of the bremsstrahlung target. The hot plasma thus generated provides a copious source of positive ions that are rapidly accelerated into the negative potential well of the incoming electron beam. As the ions propagate upstream, they partially charge neutralize the electron beam. The carefully designed stable propagation of the electron beam to the target is disrupted, and its spot size at the target begins to increase. As the ions move further upstream, they neutralize an ever-increasing length of the electron beam, causing its spot size to diverge [1,2]. For the last two years, the important physics of the stability of the radiation spot size of the DARHT facility has been under intensive study. In 1997 the concept of an electrically self-biased target was developed by Kwan and his colleagues [3,4] to limit the length of the charge neutralizing ion column, which leads to the increase of the electron beam spot on the target plane. Shortly thereafter a target chamber based on the self-biased target concept was designed and fielded on the Integrated Test Stand (ITS) at Los Alamos National Laboratory [5]. The experimental results clearly confirmed the validity of the theoretical concept and the utility of the design to achieve stable radiographic spot throughout the electron beam pulse. At the same time, the data also revealed several important and intriguing phenomena. It is the purpose of this paper to provide an interpretation of our experiments through detailed analysis and quantitative comparison to simulations. The conclusions from our study show that the ions which cause partial neutralization and subsequently lead to the increase of beam spot size on the target plane are predominantly coming from the target material itself and not from foreign contaminants. In other words, the ions are singly-charged ions with large atomic masses. Furthermore, the delay for the onset of growth of the spot size observed in the experiments was the time for the electron beam to deposit enough energy to cause ionization of target materials and the subsequent growth of the ion column to sufficient length for strong focusing of the electron beam.

2 EXPERIMENTAL ANALYSIS

The target experiments were fielded on the ITS, which is the injector for DARHT. It has an electron beam of

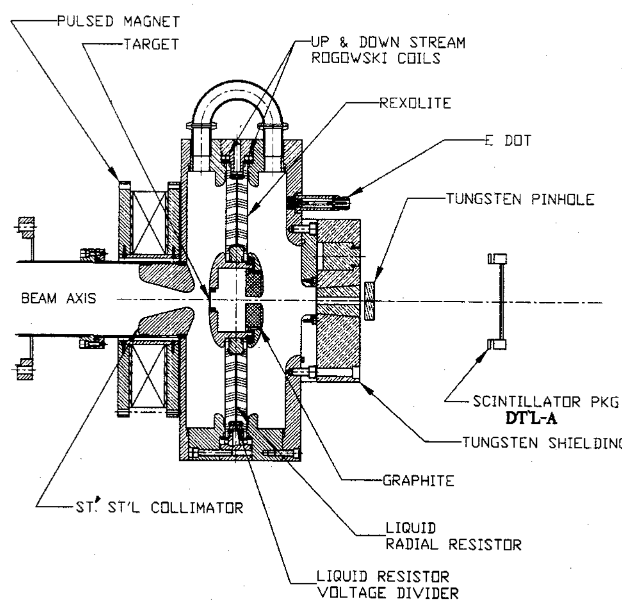

Figure 1: Experimental layout of the self-biased target chamber

energy 5.6 MeV and current up to 4 kA. The target chamber is shown in Fig. 1. For a given electron beam current, the magnitude of the self-biased target voltage can be chosen by selecting a desired resistance of the liquid radial resistor within the Rexolite. The electrical resistance can be readily varied with the change of the salt concentration of the sodium thiosulphate of the resistor. Consequently, the charge deposited by the electron beam in the target assembly would establish a bias potential between the target and the collimator. An emittance filter was used in the beam line to reduce the electron current to 3.0 kA. The resistance of the liquid resistor was set at 145 ohms and 6 ohms for two experiments, respectively. The experimental results of the time behavior of the bias potential and electron current in the resistor are shown in Fig. 2. For a resistance value of 145 ohms, a bias potential of appoximately 350 kV was developed to trap the ions and limit their axial excursion from the target. The upper part of Fig. 2 shows the electron current in the liquid resistor during the experiment.

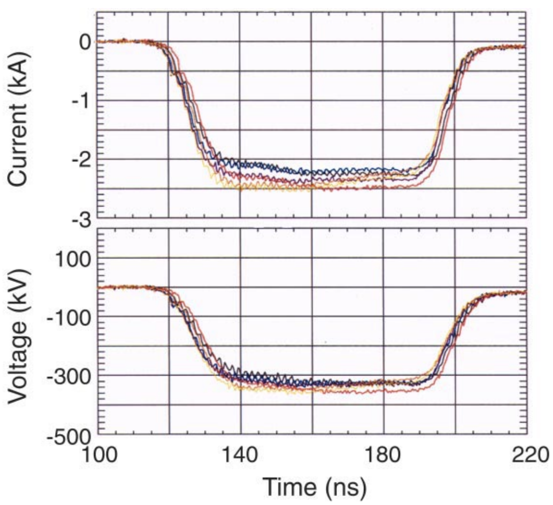

Figure 2: Experimental results of the electron current and voltage through the 145 ohms resistor. The multiple traces show the reproducibility of the experiment.

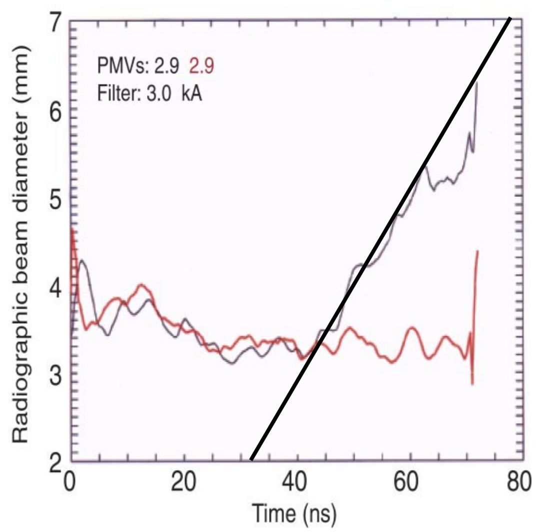

Figure 3: Radiation spot size obtained from the experiment. The slope gives the radial expansion velocity of 1.08×10^{-2} cm/ns.

In Fig. 3, we show the experimental results of the time dependence of the radiation spot size. The converter target was copper and had a thickness of 0.76 mm. We note that the radiation spot size stayed constant throughout the beam pulse in the presence of the bias potential. However, the other experiment with the resistor set to a very low value of 6 ohms produced a negligibly small bias potential and the radiation spot started to increase after about 40 ns into the beam pulse. More importantly, the rate of expansion of the electron beam spot size on the target plane is directly related to the velocity of the ions moving upstream. Comparison with simulations with different species of ions allows us to infer the particular ion species present in the experiment.

3 COMPARISON WITH COMPUTER SIMULATIONS

We have simulated the interaction of the electron beam with the converter targets in the ITS experiments using the two-dimensional, self-consistent, fully electro-magnetic, relativistic particle code Merlin. The radial resistor was modelled in the r-z simulations as a vacuum diode with resistance corresponding to different magnitudes of bias voltage generated by the electron beam to confine the ions. The root-mean-square (rms) radius of the electron beam on the target plane was monitored during simulation. Neglecting the diffusion of beam spot due to electron scatterings in the converter target, one can relate the rms radius of the electron beam to the diameter of the Los Alamos radiation spot size by a factor of 3.76 [6]. Different species of ions were used in simulations to obtain the effect on the growth of the radiation spot size when the target is not biased. Figure 4 shows the time evolution of the radiation spot from the simulations with hydrogen ions with and without the buildup of the bias potential at the target. The bias potential is found to adequately stabilize the spot size whereas the spot increases in size without the bias. Figure 5 shows the temporal dependence of the bias potential from the simulation, which attains a steady value of 350 kV after the rise of the electron beam current. The good agreement between simulation and experiment confirms the concept and the design of a bias target for high dose radiographic applications.

In the absence of a bias potential, the ion column continues to expand and therefore, the beam spot size on the target increases. The radial expansion velocities of the radiographic spot can be obtained from experiment (Fig. 3) and simulation (Fig. 4). The electric potential, which accelerates the ions upstream, is determined by the space charge of the electron beam. Consequently, the ratio of

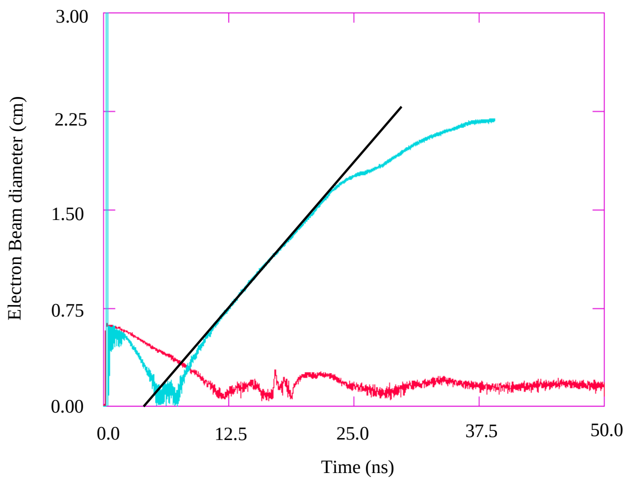

Figure 4: The electron beam diameter on the target plane from simulations with hydrogen ions.

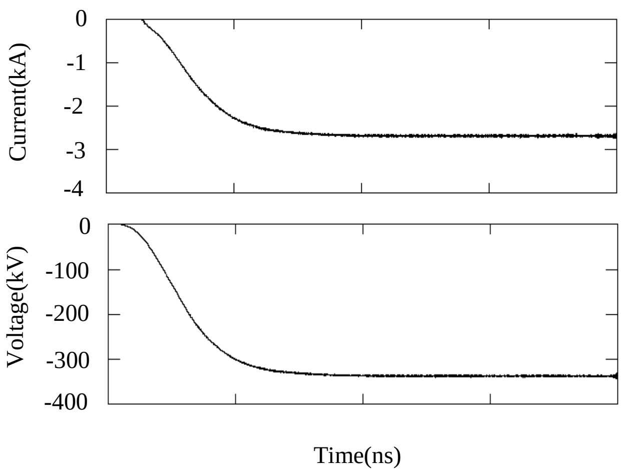

Figure 5: Bias Potential and electron current in the resistor as obtained from the simulation.

the velocities of different species of ions is inversely proportional to the ratio of the square root of the masses. Hence, we have $(M_1/M_2)^{1/2} = V_2/V_1$, where M_1 and M_2 denote the masses the ions species. For simplicity, one can rewrite the equation in terms of their atomic masses, $(A_1/A_2)^{1/2} = V_2/V_1$. The radial expansion velocities from the simulations with different ion species are tabulated in Table 1. The last column in Table 1 gives the atomic mass of the ions in the experiment as inferred from the simulations. The prediction is consistent with the target, which was copper in the experiment.

Table 1: Radial expansion velocities and ion masses

	V_{sim}(cm/ns)	A_{sim}	A_{expt}
H^+	8.67×10^{-2}	1	64.5
C^+	2.46×10^{-2}	12	62.3
O^+	2.18×10^{-2}	16	65.2
Cu^+	1.14×10^{-2}	64	70.5

The experimental data in Fig. 3 show the onset of the increase of the spot size occurred at 40 ns. This delay time is due in part to the time for vaporization to occur at the target spot and in part to the time for the target ions to form a column more than a quarter of the betatron wavelength of the electron beam near the target. The fractional pulse length τ of the electron beam needed to deposit enough energy to create sufficient ionization can be calculated according to $\tau = sT_b a/(d\varepsilon/dx)I_b$, where s and T_b are the specific heat and the boiling temperature of the target material, repectively, a is the area of beam spot, I_b is the beam current, and $d\varepsilon/dx$ is the energy loss of incident electrons in the target. For the ITS experiment, τ is found to be 14 ns, and the the time for the ion column to reach 3 cm is about 28 ns. The delay time is then estimated to be 42 ns, which is consistent with the experiment.

4 CONCLUSIONS

A self-biased target fielded on the ITS experiments demonstrated the validity of concept and utility of the design. A self-biased potential of 350 kV was observed and a stable spot was confirmed in the experiment. Good agreements with the simulations have been obtained. Furthermore, comparisons between simulations and experiments show that the ions present in the experiments were from the target material, and that the delay time for the onset of the spot size growth was due to the time needed for target ionization and the formation of an ion column of sufficient length.

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6 REFERENCES

[1] Thomas J. T. Kwan, John C. Goldstein, and Barbara G. DeVolder, “Influence of Ions on Electron Beam Spot Size in ITS/DARHT,” Los Alamos National Laboratory Research Note, XPA-RN(U)97-021 (June 1997).

[2] Dale R. Welch and Thomas P. Hughes, “Effect of Target-Emitted Ions on the Focal Spot of an Intense Electron Beam,”Laser and Particle Beams, Vol. 16, no. 2, pp.285-294, 1998.

[3] T. J. T. Kwan and C. M. Snell, “Stabilization of Radiographic Spot Size via Self-Biasing Targets,” Los Alamos National Laboratory Research Note, XPA-RN(U)97-048 (November 1997).

[4] Thomas J. T. Kwan and Charles M. Snell, “Electron Beam Spot Size Stabilization for Radiographic Applications,” Proceedings of 1998 International Congress on Plasma Physics, Prague, Czech Republic (July 1998).

[5] T. J. T. Kwan, D. C. Moir, B. G. DeVolder, C. M. Snell, M. Kang,, “Design Simulation for Spot Size Stabilization of ITS/DARHT,” Proceedings of LINAC98 Conference, Chicago, IL, Aug. 23 – 28, 1998.

[6] K. H. Mueller, “Measurement and Characterization of X-Ray Spot Size,” Proceedings of the 1989 Flash Radiology Topical Conference, American Defense Preparedness Association, pp383-391 (1989).

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