FARADAY CUP MEASUREMENTS OF THE PLASMA PLUME PRODUCED AT AN X-RAY CONVERTER*

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Abstract

The next generation of radiographic machines based on induction accelerators is expected to generate multiple, small diameter x-ray spots of high intensity. Experiments to study the interaction of the electron beam with the x-ray converter are being performed at the Lawrence Livermore National Laboratory (LLNL) using the 6-MeV, 2-kA Experimental Test Accelerator (ETA) electron beam. The physics issues of greatest concern can be separated into two categories. The multiple pulse issue involves the interaction of subsequent beam pulses with the expanding plasma plume generated by earlier pulses striking the x-ray converter. The plume expands at several millimeters per microsecond and defines the minimum transverse spacing of the pulses. The single pulse issue is more subtle and involves the extraction of light ions by the head of the beam pulse. These light ions might propagate at velocities of several millimeters per nanosecond through the body of the incoming pulse resulting in a moving focus prior to the converter. In this paper we describe Faraday cup measurements performed to quantify the plasma plume expansion and velocities of light ions.

1 INTRODUCTION

Radiographic machines based on induction accelerators produce an intense x-ray spot by focusing a short pulse of high current electrons onto a high Z material. Nominal parameters for the electron beam could be 50-100 ns pulse width, several kiloamperes, and 10-20 MeV. Producing a small and stable (constant diameter and position) x-ray spot is essential for radiographic imagining. The electron beam quality has been considered the limitation on the quality of the x-ray spot. For example, the emittance of the beam determines the smallest focus spot, and energy variation combined with transport focusing misalignments produces beam motion. Continuing advancements in induction accelerator technology has improved beam quality to a level where the interaction of the beam with the converter may be the limitation for the next generation of radiographic machines. Two areas of concern are the emission of light ions [1] that can “backstream” through the beam due to space charge potential, and interference between the beam and the plasma generated by previous pulses during multiple pulse operation.

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An on-going experimental program at LLNL is studying the interaction of an electron beam with the x-ray converter [2]. The goal is to quantify the effects of the plasma plume generated at the interaction on the initial and subsequent beam pulses, and to develop an appropriate x-ray converter configuration. Below we report on measurements from faraday cups incorporated into the experimental setup to characterize the plasma plume and determine the existence of backstreaming light ions.

2 EXPERIMENTAL LAYOUT

The faraday cups were comprised of two, electrically isolated, concentric cylinders as illustrated in Fig. 1. The inner cylinder could be biased up to 1.2 kV with respect to the grounded outer cylinder. Two geometries were used. The forward cup (refer to Fig. 2) had an OD of 5 cm and an aperture of 1.9 cm while the back cup had an OD of 1.3 cm and an aperture of 0.4 cm. The low ratio of aperture to cup length was to minimize the escape of secondary electrons generated by the impact of the positive ions with the inner cylinder. The forward cup was located about 25 cm from the beam/target intersection at an angle of 30° from the beam axis. The back cup was located about 5 cm from the intersection point and 75° from the beam axis. As shown in Fig. 2, the cups were situated at the entrance and exit, respectively, of a solenoid operating with an on-axis peak field of approximately 3 kG.

The inner cup discharged to ground through the 50 Ω input of an oscilloscope, permitting the rate of charge interception (current) to be measured. The sensitivity of the cups to ion density, assuming single ionization, is:

$$n_{\min} = \frac{I_{\min}}{Aev} \text{, where} \tag{1}$$

$n_{\min}$ is the minimum density, I_{min} is the minimum detectable current, A is the aperture area, and v is the ion velocity. For the forward and back cups, and for a nominal v of 5 mm/μs, $n_{\min}$ is $2x10^8$ cm^{-3} (I_{min} was 40 μA) and $5x10^{10}$ cm^{-3} (I_{min} was 480 μA), respectively.

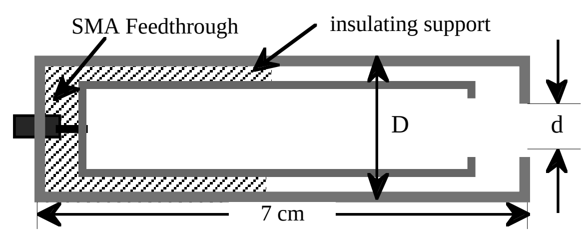

Figure 1: Schematic of the Faraday cup.

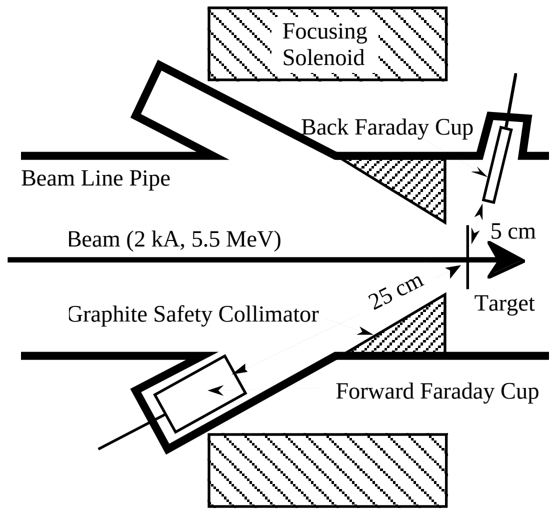

Figure 2. Schematic showing relative positions of the faraday cups with respect to the beam line and target.

The x-ray converter was comprised of a rotating wheel that held several "targets" to permit multiple shots before the x-ray converter had to be replaced. The majority of data was taken for tantalum targets of three thicknesses; 1 mm, 0.25 mm, and 0.1 mm. In addition, 1 mm thick stainless steel and 0.25 mm tungsten targets were used.

3 MEASUREMENTS

The faraday cup measurement consisted of the current (voltage) measured at the input (50 Ω termination) of an oscilloscope. See Fig. 3 and 4. Information that could be estimated from the measurements, with qualifications, included velocity, density, and beam radius. A third faraday cup was located approximately 50 cm upstream of the converter and recessed to avoid exposure to the plasma plume. This cup was directed at the beam line and served as a background reference for the other cups.

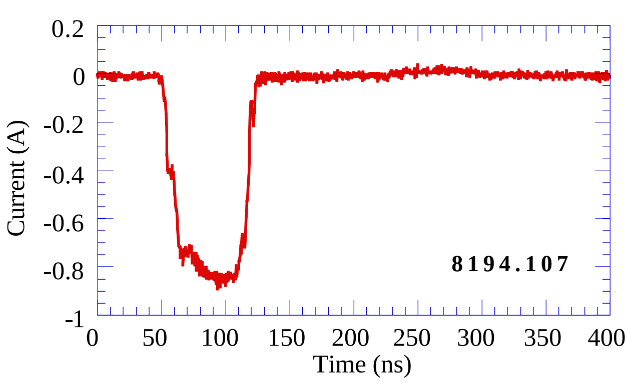

Figure 3. Typical output from the forward faraday cup.

3.1 *Prompt Signals (< 1 μs)*

A large signal was generated by the faraday cups during beam passage. A typical signal from the back cup is shown in Fig. 3 and displays the same pulse shape as the beam current monitors installed on the beam line. The small positive signal between 250-300 ns was caused by cable reflections. The forward cup produced a similar signal, but a factor of 10 to 20 smaller in amplitude.

Estimates for the energy and density of extracted ions from the target are > 250 keV and 10^{12} cm^{-3} near the x-ray converter [3,4]. For protons, this equates to a velocity of 7 mm/ns and currents of 20-100 mA at the faraday cups. However, the signals would arrive within 50 ns of electron beam passage. Numerous comparisons were made of signals at the cups with and without the x-ray converter installed to discern such a signal with no success.

3.2 *Plume Velocity*

Typical signals from the back and forward cups are displayed in Fig. 4. The back cup tended to have a single peak although the signal to noise ratio could have masked some features. The forward cup signal normally exhibited two peaks with the amplitude of the first peak varying from about 10% to over 130% of that of the second peak.

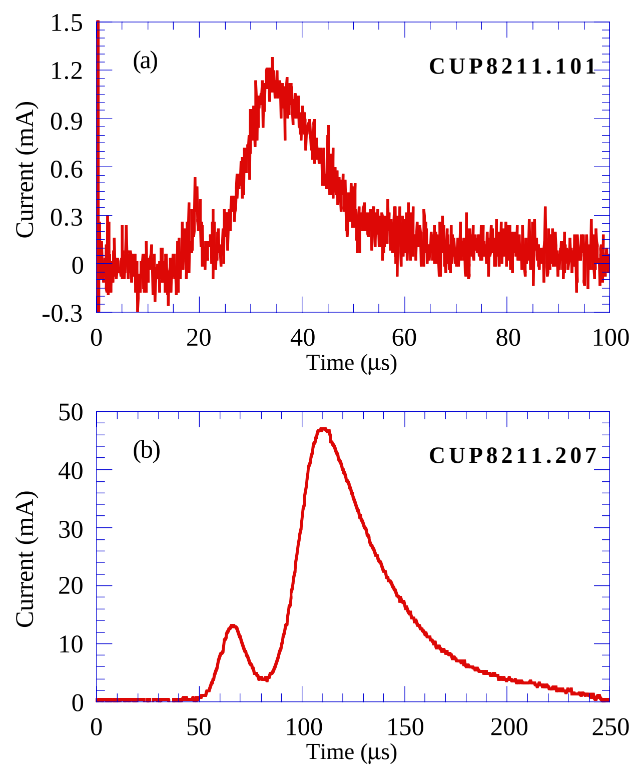

Figure 4. Typical output signals from the (a) back and (b) forward faraday cups. Beam interaction with the converter (1 mm thick Ta) occurred at time 0.

An estimate of the velocity can be made by assuming that the plasma was ejected promptly at beam time and quickly reached terminal velocity. With these assumptions the velocity would be simply the distance to the respective cup divided by arrival time at the cup after beam passage. The velocity can be related to spot size assuming a self-similar, isentropic expansion of a spherical gas cloud:

$$v = 1.64\sqrt{\frac{2E}{m}} = 2.32\sqrt{\frac{dE/dz}{\pi r^2 \rho}}\text{, where} \qquad (2)$$

E is the energy deposited into a mass m by the beam, dE/dz is the rate of energy deposition along the axis, r is the radius of the beam spot, and ρ is the mass density. While approximate, eq. (2) indicates that the velocity should vary inversely with spot size and be insensitive to target thickness. In Fig. 5, the velocity of the leading edge of the plasma plume at the forward cup (25 cm/ time of arrival) is plotted as a function of x-ray spot size for two thicknesses of Ta targets. The x-ray spot sizes shown for the 1 mm targets were measured using the roll bar technique [5] while for the 0.25 mm targets a higher resolution pin hole camera [6] was used. Eq (2) was in general agreement with measured velocities and spot sizes.

The plume velocity measured at the forward cup consistently was faster than measured at the back cup. For the distances that the cups are located from the target, the plasma plume could be expected to be expanding approximately spherically. Thus, the velocity should not be strongly dependent on the angular locations of the cups with respect to the beam. A second explanation suggested by Fig. 6, a plot of the velocity ratio between the cups as a function of target thickness, is that the beam diameter expands during transit producing a larger spot size on the back surface. Ratios are shown for the leading edge and for the peak signal.

3 .3 Plasma Density

Equation (1) can be used to crudely estimate the plasma density. Current in the Faraday cups is the combined effect of the collection of ions and electrons, and of the ejection of electrons in reaction to ion impact. Heavy ions like Ta with kinetic energy of several eV are quite likely to eject electrons on striking metal surfaces. Escape of secondary electrons increases the current signal and collection of plasma electrons lowers the current signal. Attempts to bias the inner cylinder did not produce significant changes to the cup signal. Probably of more importance is the orientation of the cup with the magnetic field lines of the focusing solenoid. The forward cup was positioned such that the magnetic field would tend to preclude the flow of electrons into or out of the cup. However, the orientation of the back cup would enhance flow. The heavy ions would not be significantly affected. The relative long length of the back cup to its aperture should minimize the escape of secondaries, with the net result of a low estimate of the density at the back cup.

Table 1: Estimated density (10^{10} cm^{-3}) at faraday cup.

Ta thickness	1 mm	0.25 mm	0.1 mm
Forward Cup	30	5	1
Back Cup	50	100	30

4 SUMMARY

No evidence was found for fast, backstreaming, light ions. However, the plasma plume was found to expand at 3-4 mm/µs (peak density) with a leading edge velocity of 7-8 mm/µs in agreement with theoretical models.

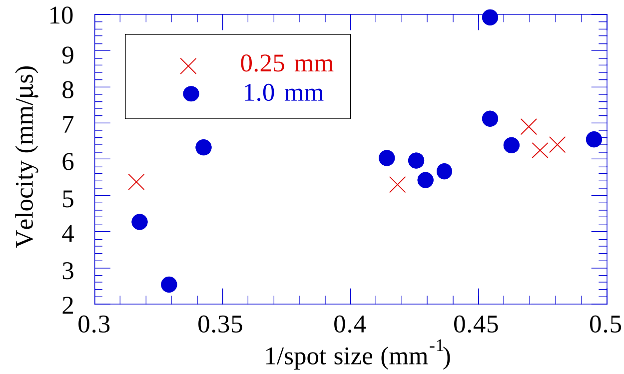

Figure 5. Velocity of the leading edge of the plume for Ta targets of two thicknesses as a function of spot size.

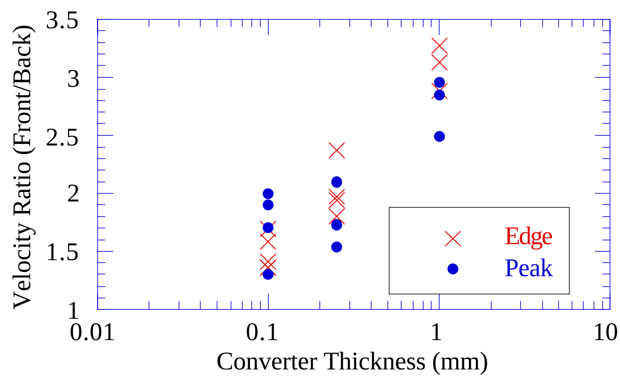

Figure 6. Ratio of the plume velocity at the forward and back faraday cups as a function of target thickness.

5 ACKNOWLEDGMENTS

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