EFFECT OF BACKSCATTERED ELECTRONS ON ELECTRON BEAM FOCUS

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Abstract

Using an induction linac, ETA-II, we are studying the interaction of a 2 kA, 6 MeV electron beam focused to a <2 mm diameter spot on high-Z foils. A focus shift was noticed when changing from 5 mil to 40 mil tantalum foil targets. This shift was subsequently attributed to the effect of a substantial fraction of the incident electron beam backscattering from the target, reducing the net beam current. This fraction varies with the thickness and density of the target. The presence and magnitude of the backscattered component was confirmed using Faraday cup collectors and beam-current monitors. Calculations confirm the magnitude of the focus shift is consistent with the observed backscattered fraction.

1 INTRODUCTION

Currently, ETA-II is configured to focus a 2 kA, 6 MeV electron beam to a small spot using a solenoid lens that generates a field of approximately 0.47 Tesla. During an experiment that involved varying the target thickness, we observed that for a fixed current in the final lens, the spot size produced depended on the thickness of the target material. After some thought, this was attributed to the changing fraction of electrons backscattered from the target. Since the targets used were range thin, the backscattered fraction was roughly proportional to the target thickness.

The focus shift is caused by changing the balance between space-charge repulsion and magnetic self-focussing of the e-beam. The backscattered electrons add to the space charge, increasing the electrostatic repulsive force, and cancel a fraction of the incident current, reducing the magnetic self-focussing force. As long as the target is not time-varying, the focus can be restored by increasing the current in the final lens.

The interaction of the 6 MeV electrons with the tantalum target was modeled using a Monte-Carlo code, and directly measured on ETA-II by a Faraday cup and beam current monitors. These diagnostics only record a fraction of the reflected electrons, but provide direct evidence of their existence. To confirm that back-scattered electrons could cause the observed focus shift, the system was modeled using a paraxial beam transport code. The code did not account for all the variables involved, but did confirm that a small fraction could produce the observed shift.

2 EXPERIMENTAL CONDITIONS

As mentioned above, ETA-II is presently configured to investigate the interaction of a high-current electron beam focussed on a high-Z target. Details of the accelerator and beam transport sections are available elsewhere[1] but are not required for the present discussion. As such, the electron beam is simply assumed to enter the influence of the final focus solenoid at a given axial location at a waist and with a given radius. Experimentally, the accelerator and transport section is tuned up and the current in the final solenoid is adjusted to give the smallest x-ray spotsize on the target. The spotsize is measured by an x-ray pinhole camera[2] placed downstream of the target. Target foils are arranged on a wheel and are rotated into position by a stepper motor.

Direct evidence of the backscattered electrons was provided by a Faraday cup and beam current monitors placed upstream of the target. The Faraday cup consisted of two, electrically isolated, concentric cylinders. The inner cylinder was not biased for this measurement and the outer cylinder was electrically grounded. The cup was 7 cm long, with an outside diameter of 5 cm and an entrance aperture of 1.9 cm. The cup was situated in front of the final solenoid, approximately 25 cm from the target. The cups were mounted 20° off-axis to allow clearance for the incident electron beam. The inner cup current was recorded through the 50 Ω input of a 500 MHz digital oscilloscope.

To assess the magnitude of the backscattered fraction transported by the beamline optics, the electron beam was measured using two current monitors located upstream from the target. The current was recorded with and without a target in place. These monitors record the voltage induced by the beam in a thin foil placed along the inner surface of the beamline. A ferrite core placed radially outside it forces the beam image current to flow through the foil, inducing a voltage of roughly 3 volts per kiloampere. This voltage is sampled at 8 locations around the beamline and is also used to locate the beam centroid. Since the monitor measures the net current, the backscattered electrons will reduce the current measured when the target is in place compared to when it is not.

3 MODELING

In an effort to understand the experimentally observed focus shifts, we modeled the interaction of the beam with the target and the subsequent effect of the backscattered electrons on the transport of the incident electron beam. The interaction of the beam with the target was modeled using the MCNP code. MCNP is a general-purpose, continuous-energy, generalized-geometry, time-dependent, coupled neutron-photon-electron Monte Carlo transport code[3]. It was developed by the Transport Methods Group (XTM) of the Applied Theoretical & Computational Physics Division (X Division) at Los Alamos National Laboratory and is presently distributed by the Radiation Safety Information Computational Center (RSICC) at Oak Ridge. The code was run for the ETA-II beam energy of 6 MeV for our case, and at 1 and 20 MeV to estimate the magnitude of the effect in other regimes. Although the code will give details of energy and angular distributions, for this study we concentrated only on the net reflected current.

To model the effect of the counter-propagating electrons on beam transport, we used Mathmatica[4] to solve the paraxial beam-envelope equation, modified to account for the backscattered electrons. This was accomplished by reducing the beam current by the backscattered fraction (f_b) for the magnetic self-pinch force and increasing the beam current for the space-charge force by the same amount. The code assumes a constant fraction of “negative current” throughout the region of transport. Although this is not rigorously correct, we only modeled the last section of transport, which partially accounts for the fact that most of the backscattered electrons will not be transported very far.

We used the code in two modes, first was to assess whether or not the f_b predicted by MCNP would be sufficient to account for the focus shift observed on ETA-II, and the second was to make estimates of the effects in other operating regimes.

4 OBSERVATIONS AND RESULTS

As stated above, the motivation for this paper was the focus shift noted when the target thickness was changed from 5 mil to 40 mil tantalum on ETA-II. The spotsize measured by the x-ray pinhole camera went from 1.2 mm (FWHM) to over 5 mm. In order to bring the spotsize back down (to 1.4 mm), the current in the final focus solenoid was raised 10%.

As a starting point, we sought to confirm the existence of the backscattered electrons that were proposed to be the cause of the shift. The first direct measurement was made by the Faraday cup. The signals recorded for a 5 mil target is plotted along with the signal from a 40 mil target in Figure 1. The difference between the two targets is quite clear, but not at the expected ratio of eight (ratio of target thicknesses). The MCNP code also gives this ratio of eight, 23% for the 40 mil target and 3% for the 5 mil

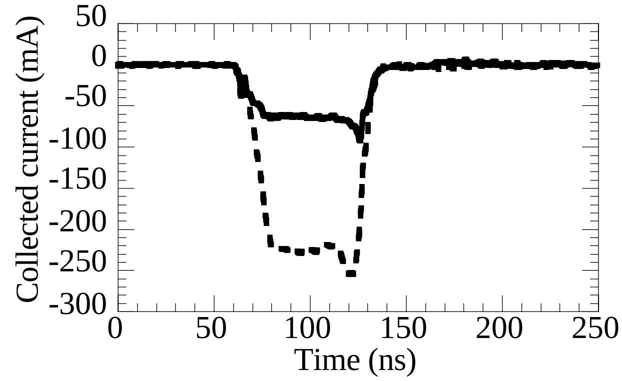

Figure 1: A Faraday cup collector clearly shows the difference in backscattered electron current with varying target thickness. The solid line is signal recorded with the 5 mil target, the dotted line with the 40 mil.

target. We have attributed this to variations in beam symmetry and small changes in fields at the target surface. Since the cup is located 25 cm away from the target, and in a relatively field-free region, this is considered a reasonable explanation.

As a further check, we looked at the beam current monitors with and without targets in place. Since the backscattered electrons are emitted at all angles, only a portion of them will be transported from the target to the monitor location by the magnetic field of the final lens. Since the target is immersed in a 0.47 T field, a greater fraction than estimated from simple geometric considerations should be transported back into the beamline. In any case, the measured current difference can be taken as a lower limit on f_b. We first measured the current on a monitor located 50 cm from a 40 mil target and observed a reduction of 6 percent. We then installed a monitor at 12 cm from the target and measured a reduction of 13%. This was taken as a lower limit on the backscattered fraction.

With this experimental data in hand, we sought to model the beam transport, taking into consideration the effects of the backscattered electrons. The procedure was as follows. The ETA-II beam parameters were input and the current in the final focus solenoid adjusted to give a focus at the magnet midplane. A percentage of backscattered electrons were added, and the focus shift noted. The coil current was then increased 10% to match what was required to focus the beam on the thicker target. The f_b was then iterated until the beam focussed back at the midplane. In the course of this process, it was noted that the beam input diameter had a strong effect on f_b required. This was reasonable as both the space-charge forces and the magnetic self-pinch forces are radius dependent for a fixed total beam current. However, taking reasonable values for input radius gave required backscattered fractions that were in

Table 1: The beam transport code results showing the effect of backscattered electrons.

Beam Energy (MeV)	Input radius (cm)	f_b from MCNP	f_b used in transport	Axial focus shift (cm)	Current increase to focus
0.9	2.0	47%	20%	4.3	26%
5.4	2.0	23%	9.35%	1.5	10%
5.4	3.0	23%	21.3%	1.5	10%
20	2.0	4%	4%	1.2	3.2%

the range between the MCNP code prediction and the current monitor measurements. A similar procedure was followed for the other two input energies, with one exception. Since we had no experimental data to match, we set the backscattered fraction and then adjusted the coil current to shift the focus back to the original location. The results for ETA-II parameters and those for 0.9 and 20 MeV beams are given in Table 1.

5 DISCUSSION AND SUMMARY

We have provided an explanation of the focus shift observed on ETA-II when switching from 5 mil to 40 mil tantalum targets. The backscattered electron fraction required to give this observed shift was calculated to be in the range of that given by the MCNP code and the beam current measurements. For a given target material and thickness, the effect is constant throughout the beam pulse, and therefore can be compensated for by adjusting the final focus solenoid current. Although our modeling did not cover all possible mechanisms, it did show that backscattered electrons can influence beam transport to a significant degree. The 20% fraction used in the code at 0.9 MeV is less than half of the 47% predicted by MCNP. A larger input radius would lessen the effect, but it is clearly something to consider when designing systems in this energy range. Figure 2 shows the beam envelope for one 0.9 MeV case. Although the focus can be shifted back to its original location by increasing the focussing field, the envelope expands significantly before pinching down to the focus. This needs to be considered when designing the vacuum enclosure and magnet bore. Also, the effect at high energy is likely less than shown in Table 1, as the 4% used in the transport code is the total fraction calculated by MCNP for a 40 mil tantalum target and actual beams may be larger than 2 cm in radius.

In summary, we have shown that backscattered electrons can strongly influence the transport of high-current electrons beams, especially at low energies. We have not attempted to rigorously model all possible conditions, nor are we proposing that the details of our simple analysis are correct to any great degree, but we hope that in pointing out the possible effects of backscattered electrons, we can help others design new experiments with confidence and perhaps explain anomalous observations on other systems.

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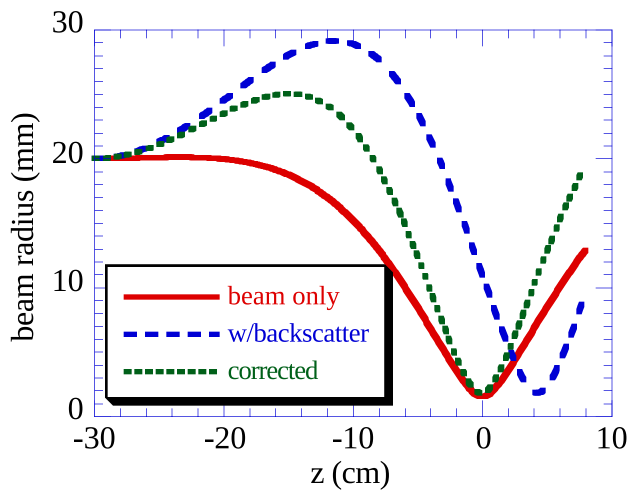

Figure 2: Envelope of a 0.9 MeV beam focussed with and without a backscattered fraction of 20%. Focus is brought back to z=0 by increasing the final coil current by 26 percent.

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[4] Mathematica 4, Wolfram Research Inc., Champaign, IL, Copyright 1988-1999.