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MAGNETIC COMPRESSION AND ELECTROSTATIC REFLECTION OF VERY HIGH v/γ ELECTRON BEAMS*

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ABSTRACT

High current sub-ohm electron-ion diodes are produced in the highly converging fringe fields at one end of a magnetic solenoid. With these diodes, the magnetic compression of a very high v/γ electron beam is investigated with and without the formation of a virtual cathode at the peak magnetic field. The magnetically focused beam transmission efficiency, area compression, and fluence gain are documented for up to 10:1 mirror ratios. When a virtual cathode is formed at the mirror peak, efficient electron beam reflexing is induced - thereby increasing the effective fluence through thin foils by a factor of six (or twice the optimum gain with conventional magnetic compression). Up to 3 MJ/g deposition in 0.1 mil copper foil is deduced from this data.

I. Introduction

Since the influx of magnetic compression experiments in the early 1970's[1,2,3] there has been little additional experimental work reported.[4,5] Consequently, there is no evidence of magnetic compression effects of beams with $v/\gamma > 10$, other than a few examples reported in an earlier paper[6] where the basic operation of sub-ohm diodes in a highly converging magnetic gradient (CMG) was discussed.

In Section III, experimental data on the magnetic compression of electron beams with $v/\gamma \sim 15$-60 is reported. The compression occurs in the drift region just beyond the CMG-diode and is referenced to the injected fluence at the anode plane. Comparisons are made with previous experiments[2] which studied $v/\gamma \sim 7$ beams using a similar CMG diode configuration. In Section IV, the effects of virtual diode formation at the mirror peak are reported. This configuration induced efficient electron beams reflexing between the real and virtual cathodes that improved with increasing magnetic compression. Applications of this configuration to thin foil deposition are described. Electron deposition in 0.1 mil copper foil that is more than an order of magnitude higher than previous observations[7] is reported.

II. The Experimental Configuration

The experiments were performed on the 3/4 Ω BLACKJACK 3 accelerator at Maxwell Laboratories using the configuration illustrated in Figure 1. The $\sim$50 ns pulse line was coupled to the diode via a low inductance (20 nH) vacuum transition region. Prepulse insulators were used to suppress cathode emission prior to the main pulse. Cathode areas less than 120 cm^2 and gaps of $\sim$ 6 mm were used with 0.25 mil aluminized Mylar anode foils.

Beam compression was obtained by adjusting the proximity of the solenoid to the diode. On-axis axial magnetic field ratios ($B_{zm}B_{zd}$) from 2:1 to 10:1 were measured (in situ). The diode field (B_{zd}) was 6-8 kG and the maximum field (B_{zm}) was $\sim$ 40 kG. As described in more detail elsewhere,[6] these converging magnetic gradient (CMG) diodes effectively match the 3/4 Ω accelerator impedance. They also contribute to beam compression, in the sense that anode areas inferred from the beam perimeter were typically 1.6 $\pm$ 0.2 times smaller than the associated cathode area.

After passing through the anode foil, the beam was drifted in 2 torr of air and subjected to one of two modes of operation. In the first mode (CMG—REB), a relativistic electron beam was compressed through a converging magnetic gradient (i.e., the gradient was axially and radially nonuniform). A carbon calorimeter monitored the energy transmission efficiency. A pinhole camera produced area compression and beam profile information.

In the second mode (CMG—REBO), a 0.08 mil aluminized Kimfoil vacuum window was located at the mirror peak (as shown in Figure 1). The region downstream of this foil was evacuated, so that the beam could not propagate. As described in Section IV, efficient electrostatic electron reflections were obtained in this manner, setting up relativistic electron reflexing in the drift region between the real and virtual cathodes. The residual energy transmission was monitored by locating a calorimeter 25 cm beyond the virtual cathode, or sufficiently distant to negligibly affect the electrostatic reflections.[8]

In order to measure the fluence gain in the CMG-REBO relative to the CMG-REB, the special diagnostic configuration in Figure 1 was used. A thin (0.1 to 0.2 mil) copper foil was placed in the drift region adjacent to the Kimfoil reflector. A magnetic coil was located far from the beam reflexing region and oriented to divert any propagating electrons. As expected, no detectable energy transfer to the calorimeter was observed for either the CMG-REBO or the CMG-REB configuration. The pinhole camera was employed as an x-ray collimator – permitting only x-rays generated in the copper converter to be viewed by the on-axis 125 micron silicon pin-diode. This was confirmed by x-ray film at the image plane, which exhibited a cleanly collimated on-axis circular exposure of diameter greater than the pin-diode. The x-rays from the diverted electrons were observed off to one side of the film, or out of view of the pin-diode. Measurements in this mode will be discussed in Section IV.

When studying the ion current in the real (or virtual) diodes, a thin (0.16 mg/cm^2) layer of CD_2 on the anode and a thick (for 1 MeV deuterons i.e., 0.8 - 2.4 mg/cm^2) coating on the cathode (or target) was used. The resulting thick target neutron yield from D-D reactions was monitored with a silver activation counter[9]

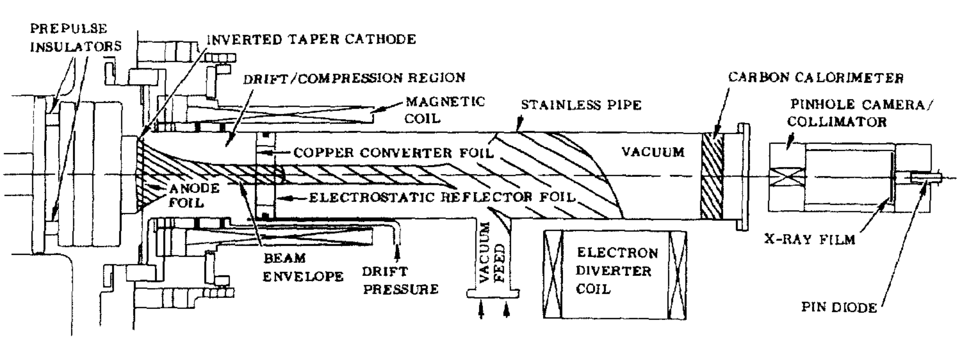


Figure 1. Experimental Configuration.

and a NE 102 scintillator – photomultiplier combination.

III. The Effects of Magnetic Compression

One interest in magnetic compression of electron beams is to increase the fluence for materials testing and x-ray converter applications. Due to compression in the diode[6] as well as in the drift region[2,6] and to anomalous electron transport[5] magnetic compression near the diode is potentially more efficient than downstream magnetic compression of a propagating beam. Alternatively, a smaller area cathode could be extended inside the solenoid to produce beam areas comparable to the compressed beam, and possibly higher fluence since magnetic compresses losses are eliminated. As described in more detail elsewhere,[6] this method suffers from irreproducibility and energy loss due to high inductance and gap closure in the small anode-cathode gaps (say 4 mm for ~ 1 Ω with a 20 cm^2 cathode).

Measured energy transmission efficiencies as a function of magnetic compression ratio are exhibited in Figure 2 for both CMG-REB's and CMG-REBO's (to be discussed in Section IV). The data was obtained by normalizing calorimeter energy measurements to the diode energy. No attempt to correct for spall, radiation, or backscatter was made. Potential calibration discrepancies (10%) were removed by normalizing the data to the calorimeter measured anode plane energy. Note that the CMG-REB data tends to decrease for increasing magnetic compression ratios out to ~ 6:1, where the energy transmission dropped significantly. One interpretation of these results[6,11] is that the electron flow in the diode was restricted by flow along highly converging external magnetic fields, and (especially for > 6:1) by pinching due to strong self-magnetic fields and $E_r \times B_z$ induced rotational flow. A more complete discussion of these effects and estimates of the related deuteron ion current enhancement will be discussed in a later paper.[10]

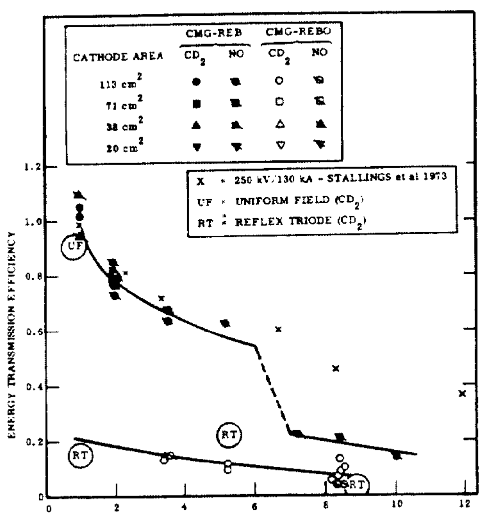


Figure 2. Energy Transmission Through Various Magnetic Mirrors.

The CMG-REB data in Figure 2 typically involved 400 - 700 kV beam voltages and 600 - 800 kA beam currents (υ/γ ~ 15-35). Since these power levels are 2 - 5 times that observed in previous experiments[2] for beams with υ/γ ~ 7, similar diode-solenoid configurations and 6 - 8 kG magnetic fields, it is interesting to compare the results. The agreement is good out to compression ratios of ~ 6:1 where our data changes to a different mode of operation (pinched beam).

Measured beam area compression ratios (A_a/A_m) as a function of magnetic compression are shown in Figure 3. The anode areas were inferred from data with a target at the anode plane by estimating the OD of pinhole camera exposures. The compressed beam area was similarly obtained so that the data in Figure 3 tends to minimize density profile effects. Different target materials (carbon, copper and tantalum) produced effectively the same beam diameter measurement for otherwise similar experimental conditions. A densitometer scan produced the beam profile shown in Figure 3, for a shot with 2:1 magnetic compression of the cathode sketched in Figure 1. Note that the basewidth of the scan is ~ 7 cm which implies an ~ 38 cm^2 area or ~ 3:1 compression (including ~ 1.6:1

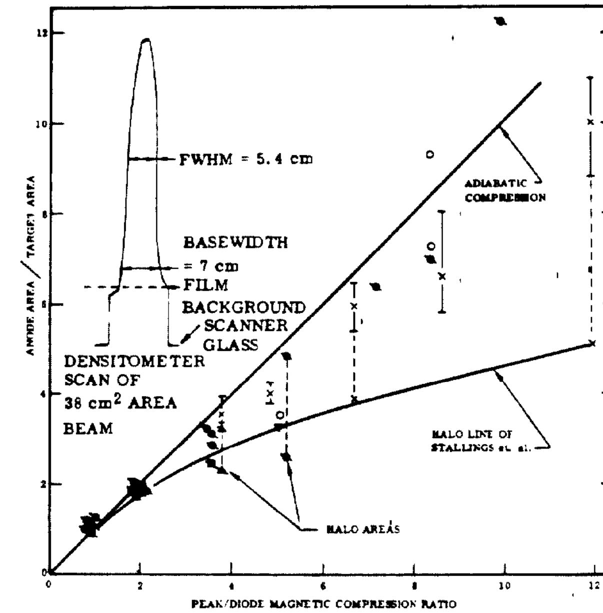
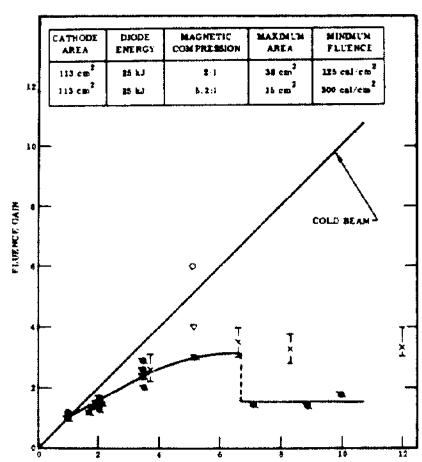


Figure 3. Beam Perimeter Inferred Area Compression Factors Through Various Magnetic Mirrors. Refer to Figure 2 for Symbol Legend.

compression of the diode to ~ 71 cm^2 at the anode plane). The FWHM of the scan is ~ 5 cm, so that the effective area is about one-half that of the beam edge inferred area. In agreement with previous experiments[2] the data in Figure 3 tends to fall below the cold beam prediction. At the higher compression ratios (over 6:1), on-axis hot spots appear in the x-ray exposures and tend to dominate the beam areas plotted in the figure. One observation noted by Stallings et al.[2] is the existence of a beam halo beyond the dominate core of the beam energy profile which violates adiabatic compression. In the BLACKJACK 3 data, this halo produced minor damage to witness plates (outside the central core of damage) but was not observed in pinhole camera photos. As a rough comparison, the perimeter inferred halo areas were measured from the witness plates and are plotted in Figure 3 (note the lower data points connected by a dashed line to the main beam area measurements).

By combining Figures 2 and 3, an estimate of the fluence gain due to magnetic compression was obtained for both experimental groups (see Figure 4). The data suggests than ~ 3:1 gain (at 5:1 compression) is generally optimum. Examples of specific shot fluence levels are tabulated in Figure 4.



CATHODE AREA	DIODE ENERGY	MAGNETIC COMPRESSION	MAXIMUM AREA	MINIMUM FLUENCE
113 cm^2	25 kJ	3:1	38 cm^2	125 cal/cm^2
113 cm^2	25 kJ	6.2:1	15 cm^2	300 cal/cm^2

Figure 4. Electron Beam Fluence Gain Through Various Magnetic Mirrors. Refer to Figure 2 for Symbol Legend.

IV. The Effects Of Electrostatic Reflection

Electron beam oscillations between a real and virtual cathode are used to optimize the dose in thin high Z foils so that enhanced soft x-ray radiation can be observed. If the oscillator is immersed in a converging magnetic gradient, the dose

Table 1. Selected Thin Foil Deposition Data Involving Magnetic Compression and Electrostatic Reflection

Shot	Mode	V_d kV	I_d kA	W_d kJ	Z_d Ω	ν/γ	A_c cm^2	A_a cm^2	B_d kG	B_m/B_d	W_m kJ	A_m cm^2	PIN Gain	Fluence Gain	0.1 mil Cu Dose MJ/g	Neutrons $\times 10^{10}$
1472	CMG-REB	453	490	14	0.92	18	113	~71	7	5.2	~8.8	~15	1.0	~2	0.49	6.0
1471	CMG-REBO	439	821	15	0.53	30	113	~71	7	5.2	~9.5	~15	1.8	~2	1.1	3.5
1482	CMG-REBO	453	475	12	0.95	18	20	~13	7	5.2	~7.6	~4	~1.8	~2	3.3	- -
1489	CMG-REBO	241	1180	16	0.20	62	113	~71	7	8.4	~1.8	~8	0.07	~2	0.045	6.4

in a foil near the virtual cathode is enhanced due to compression and multiple electron passes. Other applications of the CMG-REB include accelerator matching at the sub-ohm level[8] and ion beam generation.[10]

The energy lost through the virtual diode to a calorimeter ~ 25 cm downstream is plotted in Figure 2. Clearly the average reflection efficiency is better than the mirror reflection data for all levels of compression ranging from 80% in a uniform field to ~ 93% for 8:1 compression. The efficiency is essentially independent of CD_2 coatings in the diode. Since the 0.1 mil copper, 0.25 mil aluminized Mylar and 0.08 mil aluminized Kimfoil foils are equivalent to ~ 0.16 mil copper in thickness (or ~ 1 % of the range of 500 kV electrons in Copper) over 99% reflection efficiency per bounce must have occurred.[12]

The compressed beam areas measured in the CMG-REBO are shown in Figure 3. Note that within the scatter in the data there is no change in the compression ratio (with or without CD_2 coatings) relative to the corresponding CMG-REB. Evidently, the external and self-magnetic fields in the two diodes were sufficient to constrain the enhanced space charge electric fields due to the electron reflexing.

In order to correlate the multiple pass enhancement in copper converters, PIN diode measurements of the bremsstrahlung pulse were obtained for the CMG-REBO and CMG-REB modes under otherwise similar conditions. The total charge collected by the PIN diode (filtered by 2.5 cm of carbon and 3 mm aluminum as indicated in Figure 1) is proportional to the electron energy absorbed in the converter foil. Consequently, the integrated x-ray pulse ratio for the two modes and the measured fluence of the CMG-REB established the fluence for the CMG-REBO. Several examples of these conditions are listed in Table 1. Diodes with energy W_d ~ 12-16 kJ, currents I_d ~ 450-1200 kA and sub-ohm impedances (Z_d, the value at peak current) produced beams with peak υ/γ ~ 18 - 62, cathode areas A_c ~ 20 - 113 cm^2 and anode areas A_a ~ 13 - 71 cm^2. A 7 kG on-axis and axially directed magnetic field and 5.2:1 magnetic compression was used to produce compressed beam areas A_m ~ 4 - 15 cm^2. Normalizations of the PIN diode charge collected in the different shots to the CMG-REB value indicated up to 1.8:1 x-ray gain. In this manner effective two-way fluence gains (or more realistically, thin foil deposition gains) of 4 - 6:1 were inferred (relative to the one-way anode plane fluence). As exhibited in Figure 4, these gains are superior to the CMG-REB data. Up to 3.3 MJ/g effective dose was obtained. This level is a significant improvement over the 150 kJ/g previously measured in a magnetic mirror — REBO,[7] but is still far short of the 50 MJ/g needed to strip copper atoms and thereby enhance the K-line radiation. Evidently, more work at higher diode energy and magnetic compression, and smaller cathode areas is required.

Certain aspects of magnetic and electrostatic range shortening[14] are apparent in the data. X-ray bremsstrahlung codes [12] show that shot 1472 should have produced ~ 25 nC PIN charge collection if the electron population were cold and passed through the foil only once. The measured ~ 32 nC represents a ~ 1.3:1 enhancement due to the initial beam velocity distribution and to magnetic compression induced electron circulation in the foil, or "magnetic range shortening." When the virtual diode was used, an additional ~ 1.8:1 enhancement was obtained via electron reflexing in the foil, or "electrostatic range shortening," For comparison, a code calculation[12] predicts that ~ 10:1 enhancement should have been observed if all the energy that reached the top of the mirror (without reflexing) were completely dissipated in the foil. Evidently mirror reflections severly reduced the number of passes through the converter. These effects are of current interest in electron beam-pellet fusion.[14,15]

As mentioned earlier, when magnetic compression ratios above ~ 6:1 were used, the transmission efficiency dropped significantly and evidence of partial beam pinching was observed in the pinhole camera data. The last shot in Table 1 (8.4:1 compression) supports the low energy transmission efficiency observed for this regime, since the effective dose in 0.1 mil copper was inferred to be ~ 45 kJ/g or only 4% of that in shot 1472 (5.2:1 compression). However, both shots generated significant diode energy and similar (6 x 10^{10}) neutron levels. Since the deuteron ion current is approximately proportional to the neutron count divided by the square of the diode voltage (averaged over the voltage pulse basewidth)[13] the actual deuteron current in shot No. 1489 was ~ 3 times that in No. 1472. Consequently, a significant fraction of the diode current could have been in ions.

V. Conclusions

A configuration for magnetically compressing a relativistic electron beam near the diode (CMG-REB) has been experimentally tested. The transmission efficiency and fluence gain were found to agree with others — even though in this paper the beam υ/γ (at peak current) was up to 10 times higher. An optimum fluence gain of 3:1 was obtained with 5.2:1 compression, producing ~ 300 cal/cm^2 over ~ 15 cm^2 area of the beam (25 kJ diode energy). In addition, for magnetic compression ratios over ~ 6:1, a regime was found where energy transmission was drastically reduced due to the formation of partial beam pinching in the diode. Significant enhancement in the deuteron ion current was inferred from thick target D-D reaction induced neutrons (relative to lower magnetic compression data).

When a virtual diode was formed at the mirror peak (CMG-REBO) the residual transmission loss through the virtual diode was significantly lower for all values of magnetic compression. However, x-ray generation in a thin copper foil near the virtual diode was ~ twice that of the corresponding CMG-REB which itself was enhanced due to magnetic range shortening. This demonstrated that the effective two-way beam fluence was not reduced, but rather improved due to electron reflexing or electrostatic range shortening. Up to 3 MJ/g over 2 cm^2 effective area of 0.1 mil copper foil was inferred using a CMG-REBO with a 20 cm^2 cathode area, a modest 12 kJ diode energy, and 5.2:1 magnetic compression.

Under otherwise similar conditions, most of the CMG-REB data was overmatched to the 3/4Ω accelerator, while the CMG-REBO data was undermatched. These results were due evidently to electron reflexing in the bipolar electron-ion diode. Anode and cathode coatings of CD_2 confirmed the existence of ion currents, and acted to reduce the impedance in both modes without discernible loss in the electron transmission efficiency.

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