IREB TRANSPORT AND RISETIME COMPRESSION USING MAGNETIC FIELD GRADIENTS

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Abstract

An intense relativistic electron beam from the Naval Surface Weapons Center's Casino simulator has been transported 1.85 meters utilizing gradient-B drift in an applied magnetic field gradient produced by a straight wire. Transport efficiencies of 85-90% and beam risetime compression of up to a factor of two have been achieved routinely.

I. Introduction

Many of the uses of large scale, pulsed power systems, such as simulation and particle driven inertial confinement fusion, place ever increasing demands for higher power densities on a small target area. Until recently this has led to the manufacture of larger single diode machines. However, because of fabrication costs, operability requirements and diode inductances, designs using large single diodes have probably reached their ultimate size limit in the most recently developed machines. An alternative to large single diode design is the multiple pulse-line diode configuration which can produce a low effective impedence without straining the engineering design for the individual diodes. The multiple pulse-line diode philosophy has led to a search for technology improvements in a number of areas such as switching, diode development and generator design.

One problem that the multiple pulse-line diode design poses is the transport of the IREB from the diode where it is created to the target a meter or more away. The transport must be accomplished efficiently and reproducibly for practical multi-line systems. Several transport schemes have been suggested and experimentally tested such as laser or exploding wire designated channels, solenoidal magnetic fields and Z-pinch plasmas.

An additional requirement for many pulsed systems is that the energy must be delivered to the target in a very short pulse. This requirement cannot be met simply by shortening the pulse line length because this technique also reduces the delivered energy if the line impedence is maintained. Furthermore, diode impedences limit the pulse length if reasonable output energies are to be achieved. Fortunately, it is possible to passively compress the beam pulse after it leaves the diode by the application of appropriate magnetic fields, namely the 1/r azimuthal field produced by current in a single wire. This particular field results in gradient-B (grad-B, ∇B) drift of the electrons. The beam compression occurs when early injected low-energy electrons that are trapped by the magnetic field are caught by later produced high-energy electrons, resulting in longitudinal beam bunching. The process of grad-B transport and beam bunching was first described theoretically[1,2] and later studied experimentally[6]. The experimental work reported here with the Casino machine at the Naval Surface Weapons Center shows transport efficiencies of 85-90% over transport distances of up to 1.85 meters and beam pulse compression up to a factor of two.

Section II outlines the theoretical requirements for transport and compression with grad-B drift. A description of the experimental arrangement is provided in section III followed by a summary of results in section IV. Conclusions are stated in section V.

II. Theory

Gradient-B transport begins with a current-carrying wire strung along the axis just outside the anode of Casino (the electron source). Figure 1 illustrates a typical arrangement of the wire and the diode. Current in the wire creates a 1/r azimuthal magnetic field. It is the radial dependence of the field strength that gives the label "gradient-B" to this transport scheme. The magnitude of the field at a radial position r from the wire is given by

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14. ABSTRACT

An intense relativistic electron beam from the Naval Surface Weapons Center's Casino simulator has been transported 1.85 meters utilizing gradient-B drift in an applied magnetic field gradient produced by a straight wire. Transport efficiencies of 85-90% and beam risetime compression of up to a factor of two have been achieved routinely.

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$$B = \frac{I}{r}\,\frac{\mu o}{2\pi} \qquad (1)$$

where I is the wire current and μo is the permeability of free space. An electron entering the drift region containing the 1/r magnetic field is bent by the Lorentz force toward the axis. As the electron approaches the wire it experiences a stronger magnetic field and the radius of its orbit consequently shrinks. Upon moving away from the wire the orbit opens up again, and the result is a cycloidal motion effecting a net longitudinal drift. Gradient-B drift is this motion of the guiding center along the axis as each electron gyrates in its cyclotron orbit.

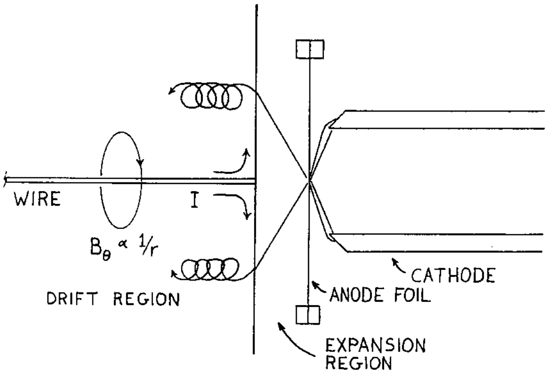

FIGURE 1.

The drift speed along the axis is

$$V_d = \pi\ \gamma\ \beta^2\ mc^2/\mu o\ q\ I \qquad (2)$$

where I is the wire current, m is the electron mass, c is the speed of light, q is the charge, γ is $(1-\beta^2)^{-1/2}$ and β is V/C, where V is the electron speed. The electron speed V remains relativistic but the speed of the guiding center V_d will be considerably smaller. Note that the drift speed is independent of the injection radius. The magnetic field will not affect any azimuthal motion the electron might possess so that the motion of the cyclotron orbit will be helical around the wire. Equation 2 was derived, however, by neglecting curvature drift and the azimuthal velocity V_θ. This assumption is justified in practice when the IREB pinches, without an external magnetic field, and then expands in the expansion region, cooling the beam and minimizing V_θ/V.

Transport-efficiencies of 85-90% can be realized with grad-B drift. A fraction of the electrons entering the drift region from the expansion region are turned back into the expansion region by the magnetic field, and another fraction is lost when electrons close to the wire collide with the wire. These two loss mechanisms primarily affect electrons approaching the wire from a narrow cone close to the axis, resulting in a transported beam which can be hollow when it reaches the converter.

Besides capturing and efficiently transporting an IREB, grad-B drift can also produce beam bunching, resulting in a risetime of the power pulse of the beam at the converter which is less than the risetime of the diode power pulse. The drift speed in Equation 2 is proportional to β and γ, so that an increase in electron energy increases the drift. A typical diode voltage ramps up to maximum voltage so that low energy electrons injected into the drift region early in time will drift more slowly than high-energy electrons injected later. The higher energy electrons can catch up to the slower ones, resulting in longitudinal beam bunching at the target which in turn increases the resulting dose rate. The actual degree of bunching will depend on several factors including the current in the wire and the length of the drift, but special attention should be paid to the possibility of tailoring the diode voltage to produce optimum compression.

III. The Experiment

Casino is a flash x-ray device used for radiation effects testing at the Naval Surface Weapons Center, White Oak, MD. Casino uses four separately driven high-energy diodes to produce intense relativistic electron beams. These beams irradiate a converter foil to produce bremsstrahlung x-rays. The production of this x-radiation is the major output of Casino. Typical diode parameters are shown in Figure 3. Using multiple beams, several refinements to Casino's output would accrue including a larger area of irradiation, more total dose and an increased dose rate. Casino currently operates with one diode at a time. In order to use two or more diodes to increase the dose, the IREB's must be transported about two meters and strike a single converter.

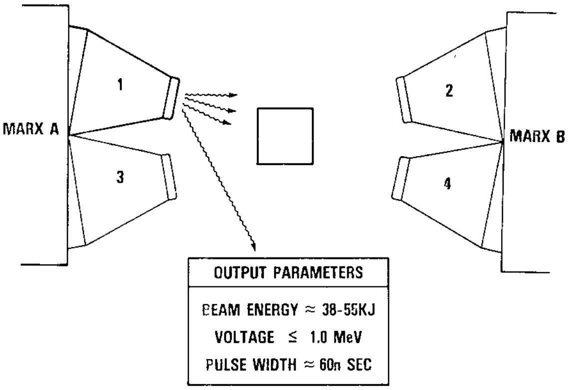

FIGURE 2

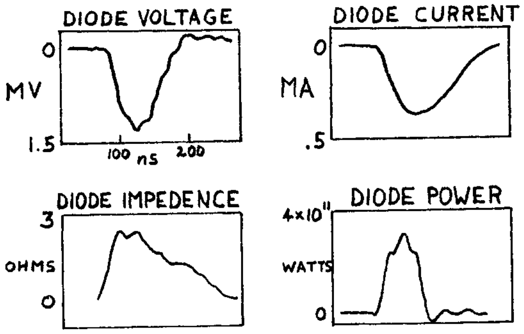

FIGURE 3.

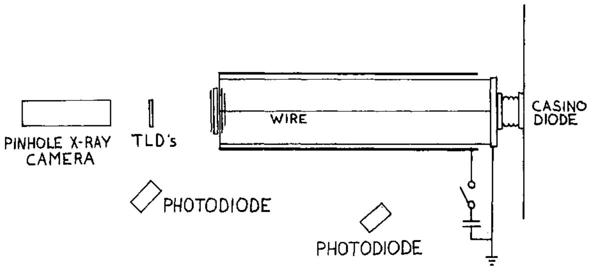

FIGURE 4.

Gradient-B drift is a promising scheme for achieving the goals of efficient IREB transport and of increasing the x-radiation dose and producing a more appropriate dose rate for simulations.

Preliminary to conducting grad-B transport experiments on Casino, the staff of Pulse Sciences, Inc. performed a numerical study[3,4] to determine the amount of bunching and transport to be expected given the existing parameters of a Casino diode as well as the drift length and the current available for the wire. Thinking ahead to multiple beams, a drift length of about two meters was dictated by the relative locations of the Casino diodes, and the maximum of 150 kA source available for the wire current. While a customized diode voltage pulse would lead to ideal beam bunching, in practice modifications to the nominal voltage pulse are very difficult to achieve with consistency. PSI ran particle orbit codes modeled around existing Casino operational characteristics and translated the output into the observable dose rate as measured by photodiode radiation detectors. They predicted a transport efficiency of 85-90% and a decrease in the rise time of the dose rate by a factor of 3-4. These results were sufficiently promising to justify an experimental effort to use grad-B transport to enhance the performance of Casino.

The experiment was arranged as shown in Figure 4. The drift chamber is a 1.85 meter long, 1/4 inch wall PVC plastic pipe 8 inches in diameter. The wire is 12 AWG(2mm dia.) bare copper electrical wire connected to a 30 kJ capacitor bank in coaxial fashion. The current from the bank rings up to a peak value of 150 kA in 15 μs, and the diode is fired near peak wire current. One of the results from the PSI study was that a value of about 150 kA-meters product of the current in the wire and the drift length produced the best beam bunching given the normal Casino diode voltage profile. This implies that a one meter drift tube would yield optimum electron beam compression when the wire current was 150 kA. If the length-current product were too low, not all the high-energy electrons would catch up to the low energy electrons. Should the product exceed the optimium value, it would mean that high-energy electrons were overtaking the low-energy electrons and striking the converter before the slower ones. In both cases, the two groups of electrons would fail to produce optimum beam bunching.

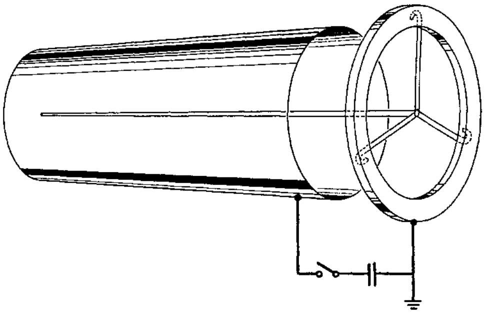

FIGURE 5

The wire was connected at the diode end of the drift tube with a three-pronged feed of 12 AWG wires soldered to the long axial wire. This crow's-foot replaced a 1 mil titanium foil as the current feed when it was discovered that the central portion of the foil, where the current density to the wire was highest, evaporated, and that the blow-off ruptured the anode foil. The effect of replacing the foil by a wire crow's foot will be discussed in section V.

Pressure in the drift chamber and expansion region was held at 1-5 torr to maintain charge and current neutralization of the IREB. Neutrality is significant in the expansion region because it allows the pinched electrons to follow straight line trajectories after passing through the anode foil. The anode foil was 1 mil titanium while the converter foil was 2 mil tantalum backstopped by 1/8 inch thick graphite followed by 1/4 inch Kevlar.

Diagnostics included photodiodes for measuring x-radiation dose rate as well as CaF_2:Mn thermoluminiscent dosimeters (TLD's) for measuring total dose, both far field at 12 and 18 inches from the converter and a cluster of five arranged in a cross pattern adjacent to the Kevlar. In addition, a pinhole x-ray camera monitored radiation patterns from the converter.

During a typical shot, the IREB pinched from a 2.5 inch diameter hollow cathode in a 5mm AK gap. The beam then expanded in a 2 cm expansion region beyond the anode foil and entered the drift tube with the current-carrying wire. Transport efficiencies were defined by the readings of the far field TLD's which measured the total x-radiation dose from the converter after the beam had drifted the length of the tube. These readings were compared to a series of measurements taken previously when, with the wire removed, the IREB struck a 2 mil tantalum converter foil placed at the entrance to the grad B field. In the series of experiments reported here, the converter foils were always held tightly adjacent to a carbon backstop so that enhancement of the radiation dose by reflexing^5 could not occur.

The photodiode signals, which recorded radiation dose rate as a function of time, were compared to detect any difference in the risetime of the dose rate. The source of x-radiation for the rear photodiode was from the tantalum converter, and the x-rays seen by the photodiode facing the diode came mostly from the copper crow's-foot current feed.

All of the machine data and the photodiode signals were recorded on Tektronix 7912 fast transient digitizers.

V. Results

With 100 kA in the wire, grad-B transport efficiencies of 85% were regularly observed. Actually, if efficient transport were the only goal, the value of the wire current would not be critical. Wire currents ranging from 80 kA to 150 kA with the same 1.85 meter drift resulted in similar transport efficiency, and in two cases, 90% transport was recorded. Witness plates placed at the location of the wire crow's foot and at the converter at the end of the drift tube indicated that the electron beam expands to a diameter of 2.5-3 inches in the expansion region, and maintains that diameter to the end of the drift tube.

Dramatic evidence of beam hollowing was provided by the tantalum converter foil. The drifted beam would evaporate a 3 inch diameter hole in the tantalum foil except for a 1/4" diameter piece in the center left intact and hanging on the copper wire which passed through it.

A modest effort to observe the effects of different pressures in the drift and expansion regions on beam transport indicated that transport efficiency was not seriously affected in a range from 1 to 10 torr, but that above 10 torr transport was noticably degraded, presumably due to collisional effects. The bulk of the transport and beam bunching work was performed at 1 torr.

Evidence of beam bunching provided by the photodiodes is shown in Figure 6. The larger curve is the photodiode signal from the converter at the end of the drift tube, while the smaller signal is from the photodiode pointed at the copper crow's foot. The rising portion of these curves is enlarged in Figure 7. The upper curve, labeled "NSWC", is from the photodiode pointed at the converter, and it displays significantly faster risetime than the photodiode signal, labeled "BLUE", which measured the radiation from the crow's foot. Over a series of ten shots the rise time of the dose rate from the converter was 1.5 times faster than the rise time of the dose rate from the crow's foot in four cases, 1.75 times faster in four other cases, and two times faster in two cases. The cause of these differences is still under consideration.

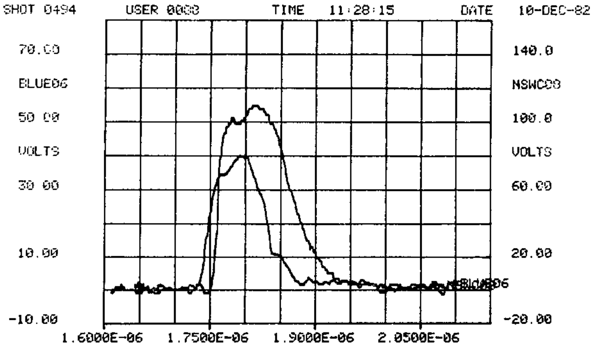

FIGURE 6.

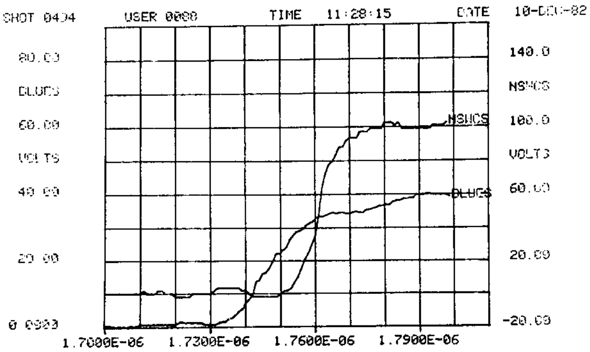

FIGURE 7.

The horizontal axis of Figures 6 and 7 is time, each division being 10 ns. Notice in Figure 7 that the converter photodiode signal begins to rise 20 ns after the front signal. A calculation of the drift speed for this shot predicts a delay between the onset of the two signals of 24 ns, and the other shots in this series show similar agreement with theory.

Figure 8 shows a contour plot and a 3-D densitometer reading of the pinhole x-ray camera film showing the radiation pattern at the converter after transport. These profiles agree with the adjacent TLD readings and are in line with numerical predictions. The valley at 10:00 o'clock in the contour plot is the shadow of the copper wire which was bent 90° to the axis of the tube after passing through the end plate.

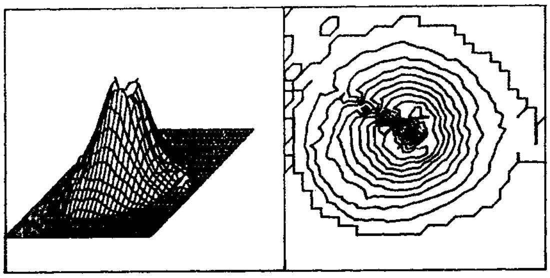

FIGURE 8.

One further observation concerning gradient-B transport is worth mentioning. The wire did not have to be perfectly straight for both efficient transport and beam bunching to occur. In fact a sag in the wire by as much as two inches off axis in the center of the drift tube did not noticably affect performance. This ability of the electrons to follow curved paths is not unexpected since the relevant curvature drift terms, in the complete theory have small effect. This raises the possibility of deliberately having the IREB's from two diodes follow curved paths in some future experiment to impact, for example, on opposite sides of the same converter foil.

VI. Conclusions

Gradient-B transport has fulfilled its promise of transporting efficiently an IREB useful distances and of beam bunching with consequent higher dose rate. However, the theoretically predicted improvements in the dose rate were not observed experimentally. Preliminary analysis[3,4] of the data indicates that the lack of expected improvement in the dose rate is due in large part to the presence of axial and radial magnetic fields within the diode and the expansion region. The radial and axial fields arise from the three discrete wires used as current feeds to the on-axis wire at the diode end of the drift chamber. A thin foil current feed rather than the crow's foot would result in a field-free region in the diode and expansion chamber and a purely azimuthal magnetic field only within the transport region, and the original grad-B calculations were based on these ideal conditions. The Br and Bz magnetic fields within the diode and expansion region produce an effective spreading of the beam at the end of the transport region and thus negate some of the effect of the grad-B bunching. The drift velocity becomes a function of the azimuthal velocity acquired by an electron as it passes through the Br and Bz fields. Since the fields produced by the crow's feet are not azimuthally symmetric, electrons which are emitted from the cathode surface at the same time will have a distribution of azimuthal velocities. This distribution of V_θ velocities causes the electrons which are emitted at the same time to spread out spacially as they grad-B drift in the transport region. This tends to increase the risetime of the radiation pulse and negate the beam bunching caused by the rising diode voltage. Preliminary calculations performed by PSI which include the effects of the crows-feet fields indicate just the expected degredation of bunching observed experimentally.

One relatively easy method for reducing the Br and Bz fields within the diode and still retain the three-wire feed is to slant the feed wires downstream in a conical projection. This geometry reduces the Br and Bz fields within the diode and expansion region. The fields within these regions will be primarily B_θ.

Several advantages of the gradient-B drift technique for increasing the peak radiated power are

1. The maximum beam power incident on the converter can be a factor of 2-4 larger than the maximum diode power.

2. The risetime of the beam power incident on the converter can be much less than the risetime of the diode power.

3. There is no (or minimum) magnetic field in the radiation test volume.

4. This technique can be used with existing radiation test facilities.

5. Grad-B transport is compatible with present diode configurations and requires only a minimum of additional hardware.

6. The maximum radiated power can be adjusted by changing the applied magnetic field (i.e. the current in the axial wire).

As with any technique gradient-B beam bunching for increasing the dose rates has some drawbacks.

1. The power amplification occurs only on the rising portion of the voltage pulse.

2. The technique does add to the complexity of the simulator.

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