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EFFICIENT INJECTION OF ELECTRON BEAMS INTO MAGNETIC GUIDE FIELDS*

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Abstract

Propagation of pulsed electron beams in grad B channels has been studied extensively theoretically[1] and experimentally[2] as a method for guiding such beams at high energy densities onto a converter target to generate intense bremsstrahlung radiation. A key problem in making this approach practical is the efficient injection of the beam from the diode into the drift tube. A method for achieving nearly 100% injection from the diode into the drift channel was developed at Kharkiv State University (KhSU)[3,4] for 50 kA beams. This method uses an injection of the beam from a ring diode into the grad B drift tube with an appropriate transition of the magnetic field from the diode into the drift tube. Scaling experiments have been performed at up to 100 kA level at KhSU and are being extended to >500 kA level on Gamble II generator at the Naval Research Laboratory.

I. INTRODUCTION

Propagation of pulsed electron beams in grad B channels has been studied extensively theoretically[1] and experimentally[2] as a method for guiding such beams at high energy densities into a converter target to generate intense bremsstrahlung radiation. Efficient injection of a high current beam from the diode into the drift tube has been the key issue in making this approach practical for simulator applications. A method for efficient injection from the diode into the drift channel was developed at Kharkiv State University (KhSU)[3,4,5] for lower current beams, ≤ 100 kA. This method uses an injection of the beam from a ring diode into the grad B drift tube, using a gradual transition of the magnetic guide field from the propagation region to the anode window. This is achieved using three rods in addition to the axial conductor, as shown in Figure. 1. This is being scaled to a level of >500 kA beam current, produced in Gamble II generator at the Naval Research Laboratory and supported by modeling studies. The experimental phase consisted of developing a diode injector, transition guide field configuration and drift tube on the 1MV, 100 kA, generator at KhSU.

Typical parameters for the NRL Gamble II test, and the KhSU Nadia generator are I_1 and I_2 of 120 kA and 40 kA, respectively. The diode voltage was ≥1 MV. This hardware was then tested using Gamble II generator for up to 650 kA diode current. Figure 1 shows the electron beam ring diode, injection and drift regions and the guide field (grad B) conductors.

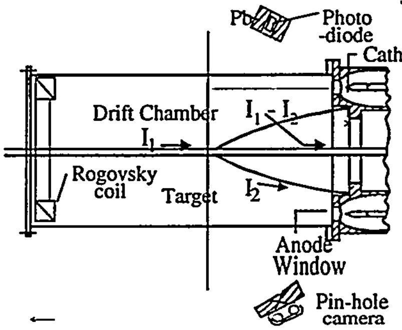

Figure 1. Ring diode, injection and drift chamber assembly for Gamble II tests. Three curved razor blade cathode sections are each supported by two convolute rods for transition from a coaxial generator to the ring diode.

II. MODELING

To evaluate the performance improvement expected as a result of the magnetic field transition from the diode region to the guide region, a simplified model assuming perfect charge and current neutralization in the transport channel and using an idealized two-dimensional description of the magnetic field was developed. The assumption of perfect charge and current neutralization in the transport region is reasonable, based on the rapid breakdown of the background gas by the electron beam and the low resistivity of the resulting plasma. The use of the idealized two-dimensional magnetic field allows very rapid calculations and separates the two-dimensional effects of the magnetic field transition from the three-dimensional effects introduced by the use of rods to form the transition. The effects of the latter were also modelled, as discussed below.

The results for a geometry similar to that used for the Gamble II experiments are shown in Figure 2, assuming normal injection of a 1 MeV electron, a 30 kA guide current in the main transport region, and a 120 kA guide current within the conical transition region.

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DISCLAIMER

Currents of 45 and 95 kA were used in the Gamble II experiment described below, where the beam current was about 600 kA.

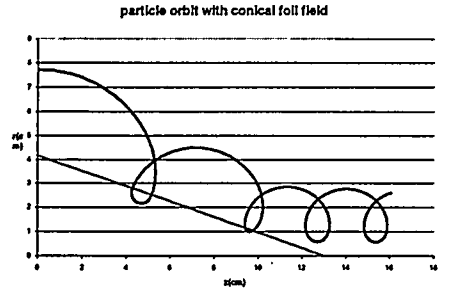


Figure 2. Orbit of a typical electron trapped by the guide-field transition extending to 16 cm.

The model was used to evaluate the acceptance angle of this magnetic field geometry, since the acceptance angle is a primary limit on the end-to-end efficiency attainable by a grad-B drift system. Figure 3 shows the acceptance phase space of the drift system with and without the magnetic field transition region. They coincide for large azimuthal injection angles, but at small azimuthal injection angles the magnetic field transition significantly increases the acceptance angle. The enhanced acceptance is the area between the dotted and solid lines on the figure. If it is assumed that the incident beam has a Gaussian distribution in angle in both the radial and azimuthal directions, and that the distribution is centered at zero, the effect of the magnetic transition region can be evaluated for different distribution widths in the radial and azimuthal direction. Figure 3 also shows the fraction of additional electrons captured with the transition region compared to the case with no transition region. For electron distributions narrow in the azimuthal direction but broad in the radial direction, similar to what would be expected for an annular pinch, the potential improvement is 15-20%.

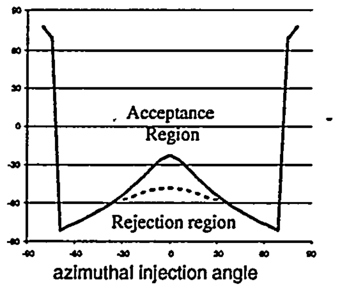
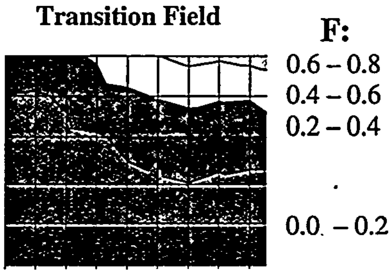


Figure 3. Modeling of electron beam injection dependence on the radial and azimuthal angles of electrons.

This model probably underestimates the improvement in acceptance due to the high field region, since it considers only two-dimensional effects. An important three-dimensional effect of the use of three spokes to define the high field region is that injected electrons gain azimuthal momentum as they interact with the spoke fields, so that they are pushed towards higher azimuthal angles where the radial acceptance angles are broader.

Figure 4 shows the fraction, F, of the electrons lost to the wall, as a function of the radial angle of incidence and of electron energy, using the X-Generator model, which incorporates 3-D characteristics. Comparison of plots of F for transition magnetic field and for uniform field shows that the transition field keeps wall losses low at all energies; substantial enhancements of wall losses (> factor of 2)occur only below about 700 keV.



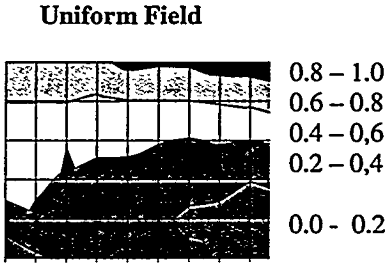
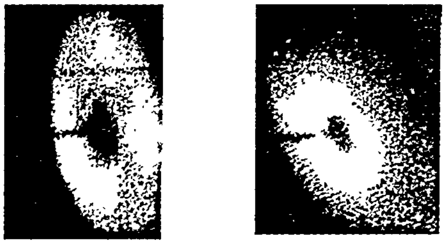


Figure 4. Fraction, F, of the electron losses to the walls, as a function of the electron energy (ordinates – from 300 keV to 1200 keV) and of radial angle of the electron incidence (abscissa – from 0 to 50 degrees).

III. KhSU Nadia EXPERIMENTS

The Nadia generator at KhSU, with an output impedance of about 7 Ohms[3], was used in preparing the hardware of the ring diode and the beam drift structures for the Gamble II generator and to test the performance of this structure. To operate the diode at the same voltage level as that in the Gamble II experiments, the diode impedance was raised by reducing the emitting surfaces and eliminating half of the rods that transfer the energy from the coaxial pulse line to the ring diode. This resulted in dividing the continuous ring cathode into three separate curved razor blade cathodes, each 1.2 cm wide. With 1.2 cm gap between the cathode and the beam injection window (metalized Mylar foil), the diode operated stably at 1.0 – 1.2 MV, with beam current of 90 – 100 kA. This configuration was used to inject three separate beams, each 30 – 33 kA, from the diode into the azimuthal magnetic guide field in the drift region. These currents provided sufficient self-field insulation in the convolutes. However, these currents were insufficient to produce a tight ring pinch at the injection window.

Beam injection and transport were investigated for two configurations of the magnetic field. The first configuration was designed to compress the beam diameter and widen the range of the energies of electrons that are confined by the guide field. This configuration has a gradual transition in the magnetic field in the injection region, which has been obtained by diverting part of the current from the axis using a set of rods shown in Figure 1. The second configuration that was tested is the uniform azimuthal field along the entire drift tube. The x-ray pinhole camera photographs in Figure 5 show the emission of x-rays from the Pb target for both cases. The X-ray pinhole photographs show, (a) an image of initial 100 kA beam propagating in the uniform guide field,with guide field current of 32 kA, to a target at 20 cm and (b) an image of a 100 kA beam,at the same target, injected into mirror guide field,with the axial currents of 32 kA and 106 kA near the target and at the anode, respectively. The diode voltages were 1.0 –1.1 MV. As can be seen, use of the gradual transition (magnetic mirror) leads to beam compression, relative to the injection into the uniform field. The behavior of these beams in the azimuthal fields agrees well with the modeling predictions.


(a) Uniform field
P = 18 Torr

(b) Mirror field
P = 40 Torr

Figure 5. X-ray pinhole images at 20 cm.

Propagation of the beam in the drift region requires a background gas to provide full current neutralization of the beam self-field. However, at pressures optimal for current neutralization, the pulsed guide field may lead to a discharge in the background gas, eliminating almost entirely the guide field from the designated region. Appropriate conditions (gas pressure and composition, materials for the drift chamber walls, guide field rise-time and other factors) for each set of the electron beam parameters must be found to ensure that premature discharge in the background gas does not occur.

IV. NRL GAMBLE II EXPERIMENTS

The main objective of the scaling experiment was to determine the performance of the diode designed for efficient injection of the electron beam at a sub-megampere level and to study losses at the injection and during propagation. The experimental set-up was similar to that for 100 kA experiments, except that the cathode razor blade sections were 7 cm long and six support rods were used. The diode operated between 3 and 4 Ohms for 300 kA tests and 1 – 2 Ohms for >500 kA currents. Doubling the cathode length had no significant effect on the diode impedance, showing that most of the electrons originate at the razor blade cathode.

The first step was to estimate the losses occurring at the anode window in the process of injecting the beam into the drift chamber. Two types of losses occur in the diode, 1) before the beam begins to pinch and 2)electrons are absorbed in the anode structure that supports the 1 cm wide 3-section circular window foil. Lowering of the diode impedance leads to a stronger ring pinching of the beam, consequently injecting more of the beam into the drift chamber. The injection efficiency was estimated by comparing the beam energy injected through the anode window and measured with a carbon calorimeter with the diode energy, as determined from the current and voltage traces. Next, the low voltage electrons that pass through the window and enter the guide field, have orbits that are small, causing the electrons to return to the anode window support ring. Figure 6 shows the three-section rings due to x-rays; the outer and the middle ring show radiation associated with the electrons failing to enter the window. The inner ring is due to the return of the low voltage electrons to the anode.

Two closely reproduced measurements of the beam energy were made using carbon calorimeter giving 11-11.5 kJ at the end of the drift region. The diode energy, based on diode waveforms, was 15-20 kJ, depending on where the pulse is truncated, i.e., on the low-voltage tail). A shot with the calorimeter at the diode (~1 cm from the window), which completely survived, gave 12.7 kJ for the same diode waveforms. This suggests that 64 % - 75 % of the diode energy, truncated when the diode voltage dropped to 300 keV and 500 keV, respectively. This also suggests that the loss in the transport efficiency is < 10 %, with most of the loss


Figure 6. X-ray image of the electron losses at the anode and on the guide field current rods. Electron flow is from left to right.

occurring at the guide current-carrying rods, as seen from the pinhole x-ray images of the drift tube.

To check the experiment against the modeling, the net field resulting from current neutralization, beam outer and inner diameters, as well as beam propagation characteristics for both guide-field configurations, were measured. As the beam current increased, the guide field maintained the confinement of the beam. The degree of current neutralization required for efficient propagation of the beam over longer distances has not yet been measured.

Guide magnetic field, with gradual transition along the axis, was increased to compare with the increase in the diameter of the area excluding the electrons around the axis (dark area in Figure. 5), as predicted by modeling. Experiment and modeling agrees. Changing the guide field configuration to uniform field resulted in poorer confinement of the beam, with an increase in beam diameter at the target; pinhole photographs show substantial, and reasonably uniform, deposition of beam electrons on the wall of the drift chamber. Pinhole camera photographs of the drift tube walls have shown electron losses on the walls, when uniform field was used; this agrees qualitatively with the modeling results in Fig. 4.

Initial analysis of the measurement of x-ray output from a thin tantalum target located 30 cm from the anode provided another check on the efficiency of injection and transport of the electron beam in 10 Torr air. Radiation code at the KhSU was used to calculate the dose in Si and compare it with the measured dose in CaF_2, converted to dose in Si, for the Gamble II shots.. The guide field currents (I_1 and I_2 of Figure 1) in the computer model, are 93 and 45 kA, respectively. The diode current and voltage oscillograms were broken up into hystograms with 17 equal intervals of 5 ns. Nearly all the length of x-ray pulse, with FWHM of 33 ns, measured by the photodiode falls into this time interval of 85 ns.

It was assumed, for the purposes of modeling, that the entire diode beam enters through the anode window into the guide field of the same configuration as that produced by the currents in Figure. 1. X-ray pinhole images and surface damage on the anode indicate that part of the pulse does not enter the window, at least in the early part of the diode current, before pinching takes place. The radial thickness of the beam injected from the diode is taken to be 10 mm (the window width), the electron angular distribution was taken to be 10 degrees. No other angular distributions were analyzed to make any estimates of losses due to this effect. The charge passing through the diode during each interval was calculated. This was used to calculate the dose in each interval, averaged over the output window area, accounting for the Mylar window and 2.3 mm of Al in the dosimeter container. The calculated average dose is 2.15 krads(Si), and the experimentally measured dose is 2.84 krads(Si). The dose distribution on the 100 x 100 mm output window area was also calculated, accounting for the target geometry. The measured dose in the center of the window was 4.17 kads(Si), which seems to be too high. Other results are in reasonable agreement, taking into account the following uncertainties. The dosimeters were calibrated using an electron beam so that the dose measurement error may be appreciable. In the experiment, the Ta target covered completely the chamber cross section, except for a small hole for the axial conductor. In the model, a rectangular target is used whose corners touch the inner walls of the chamber, and some beam electrons could miss the target. There are also errors inherent in the measurements of the current and voltage values.

V. CONCLUSION

Preliminary experimental and modeling study of injection and transport of high current electron beams in current-neutralized background gas has been performed. Initial analysis of the results indicates that high current triaxial ring diode operates very reproducibly in the pinch mode. High current density beam can be injected efficiently into the drift region, using azimuthal guide field with reduced intensity near the injection region. This was shown to improve the effectiveness of capturing the beam for the transport. The transport length was insufficient to measure losses, such as would arise from scattering with the background gas.

VI. REFERENCES

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