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Enhancement of vacuum transmission of intense electron beam through cusp magnetic field using dielectric drift tubes

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Abstract. A technique for improving the transmission of intense electron beams through cusp magnetic field in vacuum using dielectric drift tubes has been demonstrated. The plasma produced by the material of the dielectric tube increases the transmission efficiency by a factor of four over vacuum values.

Keywords. Relativistic electron beam; cusp transmission; dielectric drift tubes.

1. Introduction

Rotating relativistic electron beams have of late been found to be of considerable interest because of their application to the generation of field reversed plasma configurations (Roberson *et al* 1978; Sethian *et al* 1978), plasma heating (Chu *et al* 1974; Roberson 1978) and intense microwave generation (Tzach *et al* 1979).

Rotating relativistic electron beam is commonly produced by passing a hollow laminar electron beam through an axially symmetric nonadiabatic cusp magnetic field. When the beam passes through the cusp magnetic field, part of the axial energy is converted into rotational one because of the $J_z \times B_r$ force, where J_z is the beam's axial current density and B_r is the radial cusp magnetic field. According to single particle orbit calculation (Schmidt 1962), an annular beam of electrons injected into the cusp magnetic field will emerge out with velocity components

$$V_{\parallel} = V_0 \, [1 - (r_0/\rho)^2]^{1/2}$$

$$V_{\perp} = V_0 \, [r_0/\rho]$$

where V_0 is the initial velocity before entering the cusp, and $V_{\parallel}$ and $V_{\perp}$ are the velocities parallel and perpendicular to the magnetic field, respectively. r_0 is the radius of the annular beam and ρ is the electron Larmor radius. Extensive numerical computations (Bora and John 1981) have provided a detailed description of the particle trajectories in the cusp.

Experimental results on injection of short duration high current electron beam pulses into the nonadiabatic cusp have confirmed the theoretical predictions (Friedman 1970a, b; Rhee *et al* 1974). However, it is found that the beam propagation through the cusp is poor and that only 10-20% of the beam particles emerge on the other side of the cusp in vacuum (10^{-4} – 10^{-5} torr) *i.e.* significant amount of the beam particles are lost while propagating through the cusp. This is attributed to the build up of space charge in the cusp region and the resultant loss of axial energy.

To improve the cusp transmission efficiency, Kapetanakos (1974) performed experiments filling the cusp and drift tube with neutral gas. He observed that in the pressure range between 100-1000 milli torr, 85% of the beam energy comes out at the other side of the cusp. The main disadvantage of this technique is that it is always essential to fill the experimental chamber with the neutral gas which limits the flexibility of the experimental configuration. In beam generators with foilless diodes or grid anodes, this option is certainly ruled out as the gas filling would impair the diode performance. In experiments on beam interaction with magnetic fields, such as those studying intense microwave generation, the neutral gas ionization and subsequent current neutralisation of the beam bring additional complexities to the problem.

We report here experiments using dielectric pipes for channelling the beam in hard vacuum and the resultant improvement of beam transmission through the cusp. Use of dielectric guides has been reported in connection with collective acceleration experiments (Little *et al* 1974, 1975). Their application to improvement of beam transmission through a cusp configuration is to our knowledge being reported for the first time. The present study has been motivated by the requirement for producing strong rotating beams for possible application to acceleration of thin metallic foils using the beam magnetic field, where prefilling of the cusp region with either neutral gas or plasma is not feasible.

2. Experimental arrangement and results

The experimental system described in detail elsewhere (Jain and John 1981) alongwith the magnetic field configuration is shown in figure (1). Intense electron beam pulse of nominal parameters 200 kV, 10–12 kA, 80 nanosecond is produced by a field emission diode driven by a 5 ohm co-axial water line, pulse charged by a 20 stage Marx generator. The electron beam is emitted from 4·0 cm o.d., 2·6 cm i.d. annular brass cathode and passes through a six micron thick aluminium anode foil. The beam lasts for nearly 80 nanoseconds. A self integrated Rogowskii coil is used to monitor the diode current. Typical diode current signal is shown in figure (2a).

The magnetic field configuration is produced by a set of spatially dispersed coils energised by a capacitor bank. The cusp is made non-adiabatic by using supplementary windings and a mild steel annular field shaper. The cusp half width is 5·0 cm. The coils surround stainless steel vacuum chamber of 30·0 cm diameter and 2·3 metre in length. The chamber is pumped down to a pressure of 2×10^{-5} torr using vapour diffusion pump.

Perspex pipes of three different diameters (5, 7 and 9·5 cm) are used as drift tube to study the transmission efficiency of the electron beam through the cusp. The perspex tube is placed nearly 1·0 cm after the anode and extended through the cusp plane to the other side upto 20·0 cm. Thickness of the perspex tubes is nearly ten times the range of energetic electrons.

Faraday cup and diamagnetic loop are used as diagnostics to measure the beam transmission efficiency through the cusp. The Faraday cup is made of aluminium with 6·0 cm opening with a graphite disc as the collector. The current collected by

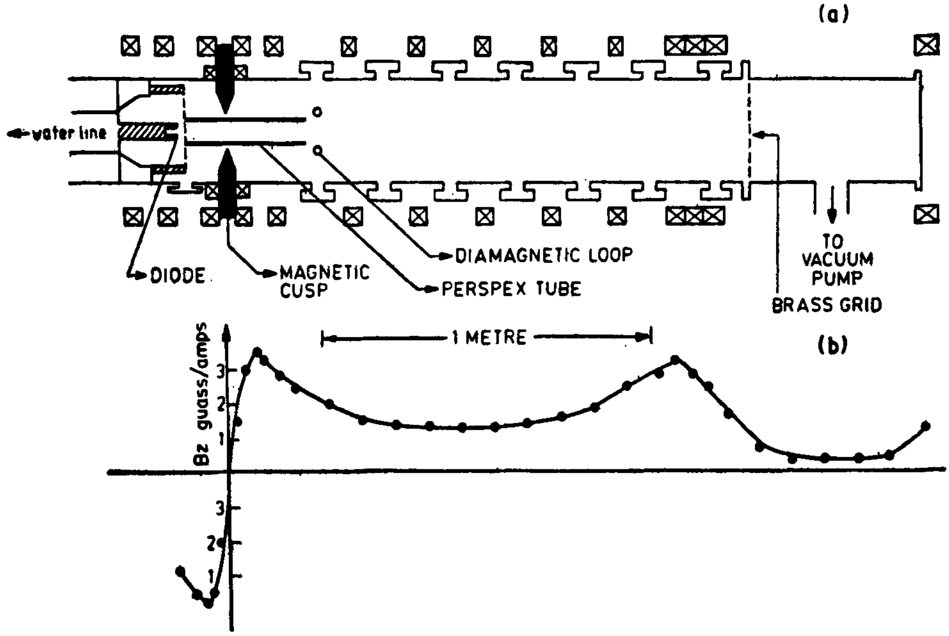

Figure 1. **a.** Schematic drawing of the experimental system. **b.** External magnetic field configuration.

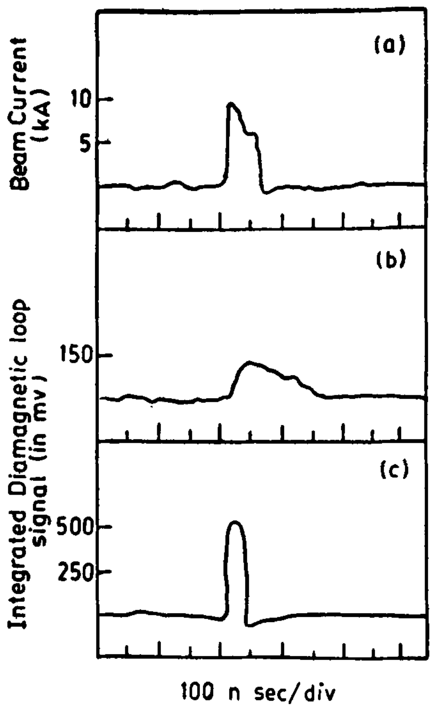

Figure 2. **a.** Diode current signal measured using a self-integrated Rogowskii Coil. **b.** Diamagnetic signal for beam propagated in vacuum. **c.** Diamagnetic loop output for beam propagation using 5·0 cm diameter perspex tube.

the cup is measured using a standard Pearson model current probe. The diamagnetic loop which essentially measures the beam induced magnetic field is made of five turns of insulated wire enclosed in a teflon covered copper tube with a poloidal cut, calibrated using a 35 ampere, 100 nanosecond square current pulse. The output of the loop is terminated and integrated using RC passive integrater at the storage oscilloscope. Both Faraday cup and diamagnetic loop are placed 22·0 cm after the cusp plane.

Though Faraday cups are conventionally used for beam propagation experiments, they are subject to a variety of surface effects such as sputtering and ionization by beam electrons and secondary electron emission, resulting in some ambiguity about the output. In rotating beam experiments, the magnetic interaction between the beam and the eddy currents induced on the collector surface can also lead to perturbation of the current collection. Such effects due to high current beams can be overcome if small Faraday cups (Greenspan *et al* 1980) are used, which sample only a section of the beam. However, our experience is that the beam is not azimuthally symmetric, perhaps due to surface nonuniformities of the cathode, resulting in large shot to shot variations. These considerations have led us to the use of diamagnetic loop which is capable of spatial integration to measure the transmitted beam. The plasma effects which would render the diamagnetic output difficult to interpret is totally absent in the present experiments, as figure 2c shows. There is no evidence even for a partial magnetic neutralisation, from the fast rise and fall of the output.

From the Faraday cup results (figure 3a) it is found that without the perspex drift tube only 8% of the beam particles were able to cross the cusp. The ratio of rotational to axial velocity was 1·8. A typical vacuum signal of the diamagnetic loop is shown figure 2b. The shots for Faraday cup and diamagnetic loop measurements are not identical.

With the introduction of a perspex tube of 5 cm diameter, the transmitted flux increases substantially. We notice that the first shot, after pumpdown from the atmospheric pressure shows significantly large transmission efficiency, after which the transmission continuously decreases reaching a stable value. This is represented in figure 4, where the diamagnetic loop output in arbitrary units is plotted against the shot number. The shot to shot duration is a few minutes, which is typically the time-taken to recharge the Marx generator and to pump out the gas load introduced into the vacuum system, due, perhaps to beam-induced wall desorption. The high transmission efficiency for freshly introduced dielectric tube and the conditioning has been observed in laminar beam propagation experiments and is attributed to the release of adsorbed gases from the tube wall. The enhanced Faraday cup and diamagnetic loop outputs, plotted in figures 3b and 2c respectively are the results after conditioning of the tube, and show an increase of transmission over the vacuum value by a factor of 2·5.

The study of the percentage transmission efficiency of the cusp with different perspex tube diameter shows that (figure 5) the beam transmission increases with tube diameter and then saturates. The maximum transmitted flux is enhanced by a factor of four compared to the vacuum value. The ordinate represents diamagnetic loop output normalized with respect to the vacuum data and in all the cases the perspex tubes are conditioned by firing a few initial shots to remove the contributions from desorbed gases.

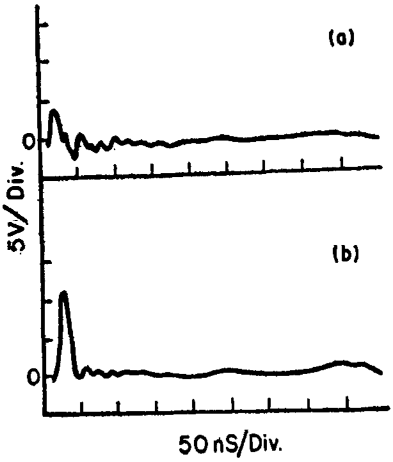

Figure 3a. Faraday cup signal for intense beam propagation in vacuum. **b.** Faraday cup output with a conditioned 5·0 cm diameter perspex tube as a beam guide.

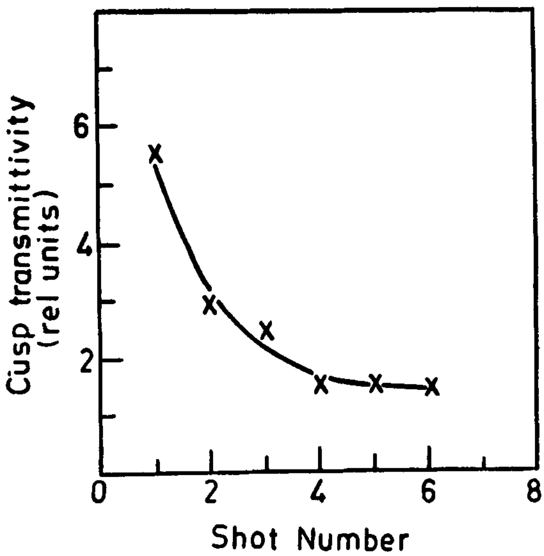

Figure 4. Variation of the cusp transmittivity with shot number after the pumpdown from atmospheric pressure. Diameter of the perspex tube used is 5 cm.

3. Discussion

The reason for enhancement of the beam transmission through the cusp in the presence of a dielectric tube can be explained as follows:

The beam is initially space charge limited and so the beam head strikes the side wall of the perspex tube. The charges are trapped at the surface. These accumulated charges therefore generate an electric field having a large component along the tube surface. The resultant electric field causes breakdown and so either a thin surface layer of the perspex, is sublimated or adsorbed gas is released and ionised, forming a background plasma in the tube. Some plasma electrons would be repelled

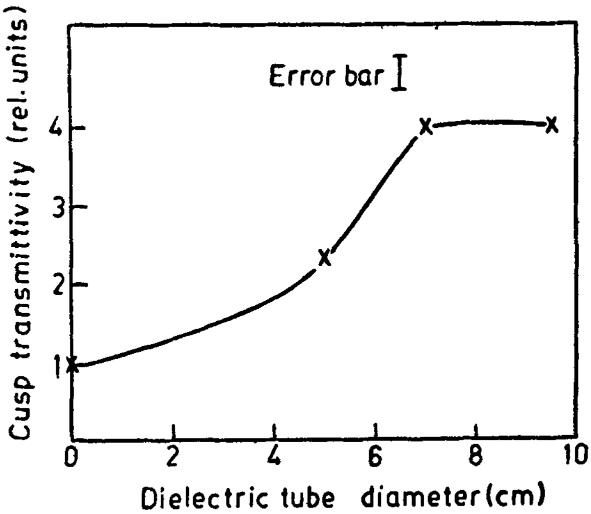

Figure 5. Variation of the diamagnetic loop output with perspex guide tube diameter. B miror = 650 gauss. In all the cases the tube was conditioned with a number of shots.

from the beam column following the beam head by electrostatic repusion, leaving behind stationary positive ions to charge neutralize the rest of the beam and hence improve the beam transmission through the cusp. Since most of the electrons at the beam head are lost at the perspex tube surfaces, an increase in risetime of the beam current with dielectric tube is expected, as observed (figure 2c).

Since the pespex tube diameters were chosen to be larger than the final electron larmor radius, one would expect transmission efficiency to be independent of tube radius. However, recent numerical studies of single particle transport through non-adiabatic cusp (Bora *et al* 1981) have shown that there is a radial translation of the particles at the cusp plane. Although it is difficult to estimate the radial translation due to the beam electric field, it should be an enhancement over the single particle translation. Thus, it is likely that the smallest diameter perspex tube is actually intercepting some of the rotating particles. This would explain the increase in transmission with larger diameter perspex tube and saturation of the transmission when the tube diameter is increased beyond the critical diameter.

The observation of high transmission efficiencies for perspex tubes freshly introduced in the system and its subsequent decay to a stable value is common with experiments for laminar beams and the reason is attributed to desorption and ionization of wall adsorbed gases by the beam. It should, however be noted that in the present experiment, the background pressure is of the order of 10^{-5} torr and the monolayer formation time for most of the atmospheric gases is of the order of 10^{-2} seconds. For water vapour, however, this time is much more than an hour. The time between shots is of the order of a few minutes. Thus it is likely that water forms the bulk of the wall molecules and that the walls are not recharged between shots to contribute significantly to the enhancement of transmission after the first shot, resulting in a reduction of the transmission with each shot. It is important to note that the perspex tube, even after conditioning is capable of significantly higher transmission compared to the vacuum value.

In conclusion, enhancement of the transmission of intense electron beams through a vacuum cusp magnetic field, using the plasma produced from a dielectric pipe has been demonstrated. An improvement by a factor of four over vacuum transmission has been achieved. Further studies aimed at increasing the transmission are in progress.

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