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# ALTERNATE TRANSPORT TECHNIQUES FOR ELECTRON INDUCTION LINACS*

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## I. INTRODUCTION

Recently, there has been a great deal of interest in producing intense, high energy electron beams in induction linear accelerators.[1-5] These machines will have applications in radiation effects studies,[6] intense neutron pulse production,[1] free electron lasers,[7] Tokamak current drive,[8] betatron injection,[9] and plasma heating.[10] Most of the induction accelerators built to date have used solenoidal focusing to confine and transport the beam. For low energy beams near the injector, solenoids prevent space charge forces from disrupting the beam.

While solenoidal focusing is effective in transporting the beam, the total solenoid energy is usually orders of magnitude larger than the beam pulse energy. The requirement for a separate solenoid electrical system at the center of the linac also places an additional physical constraint on linac design. Thus, alternate focusing methods will have significant cost and design advantages if they are effective. In this paper we will outline results and prospects for several of these techniques.

The most obvious of the alternate techniques is to use gas cells between accelerating gaps. The pinch force acts to confine the beam, and use of gas cells has also been proposed to damp oscillations due to the beam breakup instability.[11] Experimental results on a particular facet of this problem - extraction from a magnetic region into a gas cell - are discussed in Section II. The uncertainties, instabilities, and vacuum problems associated with gas focusing can be avoided if conducting foils are used instead of gas.[12] Results from the first experimental demonstration of this 'image' or 'foil' focusing technique are presented in Section III. A proposed improvement on solenoidal focusing is presented in Section IV, using a grounded rod in the center of the transport region. Quadrupole focusing using permanent magnets is not effective in the space-charge dominant early stages of an accelerator. At higher energies, however, quadrupole focusing may be advantageous. One aspect of this problem, a technique for reducing the canonical angular momentum of a beam from an immersed source, is discussed in Section V.[13] All the results presented address high current (> 10 kA) issues, and so assume immersed sources.

## II. GAS CELL TRANSPORT

Beam propagation in neutral gas is an exceedingly complicated subject. It is clear that at low pressures, (P < .5 Torr air) the two stream instability dramatically reduces energy transport efficiency.[14] At high pressures (P > 5 Torr air), the resistive hose instability limits propagation.[15] At intermediate pressures, and low (< 5 MeV) electron energies, unacceptable losses will occur if the net current varies significantly between gas cells. This effect of mismatch in net current has not been explained with a detailed theory; however, it is clearly demonstrated in recent experiments.[16] Assuming that both the hose and mismatch effects are unimportant for the beam at the end of the solenoids, extraction of the beam from the solenoidal field in vacuum to a field-free gas cell is the key issue.

The experimental setup is shown in Fig. 1. Our experiment was performed using the 1 MV, 20-30 kA VISHNU accelerator at the Air Force Weapons Laboratory. The beam was created in a magnetic field in a foil diode with a hollow cathode. The magnetic field drops to near zero a few cm beyond the foil. We have studied energy transport, net current, beam rotation, emittance, diamagnetism, and beam stability in the first 65 cm beyond the diode.

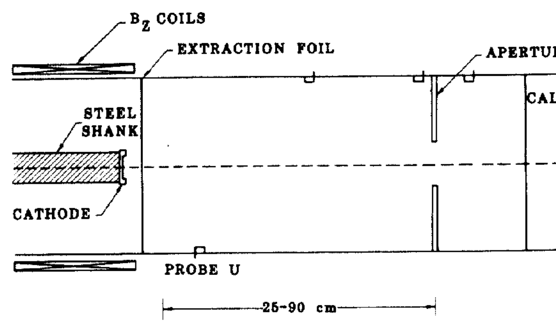


Figure 1. Gas propagation experimental configuration.

Theoretically, we expect that a balance between rotation resulting from the half-cusp field, and the $v_z \times B_\theta$ pinch force causes the downstream equilibrium radius to be

$$\frac{r}{r_c} = \frac{r_c \omega_c}{2c} \left(\frac{I_A}{I}\right)^{1/2} \qquad (1)$$

where $r_c$ is the cathode radius, $\omega_c = (eB_c/\gamma mc)$, $B_c$ is the axial magnetic field at the anode, $I_A$ is the Alfven current, and I is the net (beam plus plasma) current in the gas. In general, we find that the radius measured with radiochromic witness foils, is in good agreement with Eq. (1). The beam is observed to retain its initially annular profile due to rotation, during the first 25 cm of propagation. A marked filamentation instability is observed to develop between axial positions 4 and 25 cm from the foil. This occurs for all pressures. Energy transport exceeds 80% over the short distance observed. If an aperture of 2.5 cm radius is placed in front of the calorimeter at z = 50 cm the transport efficiency is less as shown in Fig. 2. This demonstrates that approximately half the beam is outside of the aperture. Since this attenuation occurs even for hose-stable pressures, we attribute it to filamentation. More information on propagation of rotating beams is available in Ref. 17.

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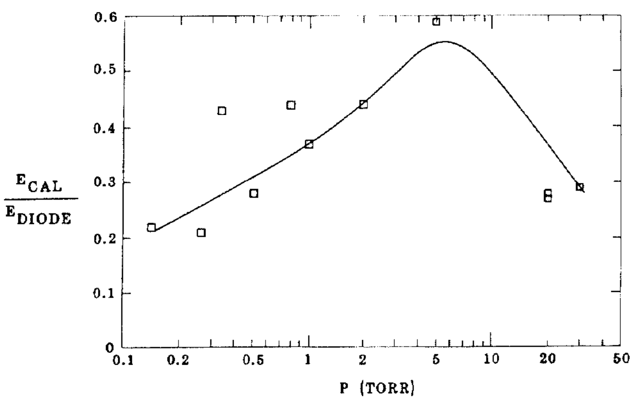


Figure 2. Ratio of apertured transported energy ($R < 2.5$ cm) to injected diode energy vs. pressure for a cathode $B_z = 3.7$ kG.

## III. FOIL FOCUSING

Focusing of an intense beam using conducting foils to supply positive image charge "image focusing" at the center of an intense beam has recently been proposed.[12]

We have performed an experiment in order to test the feasibility of this idea. Operating at ~ 1 MeV and 20 kA, the experimental configuration was as shown in Fig. 3. Best results were obtained when a 10 cm radius drift tube was intercepted by 9 aerodag coated Kapton foils over a 1.1 m length. The system was kept at pressures below $10^{-3}$ Torr and the beam was injected from a 1.5 cm radius solid cathode immersed in a weak (< 1 kG) magnetic field. Current was monitored at axial positions of 0, .5, and 1.2 m.

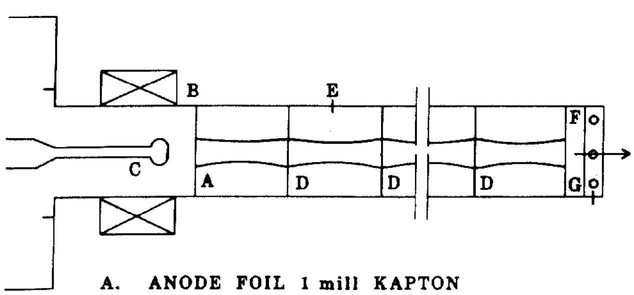


Figure 3. Foil focusing experimental schematic.

Initial tests were performed with single foils at 7.5, 12, and 17 cm from the anode (first) foil. We found that propagation was best for the 12 cm spacing. For the 17 cm case, most of the current was lost before reaching the end plate. This was probably due to virtual cathode formation. In the 7.5 cm case the beam pinched down to a small size at the system end plate. A series of two 7 cm spaced foils showed that at the end plate the beam had dispersed.

In strong focusing systems such as with foils it is possible to over-focus the beam; that is, impart enough radially inward velocity to cause particles to cross the axis. If the crossing angle is sufficiently large, the particles strike the walls before they can be refocused. This probably occurred for the 7.5 cm case above.

Current transport as a function of distance is shown in Fig. 4 for various cathode magnetic fields. Approximately half the current is lost over the first .5 m with approximately 5% loss over the remaining .6 m. Based on the calculations of Ref. 12 the beam is somewhat overfocused in this case. Virtual cathode effects at these low beam energies prevent operation at the optimum foil spacing. In spite of this, the full space charge limiting current one could propagate in the absence of foils is still propagated the full distance. Humphries[18] has performed calculations for a foil focused beam in a pillbox-shaped region. Taking results from Ref. 18 we estimate that the inward force averaged over the axial position between .5 and 1.1 m is ~ .6 $eB_\theta$. In the limit that the foils are close together, we may define an effective divergence angle $\theta$ and betatron wavelength $\lambda$, based on this value. For this experiment we find $\lambda$ ~ 66 cm and $\theta$ ~ 1/2. Emittance box data indicate that the change in the average angle of the electron velocity to the z axis through a foil is also in good agreement with Ref. 12.

We conclude that at higher energies, foil focusing should be effective in confining and transporting an intense beam.

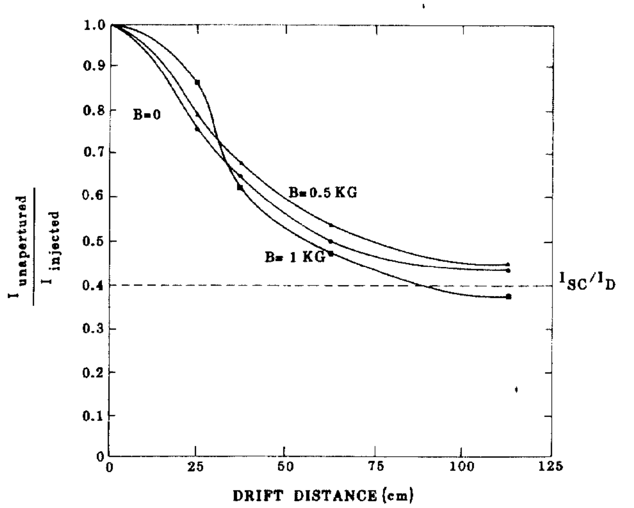


Figure 4. Normalized current transport vs. drift distance for the set up of Fig. 3.

## IV. COAXIAL DRIFT TUBES

A beam transport system which utilizes coaxial drift tubes as shown in Fig. 5 has a number of advantages when compared to a conventional solenoidal system. The most important improvement is in the radial electric field configuration. The system is nearly symmetric around the beam in the limit of close cylinders. As a consequence, both radial oscillations[19] and the image displacement[20] effect are expected to be negligible. This is particularly important in the diode region. The radial component of the electric field is small in this region and production of a very low temperature beam will be possible for this configuration.

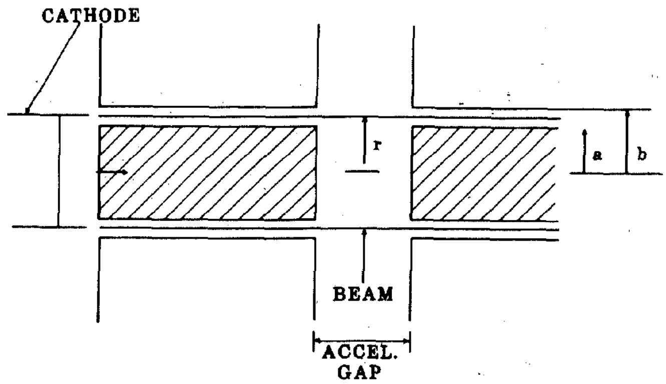


Figure 5. Cross-sectional view of a coaxial drift tube transport system.

Another selling point of the coaxial drift tube system is that the space charge limiting current is increased by a factor[21] $(1 - (\ln b/r)/(\ln b/a))^{-1}$. Note that the coaxial drift tube is similar to the wire-focusing techniques which have been suggested.[11]

## V. ELIMINATING BEAM ROTATION

We wish to address a hybrid quadrupole/solenoid focusing technique. In the early stages solenoid focusing is desirable because of space charge. At the later stages, focusing with permanent magnet quadrupoles has tremendous cost and convenience advantages. Rotation is induced if the beam is removed from the magnetic field, as discussed in Sec. II. This imparts a large outward centrifugal force to beam particles, increasing the required quadrupole strength.

In this section we propose a technique for 'unspinning' the beam, in other words, a technique for removing the net beam canonical angular momentum. Note that bulk rotation does not contribute to the true emittance.

Setting aside specifics for the moment, it is possible to take an annular beam and bunch it slowly in $\theta$. This process is depicted in Fig. 6. The 'final' beam has zero $P_\theta$ around a new axis centered at $x = -a$, and $y = 0$. If the new axis makes an angle $\phi \simeq a\omega_c/2c$ ($a$ = beam radius, $\omega_c$ = angular cyclotron frequency $eB/\gamma mc$) with the old axis along y, the beam will have no $P_\theta$ around the new axis. The magnetic field is arranged to end at the transition point between the two axes.

This technique reduces the problem of eliminating rotation to the task of bunching the beam in $\theta$. This may be accomplished in a number of ways. For example, plates inserted into the beam line will attract the beam if they carry no current (for example, the bunching plate of Fig. 5). A helical array of such plates will attract the beam, and cause the particles to drift in $\theta$ (and r). If the helix pitch is near $v_\theta/c$, the helix field will 'sweep up' the beam in one complete twist. Note that as long as the bunching plates do not carry current, the drift velocity induced varies as $1/\gamma$ ($\gamma$ = relativistic factor).

A number of other helical drift/bunching techniques are also possible. For example, a helical slot near an annular beam in gas could also be used to 'unspin' the beam. As the slot attracts the beam, causing the helical pitch to decrease with axial distance, it applies drag a force on the rotational motion.

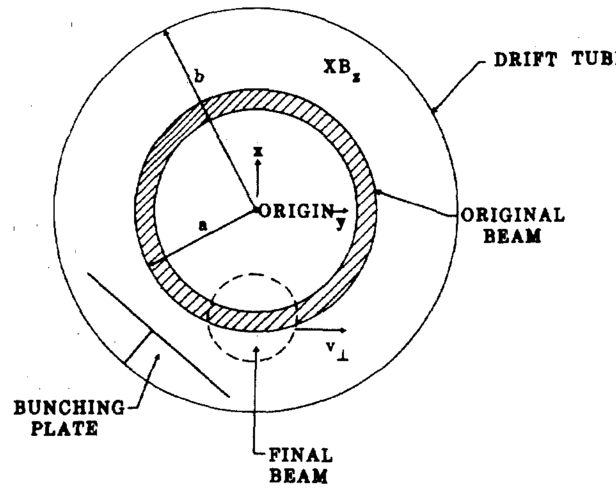


Figure 6. Idealized cross-sectional geometry of the $P_\theta$ elimination technique.

Such techniques should be effective at decreasing the outward force on the beam particles while the true emittance (no rotation) is only modestly increased. This would allow use of quadruples over significant lengths of an accelerator at high currents.

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