ELECTRON AND ION BEAM TRANSPORT TO FUSION TARGETS

J. R. Freeman, L. Baker, P. A. Miller, L. P. Mix,
J. N. Olsen, J. W. Poukey, and T. P. Wright
Sandia Laboratories, Albuquerque, New Mexico, USA 87185

ABSTRACT

ICF reactors [1] have been proposed which incorporate a gas-filled chamber to reduce x-ray and debris loading of the first wall. Focused beams of either electrons or ions must be transported efficiently for 2-4 m to a centrally located fusion target. Laser-initiated current-carrying plasma discharge channels provide the guiding magnetic field and the charge- and current-neutralizing medium required for beam propagation. Computational studies of plasma channel formation in air using a 1-D MHD model with multi-group radiation diffusion have provided a good comparison with the expansion velocity and time dependent refractivity profile determined by holographic interferometry. Trajectory calculations have identified a beam expansion mechanism which combines with the usual ohmic dissipation to reduce somewhat the transported beam fluence for electrons. Additional trajectory calculations have been performed for both electrons and light ions to predict the limits on the particle current density which can be delivered to a central target by overlapping the many independently-generated beams. Critical features of the use of plasma channels for transport and overlap of charged particle beams are being tested experimentally with up to twelve electron beams from the Proto II accelerator.

*Work supported by the U. S. Department of Energy.
I. INTRODUCTION

ICF reactors [1] have been proposed based on multiple particle beams. These designs incorporate a gas-filled chamber of radius 2-4 m to reduce the x-ray and debris loading of the first wall. Although the earliest designs were based on the use of electrons, the recent advances [2,3] in light ion beam production and focusing have led to considerable interest in their use. Light ions appear more attractive than electrons for reactor applications because they can be bunched in time during transport, they can be overlapped more efficiently at the target, and they have more favorable energy deposition characteristics. For near-term proof-of-principle experiments, however, either electrons or ions can be employed.

Current-carrying plasma channels have been proposed for both electrons [4,5] and ions [6]. The plasma channels are very small diameter axial gas discharges which are produced prior to the particle beam focusing and injection. These channels provide a medium to neutralize the self-fields of the beams and also contain azimuthal magnetic fields of sufficient strength to confine the transverse momenta of the particles. Because of the short beam duration, the channel inertia is sufficient to preclude significant radial expansion.

Scaling considerations of the channels are described in Sec. II.

Experimental work on channel production and electron beam transport has been previously reported [5,6,7]. (Preliminary results for ion beam propagation are also now available [8].) In Sec. III we describe results from an experiment in which six beams from the Proto II accelerator were overlapped onto a cylindrical target to study the efficiency of deposition as a function of target radius. These results provide information about the beam distribution function at the channel input. For reactors, laser initiation of the channels has been proposed [9]. Initial studies using a Nd:glass laser are also reported in Sec. III.

II. PLASMA CHANNEL SCALING

In an idealized channel model, the plasma conductivity is infinite at beam injection time and the channel is perfectly rigid in space. As a result, any injected particle beam will be completely space charge and current
neutralized. This means that no collective interactions will occur between beam particles, and the beam transport properties of the channel system may be calculated by single particle trajectory models. The beam particles are guided and confined by the fixed azimuthal magnetic field generated by the channel current. The channel current required to confine the beam is given by the Alfvén current (17,000 Bv) for the case of electrons, and by

\[ I_c = \frac{2\pi \theta^2(2M_iV/Ze)^{1/2}}{\nu_0} \]

for the case of ions where paraxial approximations apply. (SI units employed.) \( \theta \) is the maximum transverse angle of the ions of energy \( ZeV \) in the channel, which is determined by the geometry of the focusing system. For 2 MV electrons, \( I_A = I_c = 85 \) kA; for 2 MV protons with \( \theta = 10^\circ \), \( I_c = 31 \) kA; and for 15 MV carbon +4 ions with \( \theta = 7^\circ \), \( I_c = 72 \) kA. Thus there are a variety of species which can be transported with channel currents less than 100 kA.

For the case of real, non-ideal channels, finite conductivity effects become important and the channel magnetic field may no longer be assumed to be perfectly rigid in space. These effects give rise to several interlocking conditions and restrictions on channel formation and on beam transport. For the case of driving a single channel of length \( l \) by a bank of capacity \( C \) with initial charge voltage \( V_o \), one may analyze the problem by assuming that the channel starts with zero initial radius, expands with constant radial velocity \( s \), and has constant conductivity \( \sigma \). These approximations have been shown to be adequate for present purposes by detailed CHARTB hydrocode calculations and by experiments [7]. For laboratory air, typically \( s \sim 1.5 \) mm/\( \mu \)s and \( \sigma \sim 2 \times 10^4 \) mho/m. One then finds from a simple circuit model that the peak current and the time of peak current are given by

\[ I_{\text{peak}} = \left(\frac{4m}{\sigma^2}\right)^{1/3}V_o \cdot (sC)^{2/3} \cdot (\sigma/t) \]

\[ t_{\text{peak}} = \left(\frac{2C}{m\sigma^2}\right)^{1/3} \]

provided that the bank inductance can be neglected, or \( L_{\text{bank}} \ll \frac{t_{\text{peak}}}{C} \).

This last condition can be difficult to satisfy for systems in which many
channels are to be driven in parallel. Further analysis also indicates that
the average transported beam current density will be

\[ J_B = \frac{V_o I_B}{2LI_c} \]

This important result relates the bank voltage per unit channel length, the
channel conductivity, and the ratio of beam to channel current. Finite
conductivity causes the transported beam to be retarded by the induced
electric field which drives the return current. Simple analysis shows that
the beam will be almost completely current neutralized so that the induced
field is approximately given by \( J_B/\sigma \). If a beam of energy flux \( \Gamma_o \) is injected
into a channel, it will experience a fractional energy loss due to
this induced field of \( \Delta V/V < J_c \sigma /\sigma V^2 \). As the beam loses energy, the channel
will heat up, raising \( \sigma \), thus reducing further loss somewhat. This induced
electric field also can cause some beam envelope spreading, which has been
reported elsewhere [10].

The channels are formed in gas with an initial pressure generally in the
range of 0.1 to 1 atmosphere. The mass density in the channel at beam injection
time is reduced by the discharge from ambient density by factors of from a
few to over 100, depending on gas species, drive level, and initial pressure.
The operating regime must be picked such that the mass density at beam
injection time is low enough so that beam absorption and scattering are low.
CHARTB calculations show that this particular condition is satisfied for
reactor-grade standoff distances by 1 atmosphere air for electrons, and, for
example, by hydrogen at nearly that pressure for ions. (In the latter case,
a few percent of higher Z gas would be added for first wall protection from
pellet x-rays.) One restriction on the minimum acceptable gas density is
determined by the transverse pressure which the beam exerts on the channel
mass via coupling to the magnetic field. This pressure will accelerate the
channel mass outward with the expansion rate limited only by channel inertia. The
regime of importance of such effects may be estimated by

\[ \Delta r_c/r_c \sim \Gamma_0 t_B^2 \rho^2/r_c^2 \beta_{cp} \]
where \( r_c \) is the channel radius, \( t_B \) is the beam pulse length, and \( \rho \) is the ambient gas mass density. (\( \Theta \approx 1 \) for electrons.)

The issue of beam-channel stability can be broken into two parts. The channels themselves will be unstable to perturbations of sausage and kink type, but growth rates of such MHD instabilities will be slow. In a worst case for a typical channel in hydrogen at 0.1 atmosphere initial pressure, effects due to the surrounding gas blanket \([11]\) and channel resistivity combine to yield a calculated growth rate of only \( 0.3/\mu s \). For air, the rates are many times slower. The microinstability of the channels in the presence of the beams is a subject of intense study \([12,13,14]\). Filamentation of the return current could lead to scattering of the beam during transport. Present results indicate that this instability could be important for proton beams at current densities well above \( 1 \) MA/cm\(^2\), and that instabilities in general will be less important in systems with heavier ions such as carbon or electrons in channels.

In a reactor system, the energy used in the channel driver should be kept to a minimum. For a reactor geometry with \( N \) beams and a total beam power \( P \), the energy stored in the magnetic fields of the channels and return current paths and the resistively dissipated energy are approximated by

\[
W_{\text{mag}} = \frac{\mu_0}{4} L I_c^2 \left[ n_{\text{ln}} \left( \frac{n^3 t^2 r_c}{NP} \right) + \frac{1}{4} N^2 \right]
\]

\[
W_{\text{res}} = 2N^2 I_c^2 \frac{t}{\tau_0} \frac{\nu \nu_{\text{peak}}/P}{P}.
\]

About 30% of \( W_{\text{res}} \) would be recovered in the thermal cycle, but \( W_{\text{mag}} \) is in principle totally recoverable. Furthermore, there is the intriguing possibility of letting the expanding pellet debris do work on the surrounding magnetic field and gaining electrical energy by direct conversion \([15]\).

All of the above effects must be taken into account in designing a reference system. The major result of satisfying all the constraints simultaneously for a reactor is that the energy flux injected into the channels must be low, typically only a few TW/cm\(^2\). For example, one reference system might have 36 beams, \( P = 100 \) TW, \( \ell = 2 \) m, \( I_c = 70 \) kA, and \( \Gamma_0 = 2 \times 10^{12} \) W/cm\(^2\).
For these values $W_{\text{res}} = 380 \text{ kJ}, W_{\text{mag}} = 550 \text{ kJ},$ and $\Delta V/V \sim 25\%$ for a 2 MV beam. This set of numbers is consistent for either electron beams or ions beams. The difference between electrons and ions is that further stages of energy concentration such as beam bunching and overlap which are necessary for achieving ignition are more effective for ions. For a non-reactor ignition experiment, of course, the various restrictions are less severe, and satisfactory sets of system parameters may be determined for both electrons and ions.

A method for increasing the power of an ion beam at the target above that available at the source is space-time compression [16,17]. A voltage pulse which rises with time will cause drifting ions generated late in the pulse to overtake those generated earlier. This process of course is not effective with electron beams which are relativistic. Distances over which bunching occurs depends on the shape of the voltage pulse. Practical considerations of voltage accuracy and reproducibility and of triggering simultaneity of multiple modules imply that bunching factors near five are achievable. Bunching distances for protons are up to a few meters typically, so that channel transport will be used with bunching systems unless very low beam divergence is achieved. The principles behind the bunching phenomenon are simple and will be tested in intense, focusing diode experiments quite soon.

Many independently generated beams of charged particles will be transported in plasma channels to a common target. Significant intensification can be achieved by beam overlap at the target, but the degree of intensification is more limited than that obtainable with beams of light. A 3-D trajectory code has been used to optimize multichannel fields and to determine the minimum target radius $R_m$ which can efficiently inter-ent the particle beam. The geometrical overlap radius $R_0$ is defined as the radius at which incoming channel edges merge. For a single coplanar spoke-like array of channels, the overlap radius is related to the channel radius $r_c$ by $R_0 \sim N r_c / \pi$. The current density gain on a cylinder of height $2 r_c$ at $R_m$ is given by $G = \pi R_0 / 4 R_m$ and the code is used to determine $R_m$ for various initial beam conditions. The specifics of the calculations have been elaborated elsewhere [18].

For the case of intense electron beams which have large transverse energy, the channel current will be near the Alfvén current and beam overlap will be limited. With single coplanar disks of 6 to 40 incident beams,
calculations generally indicate $R_0/R_n \sim 4$, so that $G \sim 3$. A multiple electron beam transport and overlap experiment has been carried out at Sandia on the Proto II accelerator. In this work, six beams with about 8 kJ each were transported 46 cm from diodes to a 2 cm diameter cylindrical aluminum target with 90% efficiency. The transport efficiency at small radii is being measured in detail to verify predictions. Confirmation of our overlap model for electrons will lend confidence to calculations which predict higher current density gains for lower transverse energy ion beams.

For ion beams, overlap results will be sensitive to changes in the beam distribution function. The power gain on a spherical target is given by

$$G = \sigma(r_t) \frac{N r_c^2}{4 r_t^2}.$$  

For a beam peaked on axis $\sigma = 1$ for $r_c = r_c / \sqrt{2}$, according to the 3-D trajectory calculations. This predicts that current density gains near 10 are possible for systems like Sandia's 36-module, 30 TW, EBFA-I (under construction [19]). Furthermore, multi-layer arrangements in which the beams are not all coplanar may give substantially higher overlap gains. Supporting calculations are in progress. Systems with two or three layers may be optimum, though the ultimate arrangement will depend on target deposition symmetry requirements as well as overlap gain optimization.

III. EXPERIMENTAL RESULTS

The first experiments designed to study multiple beam propagation and overlap were carried out recently on the Proto II accelerator. Fig. 1 shows the configuration in which twelve separate diode/channel combinations were employed to overlap the beams onto a cylindrical target. The initial experiments transported only six of the beams to the target, with the remaining six terminated at witness plate anodes to assess pinch quality and to provide bremsstrahlung dose data for comparison with the transported beams. The channels had a length of 46 cm and a radius of 0.8 cm. A 100 kV capacitor bank system of 20.6 µF and 230 nH was used to drive the channels.

The accelerator output waveforms are shown in Fig. 2. Experiments were performed using target cylinders of radius equal to $r_o$, the overlap radius of the channels, and $0.6 \ r_o$, where $r_o = r_c / \sin \pi/N$, $r_c$ is the channel radius and $N$ is the number of channels. An x-ray pinhole camera was used to determine
Fig. 1. Photograph showing channels in air. This view is normally blocked by vacuum chamber hardware.

Fig. 2. Waveforms from a Proto II beam propagation shot. Both raw and inductively corrected voltage waveforms are shown on VTAV plot. ITOT and PTOT are total diode current and power.

The azimuthal variation of the deposition in the cylinder. For the target of radius $r_0$, the pinhole photography indicated discrete areas of deposition where the channels intersected the target cylinder; a uniform azimuthal x-ray pattern was observed for the smaller radius ($r = 0.6 r_0$) target. This azimuthal averaging in the case of smaller cylinders could be extremely important for any multi-beam reactor approach since the target loading asymmetries due to low output from one beam would be greatly reduced.

The transport efficiency is determined by comparing the dose to CaF₂ TLD's located directly behind the witness-plate anodes to those located at one end of the target cylinder. The electron-photon Monte Carlo transport code CYLTRAN [20] was used to normalize the results for the two geometries. Although the absolute value of the TLD dose was a sensitive function of the assumed value of the incident electron energy, the relative dose for the two geometries was only a weak function. Assuming an electron energy of $\sim 1$ MeV, we obtained estimates of 94% and 91% efficiency for electron transport to cylinders with $r = r_0$ and $r = 60\% r_0$, respectively. These figures include
the losses due to pinch formation time, channel injection, and beam propagation in the channel. Ion losses are not included. The strong voltage scaling of the inferred deposition tends to emphasize the transport of higher energy electrons. Figure 3 displays these two data points along with a theoretically predicted curve of relative dose vs. radius.

![Fig. 3. Normalized beam transport efficiency. Solid line is calculated and points are data based on TLD measurements for 1.6 and 0.95 cm radius targets.](image)

TARGET RADIUS / OVERLAP RADIUS

For reactor applications, laser initiation of the channels will be required. A pulsed Nd:glass laser (~ 5 J, 20 ns) was used in preliminary experiments to guide 6-12 cm discharges in 200-100 Torr of air. Although guiding of the discharge was clearly observed, the breakdown showed an undesirable tendency to follow internal structures (hot spots) in the focused laser beam. It is expected that a better combination of laser wavelength and target gas would improve the quality of the guided discharge. One combination being studied at the present time is the use of a CO$_2$ laser for molecular-vibrational absorption in NH$_3$ or C$_2$H$_4$. 
References


2. JOHNSON, D. J., to be published.


