grad *B* Focusing and Deposition of Relativistic Electron Beams

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∇B transport, bunching, and focusing of relativistic electron beams give power deposition levels which may provide the absorbed fluxes of 100 TW/cm^2 believed necessary to drive breakeven inertial-confinement-fusion targets. Predicted depositions in excess of 100 (TW/g)/MA are presented here. These levels are up to two orders of magnitude higher than those previously calculated and appear to meet the absorbed-flux requirement.

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Present electron-beam ablatively driven target designs[1] for inertial confinement fusion (ICF) require absorbed power fluxes near 100 TW/cm^2. Recent predictions[2,3] of power deposition for both single and multiple relativistic-electron-beam (REB) scenarios gave mean specific power depositions (MSPD's in absorbed power per unit mass) in the range of 1 – 10 (TW/g)/MA corresponding to power fluxes far short of this requirement. However, a new REB transport, bunching, and focusing scheme has recently been suggested[4,5] which appears capable of producing deposition levels sufficient to drive some breakeven ICF targets.

In this new scheme, electron flow is controlled by an imposed structure of external magnetic fields imbedded in a high-density plasma, $\rho > 10^{-5}$ g/cm^3. In these hot (tens of electron volts) and very dense plasmas there will be only small changes in the magnetic fields on the beam time scale of 10^{-8} sec. In these external magnetic fields, the electrons undergo ∇B drifts which dominate $\vec{E}\times\vec{B}$ drift for the relativistic electrons ($\gamma \approx 3$). The details of the charge and current neutralized beam injection and bunching in the transport region are treated in a separate paper.[4] Here we consider the additional effects of beam focusing and calculate deposition levels in various targets.

By causing a rapid axial transition to a weaker magnetic field, the beam electrons can be made to reflex at the transition and focus to smaller radii. Such a transition occurs when the current-carrying region suddenly expands to include the beam cross section. Two methods of achieving this effect are shown in Figs. 1(a) and 2(a), utilizing a thin foil and a sharp axial plasma current gradient, respectively. The thin-foil case will be considered first.

In Fig. 1(a) an annular beam of 1.0-MeV electrons with an outer radius $r_b = 3$ mm drifts (left to right) toward a thin Cu target foil in the magnetic field of a high-current Cu rod (300 kA). At the foil the current is split between that of a Cu wire (26 kA) of radius $r_w = 0.1$ mm, and uniform plasma current (274 kA) of radius $r_c = 3$ mm. Several ways of splitting the current can be suggested, such as using separate drivers for the wire and plasma currents, or an exploding wire which continues to carry a fraction of the current. Since the magnetic field at a given radius is weaker on the transmission (right-hand) side of the foil, the larger radius of curvature of the sample electron orbit on this side results in a net inward displacement or focusing of the electrons as they take larger inward radial steps on the transmission side, and smaller outward radial steps on the injection side.

The current splitting on the transmission side of the foil is chosen to achieve a stagnation effect. The minimum in the radially dependent field magnitude occurs at a radius $r_{\min}$ much less than the channel radius r_c. ∇B drift on both sides of the foil will then be towards the foil for most of the beam. The current-splitting condition is determined by requiring $r_A^2 \leqslant r_{\min}^2 \ll r_c^2$, where r_A is the radius that encloses the Alfvén current at the initial electron energy. For small wires ($r_w^2 \ll r_{\min}^2$), the current splitting satisfies $(2r_w^2/r_c^2)I_c \ll I_w < I_c$, and $r_{\min}^2 \approx (I_w/I_c) r_c^2$, where I_w is the wire current and I_c is the net current in the plasma. The plasma current density is assumed to be uniform. The condition $r_A \lesssim r_{\min}$ is equivalent to $I_w \lesssim \frac{1}{2} I_A$, where I_A is the Alfvén current (~47 kA at 1.0 MeV). The parameters in Fig. 1(a) give $r_{\min} \approx 0.9$ mm. This method of current splitting is used in the Monte Carlo collisional model em-

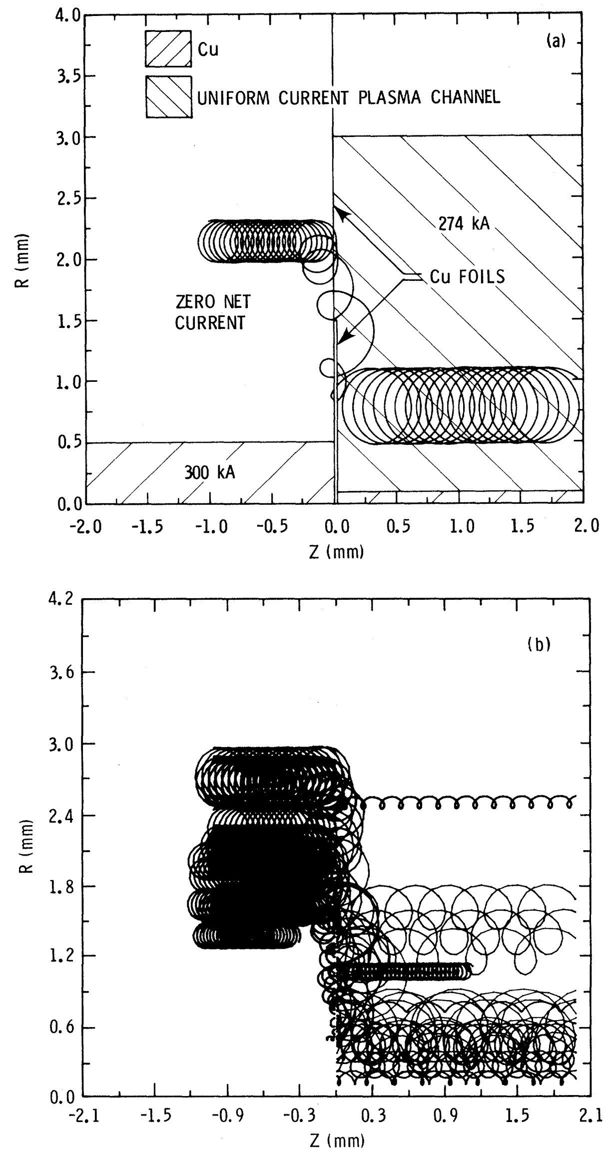

FIG. 1. (a) Sample electron trajectory in ∇B drift transport region with thin-foil transition; (b) random trajectories showing reflexing and focusing at the foil target.

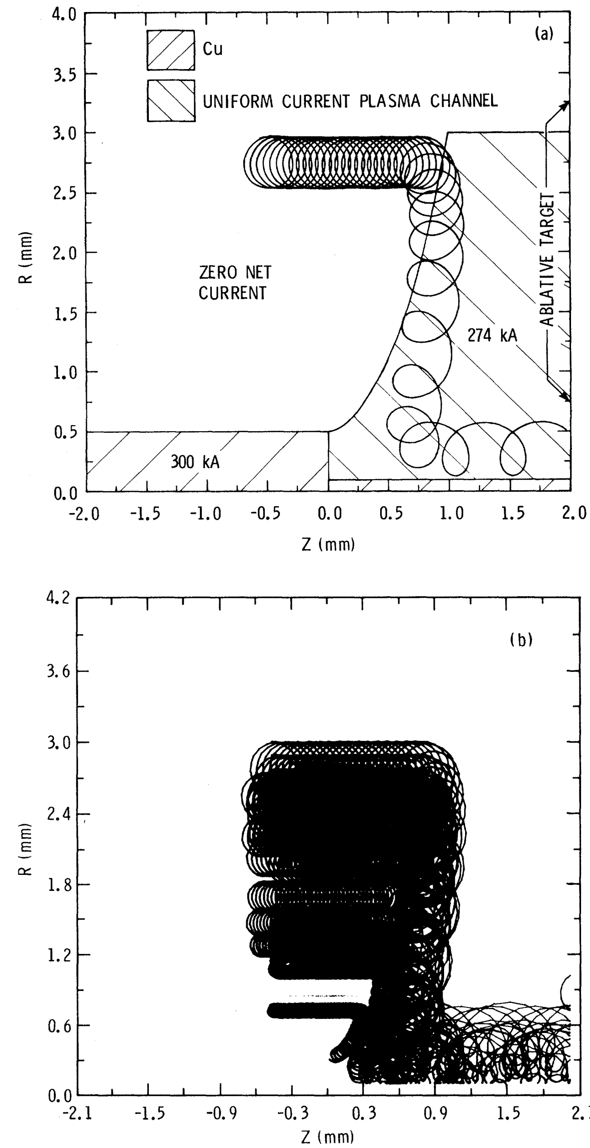

FIG. 2. (a) Sample electron trajectory with axial plasma gradient transition; (b) random trajectories showing collisionless focusing in front of the thick target.

ployed to describe the beam-target interaction. This model has been documented elsewhere.[6] Justification for this model in the present study is based on the assumptions that the externally driven magnetic fields are well established at the time of beam injection and that the plasma conductivity is sufficiently high to short out the beam self-fields on the short time scale of the REB pulse length.

Results from the thin-foil calculation are shown in Fig. 1(b). Beam-electron trajectories were initiated at the plane $z = -1.0$ mm. Position coordinates were sampled from a uniform spatial distribution. Directions were sampled from a cosine-law distribution with two modifications. First, to be consistent with a propagating beam, the radial component of velocity was forced to zero at the outer radius of the beam. Second, the restricted azimuthal velocity distribution due to the initial beam-expansion region[4] was simulated by sampling azimuthal directions within $\pm 10^{\circ}$ of the cylindrical radial position vectors.

The 4-mm-radius target foil was 5 μm thick outside a radius of 1.5 mm and 25 μm thick inside. The purpose of the thinner foil at large radii was to minimize axial loss through curvature drift[2] due to a collisional increase in the azimuthal velocity before focusing had occurred. The 5 trajectories outside r_{min} on the transmission side are examples of curvature-drift loss. Trajectories within the Cu regions are not plotted.

Because of reflexing (about eight passes) the MSPD obtained within the initial beam radius was 96.1 (TW/g)/MA. The additional effect of focusing resulted in a peak value of 140 (TW/g)/MA. This is an order of magnitude above the highest values previously obtained for single foils, and two orders of magnitude above the average value of 1 (TW/g)/MA obtained for various multibeam configurations.[3] The deposition enhancement over the classical collisional stopping power is about a factor of 30.

Although these thin-foil calculations are applicable to near-term exploding pusher targets, it is important to consider deposition in thick targets which can be applied to ablative-pusher breakeven designs. A method of transporting and focusing the beam by an axial plasma gradient is shown in Fig. 2(a), along with a sample trajectory plot. The target foil and resulting step-function transition of Fig. 1 have been replaced by a transition region in which the channel radius is given by $r_c(\text{cm}) = 0.05 + 25.0z^2$. This configuration provides tight beam focusing in front of the ablative target. Figure 2(b) shows sample electron trajectories. Note that there is no collisional scattering into the curvature-drift loss mechanism so that the beam efficiently focuses to the Alfvén radius (0.9 mm) before it strikes the target. The MSPD inside a radius of 1 mm and a depth of 0.5 mm in parylene (C_8H_7Cl) was found to be 50 (TW/g)/MA with a peak value of 97.5 (TW/g)/MA inside a radius of 0.5 mm.

Even without beam bunching, these deposition levels are 1–2 orders of magnitude higher than previously obtained. With a factor of 5 from bunching[4] and an injected beam current of 0.5 MA, the power deposition corresponding to 100 (TW/g)/MA is 250 TW/g per beam without beam-overlap enhancement.[2,7] The deposition in a carbon ablative target should be at least as good as in the parylene because the former is more dense. With a nominal 1-cm-diam, 700-mg carbon target, these deposition levels amount to a deposited power flux of 110 TW/cm^2 for an overlap factor of 2. This power flux should be sufficient to drive some ablative target designs reported elsewhere.[1]

Additional questions need to be answered before the ∇B-drift scheme can be applied to ICF target irradiation. Among these are the hydro effects due to high-current-density bunched beams, preheat, and the design of a realistic spherical configuration with use of multiple beams with ∇B transport and focusing. The favorable deposition levels reported here indicate that further investigations into these areas are worthwhile.

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