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CHARACTERISTICS IN STRONG PINCHES (U)

Thomas P. Wright and G. Ronald Hadley

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ABSTRACT

Radial profiles of electron beam fluid velocity, density, and temperature at the anode plane pinch region are presented for the first time. Beam characteristics are obtained from comparison of empirical and code results. The identification of the radially converging (vs. stagnating) nature of the beam in the pinch region implies that smaller, hotter pinches should be attainable. This result is desirable for attaining power densities interesting for inertial fusion applications.

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The focusing properties of high current relativistic electron beam diodes are under continuing investigation because of the need to optimize the power density for inertial confinement fusion concepts. It has been clearly established¹ that strongly pinching, high aspect ratio diodes (aspect ratio = R/d , with R the diode radius and d the gap width) must have a region of almost purely radial flow. However, the determination of the beam characteristics in the pinch region at the anode has not been previously presented. The relative degree of irradiation symmetry in target experiments² together with the typical pinch dimensions of a few millimeters³ has led to speculation that the beam may be approaching a stagnation limit where the target is bathed in a hot electron gas. However, a study of pinching limits⁴ has shown that minimum pinch dimensions have not been obtained, assuming reasonable initial cathode beam temperatures. Conversely, if the pinches are fully constricted, then cathode beam temperatures on the order of tens of keV are predicted by the model.⁴ Recent work has been reported⁵ on increasing beam temperature by high-Z anode scattering and its effects on pinch dimensions.

Here we report two new developments. The first is a method of obtaining pinched beam characteristics at the anode plane using experimental data to integrate steady-state relativistic fluid equations developed earlier.⁴ The resulting radial profiles of the beam density, velocity, temperature and other macroscopic quantities are semi-empirical, depending only on the local values of the beam in the pinch at the anode plane, regardless of the physical mechanisms which cause or limit pinching in diodes, provided that the electrons remain relatively monoenergetic at the diode voltage. The second development is the identification of the radially converging nature of the beam in the pinch region. This conclusion is strengthened by comparison with a diode fluid simulation code which calculates the electron flow over the whole diode using only the diode voltage and aspect ratios as input parameters.

A novel aspect of the semi-empirical approach is that the beam profiles can be derived from the data without knowledge of cathode geometry or beam flow in the diode. To see how this approach works in principle, we assume that it is possible to determine $J_z(r)$ at the anode using an appropriate diagnostic. The expression for the current density at the anode which occurs in the fluid equation is

$$\vec{J} = J_0 G(a) \vec{a}/a, \quad (1)$$

where J_0 is a constant, $\vec{a}/a$ gives the direction cosines of the fluid velocity, $a = (a_r^2 + a_z^2)^{1/2}$ is a measure of the effective temperature of the beam, and $G(a)$ is an isotropy function.⁴ Since $J_z(r)$ is known, the self-magnetic field B_θ can be determined, and the $J_z B_\theta$ term in the radial

force equation (Eq. 13b, ref. 4b) is a known function of radial position at the anode:

$$\frac{\partial}{\partial r} \left(\frac{G}{a} \right) + \frac{G\vec{a}}{a} \cdot \nabla(f\vec{a}_r) = \frac{2}{r} |J_z(r)| \frac{I(r)}{I_A}, \quad (2)$$

with $I(r) = 2\pi \int_0^r J_z(r') r' dr'$, $f(a) = (\text{acoth} a - 1)^{-1} - 3a^{-2}$, with I_A the Alfvén-Lawson critical current.⁴ Equation (2) can be iteratively solved to obtain $a^{-1} G(a)$ as a function of r , and $(a_z/a) G(a)$ is obtained by setting the z -component of Eq. (1) equal to the experimentally obtained J_z profile. The two integration constants are determined at $r = 0$ where $J_z(0)$ is known and $\vec{a} = a_0 \hat{e}_z$ (no radial fluid velocity on axis for an azimuthally symmetric system). Therefore we can obtain $\vec{a}(r)$ which in turn determines the macroscopic beam characteristics.⁴ A measure of beam stagnation (or reciprocal temperature) is given by the ratio of the fluid speed to the particle speed $b \equiv |\vec{v}|/v_p = \text{coth}(a) - a^{-1}$, while the fluid velocity and beam density profile are given by $\vec{v} = v_p \vec{a}/a$, and $\hat{n} = G(a)/b$.

Turning now to a specific experiment, we consider x-ray pinhole data⁷ of the pinch obtained using the HYDRA accelerator operated at 750 kV, 290 kA. The x-ray film is exposed by the bremsstrahlung coming from the electron deposition in the planar carbon anode. The deposition profile is determined by the electron current density in the axial direction and the electron energy. If the x-ray pinhole profile on the film can be related to the beam deposition at the anode plane, we have a measure of the axial electron current density profile, and the procedure described above can be employed.

Figure 1 contains the axial current density profile as obtained from the pinhole photograph. For the purpose of illustration, we will approximate the profile by a Gaussian with $J_z = J_{\max} \exp(-r^2/r_0^2)$, $J_{\max} = 450 \text{ kA/cm}^2$, and e-fold length $r_0 = 3.12 \text{ mm}$. Although an analytical profile is used here to provide closed form integrations, the integrations can obviously be performed numerically to obtain the beam characteristics from the data itself.

The solid curves in figures 1 and 2 show the semi-empirical profiles of the pinched beam as derived from the data. The density profile is seen to be somewhat broader than the J_z profile in Fig. 1. This is consistent with the flattening⁴ of the beam density profile in high current pinches. In Fig. 2, the beam velocity off axis is predominantly radial, giving a picture of a radially converging beam that is intercepted by the anode. This is consistent with previous work⁴ on minimum pinch conditions which indicate that the pinches obtained to date in diode studies have not approached the minimum pinch limit imposed by the electron fluid equation of state. The axial drift, v_z , of the beam remains small over the whole profile. The degree of beam stagnation or a measure of reciprocal beam temperature is given in Fig. 2 by the curve giving the ratio of the fluid speed to the particle speed. The beam is hotter on axis with $|\vec{v}(0)|/v_p = 0.25$, and grows colder as the radial coordinate increases.

An independent check of the solutions obtained above is accomplished by using a two-dimensional relativistic fluid code⁶ written for the purpose of diode simulation which can predict a set of radial velocity profiles. The code handles electric and magnetic fields,

FIGURE 1

X-ray pinhole data, Gaussian approximation,
and derived beam electron density profile.

FIGURE 2

Radial profiles of normalized velocity components and fluid speed from the model (solid lines) and the 2-D fluid code (dotted lines).

electron emission from the cathode, and ion emission from the anode in a self-consistent way. It is run until a quasi-steady state occurs using only the voltage and aspect ratio from the experiment as input parameters. The results from the code were obtained for a diode voltage of 750 kV and an aspect ratio of ten. The code predicts 200 kA of electron current and 80 kA of ion current. The predicted radial velocity profiles obtained from the code are shown as the dashed curves in Fig. 2. The qualitative agreement between the two sets of curves is good, verifying the radially converging nature of the beam in the pinch region. The quantitative differences do not alter this conclusion, and in fact, may be expected to arise to some degree since the empirical profile may contain additional physical mechanisms (i.e., anode scattering) which are not included in the simulation code. Also, the apparent quantitative variation at large radius in $|v_z|/|\vec{v}|$ is not significant because the Gaussian profile assumed for the semi-empirical results falls below the experimental profile beyond 4 mm, and in the code calculation the error in v_z increases because it becomes small compared to the dominant velocity component v_r .

The advantages of this new semi-empirical method of obtaining macroscopic beam parameters from experimental data is seen in the conclusions which can be drawn from the HYDRA example presented here. It has been shown that, for this data, the beam is still radially converging when it runs into the anode, and that the stagnant picture must be discarded as the pinch limiting mechanism. This picture is consistent with the relative symmetry of irradiation seen in experiments;² radial convergence is as important as the hot electron gas concept.

These results indicate that tighter pinching should be achievable in diodes and suggest further efforts to realize this goal.

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