Electron-Beam Guiding by a Reduced-Density Channel

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A new regime of density-channel guiding of a relativistic electron beam in air has been found using a three-dimensional charged-particle simulation code, and confirmed in a double-pulse electron-beam experiment. The guiding results from the temperature dependence of the electron-neutral momentum-transfer frequency ν_m. The mechanism does not require a deep channel to obtain a significant guiding force. For the 13-kA MEDEA II (and beams of similar parameters), guiding persists 10 ns into the beam pulse with the force per channel displacement as high as 4 G/cm.

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Reduced-density channels play an important role in several applications of transport of charged-particle beams through neutral gas.[1-4] A reduced-density channel improves transport of the beams by reducing energy loss and scatter on the background gas. However, it is necessary that the beam remains in the channel. Recently we have discovered, using the three-dimensional particle-in-cell simulation code IPROP,[5] a guiding force of an initially un-ionized reduced-density channel on an intense relativistic electron-beam (IREB) pulse. The force has subsequently been observed at the Naval Research Laboratory[6] and at McDonnell Douglas Research Laboratories (MDRL). The mechanism does not require the aid of auxiliary guiding equipment, such as wires, lasers, and magnetic fields. In the MDRL experiment, a channel produced by a first IREB pulse was used to attract a second IREB pulse. The results indicate that, under the appropriate conditions, a beam injected into a channel will tend to propagate in the channel. In this paper, cgs units are used unless otherwise specified. Electric and magnetic fields are normalized by e/m_ec^2 and e/m_ec, respectively.

Unlike the classical electrostatic guiding,[7] which is driven by the interaction with a diffuse channel of conductivity, guiding in this new regime results from the temperature dependence of the electron-neutral momentum-transfer frequency ν_m. The higher temperatures found in a channel of reduced density produce a greater ν_m and reduce conductivity and, hence, plasma return currents in that region. This magnetically attracts the IREB. A particular advantage of the "magnetic" guiding is the weak dependence of the guiding force on channel radius and depth. Unlike electrostatic guiding, the channel radius r_c need not be greater than the beam radius a_b to produce a significant guiding force. The magnetic guiding force is produced by the reduced scalar conductivity σ in the density channel. In cm^{-1} units, $\sigma = e^2 n_e/m_e c \nu_m$, where n_e is the plasma electron density. For plasma electron temperatures T_e from 1 to 20 eV, the momentum-transfer frequency in molecular nitrogen roughly scales as the $T_e^{1/2}$.[8] For a weakly ionized gas, the electron temperature in air roughly scales as the electron energy gain between collision with neutrals, i.e., as a linear function of the electric field per neutral density, E/p. Lower-density regions produce reduced axial plasma return currents.

We can derive a simple scaling expression for the early-time guiding force of a beam propagating in an offset sharp-edged channel where the ratio of channel to beam radius is less than unity. The problem is simplified by assuming that the plasma electron generation occurs from beam ionization only and the axial beam current density J_z is constant for $r < a_b$. Thus, the conductivity of ambient air, σ_a, and that in the channel, σ_c, are determined by the ambient air density p_a and the density within the channel, p_c. The induced axial electric field E_z, roughly constant near the axis, drives the plasma return currents σE_z. If we assume that the induced current is small, then $E_z = \mathcal{L}\,\partial\nu/\partial t$, where $\mathcal{L}$ is the dimensionless inductance of the drift tube, typically 3–6, and ν is the beam current in units of e/m_ec^2. E_z is actually driven by $\partial\nu_n/\partial t$, not $\partial\nu/\partial t$, where ν_n is the net current (the sum of the beam and plasma currents). $\partial\nu_n/\partial t$ can be nonzero even when ν is constant. After Fourier decomposition of the fields and conductivities into monopole and dipole components, the dipole magnetic fields resulting from a small channel offset ε are easily calculated from Ampere's law and $\nabla\cdot\mathbf{B}=0$. The fields are driven by two axial-current source terms resulting from the IREB and the induced plasma return currents. Integrating the dipole fields within the beam radius, we find that the beam samples an average dipole force given by

$$F_d = \frac{32}{3}\epsilon\mathcal{L}\frac{\partial\nu}{\partial t}\left(\frac{r_c}{a_b}\right)^2(\sigma_a - \sigma_c)\,. \quad (1)$$

The conductivity may be calculated from the rate of beam ionization, $\sigma = \int\delta\hat{t}\lambda J_z(\hat{t})$, where λ (dimensionless) is given by[5]

$$\lambda \approx 4\times 10^{10}\nu_m^{-1}\,. \quad (2)$$

Accounting for the E/p dependence of ν_m and observing that the constants approximately cancel,

$$F_d \approx \epsilon(\nu r_c/a_b^2)^2[(p_a/p_c)^{1/2} - 1]\,. \quad (3)$$

Thus, the guiding force scales quadratically with the beam current with a weak dependence on channel depth. IPROP simulations show that the force is maximized for $a_b \approx r_c$. A similar scaling formula has been derived by Fernsler[9] for the maximum guiding force given various beam and channel radial profiles.

We generally find good agreement at early times between the above force scaling and IPROP, which has a fully electromagnetic field solver and a complicated air-chemistry package. The theory breaks down late in time when dissociative recombination of the plasma electrons becomes important. The recombination rate is smaller in the low-density regions, causing greater conductivity in the channel and eventually yielding a net repulsive force. In general, the loss of plasma electrons becomes comparable to their production by beam ionization at a time in the pulse given roughly by $10a_b/(\nu p_c)^{1/2}$ cm, for p_c in atmospheres. This channel repulsion should not affect the overall guiding of the beam, since the magnetic coupling of the beam body to the head region is strong.

If the channel force is repulsive in the beam head, the beam will not be guided, as in the case where avalanche ionization is significant. Avalanche ionization is the result of secondary electrons being accelerated by an electric field causing a cascade of new ionizations. It is a strong function of E/p. Too deep a density reduction in the channel initiates an avalanche in the beam head and repulses the entire beam.

The MEDEA II electron-beam generator[10] consists of two oil-filled pulse lines in series, each independently pulse charged by a resonant-transformer-coupled charging circuit. It produces two independent IREB pulses from the same diode with interpulse delays as short as 200 μs. Typical machine parameters in these experiments were 1.2-MV diode voltage and 13-kA maximum beam current in a 10-ns pulse. The IREBs were passed through a short low-pressure gas cell and two scattering foils before injection into the experimental chamber.

The guiding experiment was performed in a 30-cm-i.d. glass tube lined with brass screen. Figure 1 shows the configuration used. The magnetic deflection coil provided a pulsed magnetic field B_y on the order of 10 G. B_y was turned off after the first pulse and was allowed to decay 1.75 ms before the second pulse was injected. By this time, the residual external magnetic field and channel ionization had decayed to negligible levels. The experiment was designed to minimize the effect of the wall forces on the second pulse. The magnetic restoring field of a conducting pipe of radius a_w acting on a beam with a small offset x is given by $F_w = x\nu_n/a_w^2$. Thus, an IREB responds to the wall force by executing simple harmonic motion. The length of the experiment (65 cm) was chosen to be significantly shorter than the oscillation period of this motion (150 cm). If the first pulse is deflected off axis, then the wall guiding and channel guiding forces on the second pulse will be in opposite directions. Thus, channel guiding can be observed unambiguously. The positions of the centroid of ν_n were measured by a resistive-wall current monitor.[11] The neutral density depression was measured with a laser-

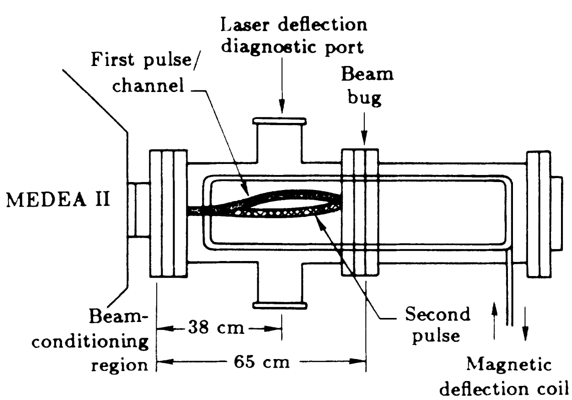

FIG. 1. Configuration for guiding experiments. IREB pulses are injected from MEDEA II into the experimental chamber. The first pulse is deflected vertically by an externally imposed magnetic field; the second pulse is deflected by the channel guiding force.

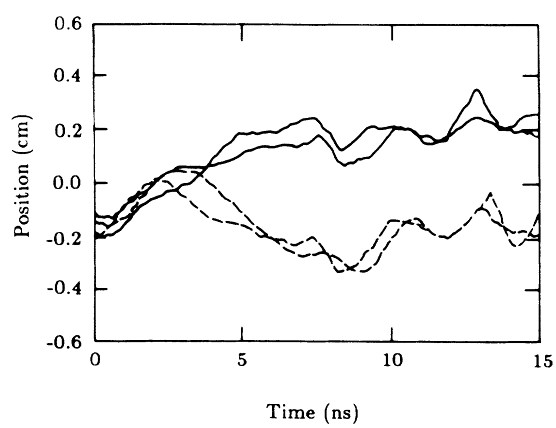

FIG. 2. Raw second-pulse position data in the vertical plane for a series of four shots. The first pulse was alternately deflected up and down. Solid curves: First pulse was deflected up. Dashed curves: First pulse was deflected down.

beam deflection probe.[12] The gas used in these experiments was a mixture of dry synthetic air mixed with a relaxant additive, either CO_2 at a 6% concentration or NH_3 at a 2% concentration. The CO_2 and NH_3 molecules served as energy-transfer partners for vibrationally excited N_2. As the excited N_2 vibrational states were depopulated, their energy enhanced the thermal expansion of the channel substantially.

The strongest guiding occurred at an ambient pressure of 400 Torr. At this pressure, the first pulse produced a channel with a 2.2-cm radius with a 26% density reduction. In Fig. 2, typical raw data for a sequence of four shots fired alternately up and down are shown. There is a small systematic offset when the sum and difference signals are small in the first 2 ns. After 2 ns, the deflections of the second pulse correlated with first-pulse position are clear. Figure 3 shows a summary of all the 400-Torr data points (44 shots were taken at this condition). Systematic offsets in the second-pulse deflections were subtracted from the data, leaving only the correlated deflections. Time slices of the data are shown: A positive deflection indicates guiding; a negative deflection indicates repulsion. The error bars represent 90%-confidence limits of the data. Also shown for comparison is the net current wave form at the same position. Note that the deflection became strong and positive in the body of the pulse. In the body of the pulse, all 44 shots were deflected toward the center of the channel. Similar data were obtained at 550 Torr. A study of the avalanche threshold showed positive deflections above 250 Torr. Lower pressures showed a negative deflection, attributed to the effect of the avalanche. At pressures above 550 Torr, air scattering increases the beam radii and reduces guiding.

We simulated the two-pulse MEDEA experiment at 400 Torr with IPROP by first calculating the x plane position, $x_{ch}(z)$, of the reduced-density channel created by the first pulse. The first pulse was propagated in a magnetic field $B_y = 10$ G. The beam was deflected to positive x until the wall force matched B_y. In the IPROP simulation, the axis of energy deposition was then calculated and assumed to define x_{ch} for the second pulse. The measured channel parameters were then used in the calculation. The mean x position of the second pulse at $z = 65$ cm is plotted in Fig. 3. Note that the beam body moves a maximum of 2 mm in the direction of the channel axis as measured in the experiment. As observed in experiment, IPROP calculates positive guiding for pressures above 250 Torr.

Both simulation and experimental results clearly show that an electron beam tracks an electron-beam-generated channel. The guiding force peaks in the body of the pulse. In the IPROP simulations, the entire beam was attracted to the channel at 400 Torr. The avalanche threshold was observed at 250 Torr for this beam, consistent with the $E/p = 70$ kV/cm atm threshold calculated in simulation.

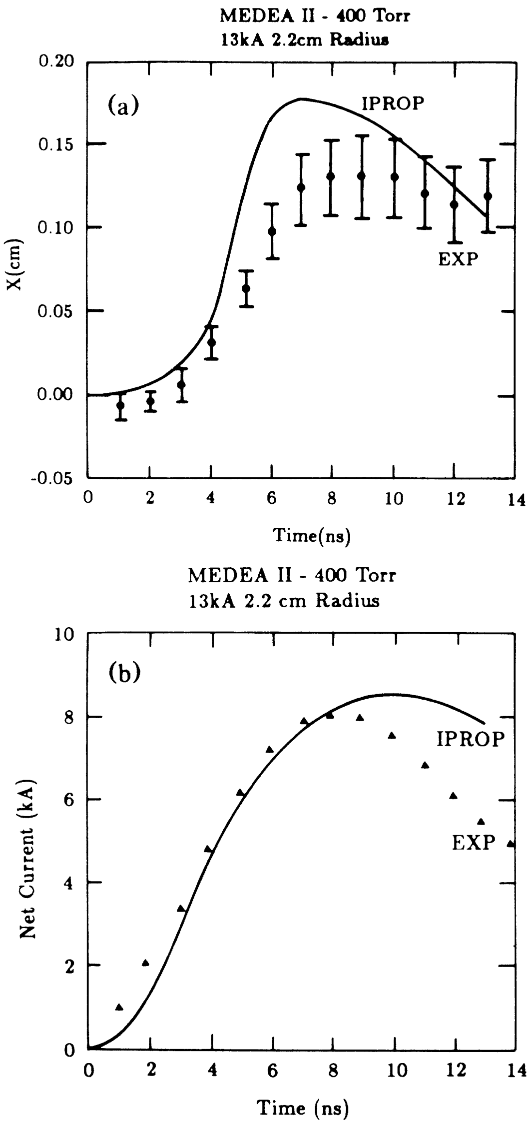

FIG. 3. Comparison between the guiding data and simulation results at 400 Torr as a function of time at $z = 65$ cm with the first deflected up: (a) Mean deflections and (b) net currents of the second pulse.

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