Electron-Beam Guiding and Phase-Mix Damping by a Laser-Ionized Channel

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An ultraviolet-laser-ionized channel in low-pressure benzene has been successfully used to guide and focus a 7-kA relativistic electron beam over distances up to 4 m. In addition, phase-mix damping of coherent, transverse beam motion has been demonstrated. A simple analytical model of the equilibrium beam profile is presented which is in reasonable agreement with the data.

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Laser-generated channels have long been considered as possible methods for particle-beam transport in inertial-confinement fusion applications.[1] Particle-beam transport has been considered in reduced-density channels,[2] gas-breakdown channels,[3] localized gas-filled channels,[4] and in laser-preionized discharge channels.[5–7]

In principle, rapid collisionless expulsion of plasma electrons from a laser-preionized channel in very-low-pressure gas because of the radial electric field of a relativistic electron beam (REB) can produce a positive channel which will guide and focus the beam. This propagation mode is a variation of the highly stable low-pressure "ion-focused regime" noted by Briggs *et al.*[8] in which the gas ionization is due solely to beam-gas collisions. Previously, REB guiding, focusing, and damping by means of an electrostatically charged wire has proven to be a useful technique in the experimental test accelerator (8 kA, 4.5 MeV, 25 ns, 1 Hz).[9] We report here the first use of a uv-laser-ionized channel for REB guiding, focusing, and damping in beam-transport experiments over distances of several meters.

Our experiment was designed to satisfy the following conditions which appeared necessary for channel guiding and damping in the ion-focused regime:

(1) The channel radius should be smaller than the beam radius (~ 1 cm) in order that the radial focusing force be anharmonic and lead to phase-mix damping of transverse beam motion.

(2) The electron-beam density should be greater than the channel-ionization density to assure complete plasma-electron expulsion and to prevent a two-stream instability.[8]

(3) The betatron wavelength λ_β should be short compared to the channel length to assure reaching equilibrium in the channel.

Multiphoton uv ionization of organic molecles can produce a highly ionized channel with molecular ionization fractions approaching 10–20%. From existing data[10–13] on rare-gas–halide laser photoionization cross sections and efficiencies, we estimate that two-photon ionization of low-pressure ($\lesssim 10$ mT) benzene gas with a KrF laser (248 nm) should meet the experimental conditions. The cross sections of benzene with respect to both KrF-laser–induced ionization[10] and collisional ionization via electron beams are well known.[14]

Figure 1 shows the experimental configuration which replaced the wire zone on the experimental test accelerator.[9] A commercial injection-locked KrF laser (Lambda Physik EMG 150 ES) was chosen for its high brightness (500 mJ, 27 ns, 0.2 mrad). The output beam of the laser could be varied (with the use of external telescopes) from an area of 0.09 to 2.6 cm^2. A variable leak valve and differential pumping allowed pressures of 0.01 to 10 mT of benzene in the experimental zone. The benzene pressure profile was constant to within $\pm 25\%$. The experimental zone was separated from the accelerator by a 0.0012-in. titanium foil. Most data were taken in the range of 0.5–2-mT pressure and 0.2–0.5-J/cm^2 laser fluence with small channels (radius $a \simeq 0.25$ cm) and large channels ($a \simeq 0.83$ cm). The laser-ionization fraction was calculated from the measured laser fluence and benzene pressure using a four-level rate-equation model[15] and varied from 0.003 to 0.15. The primary diagnostics on the experiment were resistive-wall current monitors, rf-loop probes, and x-ray-generating wire probes.[16]

Figure 2 shows the beam current at monitor 9 (4.25 m of channel length) at a pressure of 0.5 mT of benzene with the laser on and with the laser blocked. The

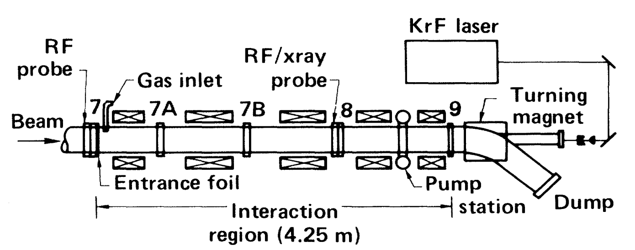

FIG. 1. Experimental configuration on the experimental test accelerator. The station numbers refer to resistive-wall current monitors. Solenoidal transport magnets are shown in cross section.

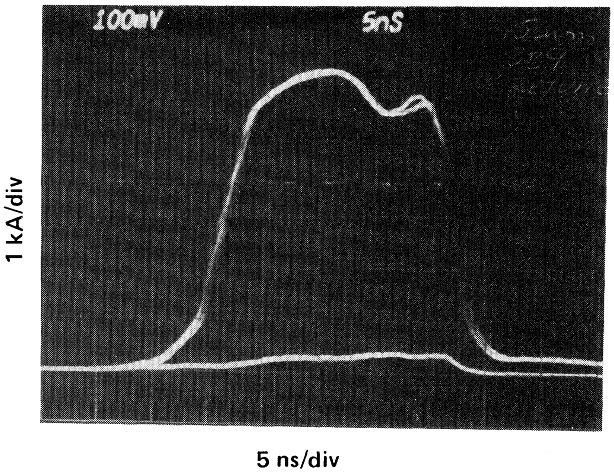

FIG. 2. Beam current at monitor 9 with the laser channel present (upper traces) and with the laser off (lower traces). All solenoidal magnets were off, 0.5-mT benzene pressure, small laser beam ($a \simeq 0.26$ cm), 0.41-J cm^{-2} laser fluence, $n_i \simeq 5.6 \times 10^{11}$ cm^{-3}.

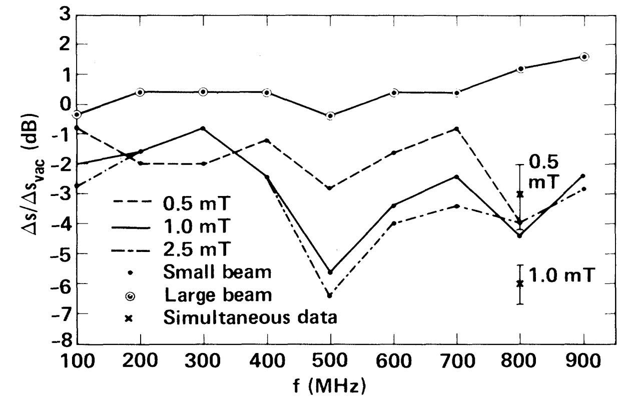

FIG. 3. Laser-channel damping of low-frequency (sweep) and high-frequency (beam-breakup) beam motion. The time-averaged rf-probe signals were measured with a spectrum analyzer and are normalized to vacuum (solenoidal) transport values. Δs refers to the ratio of the downstream-to-upstream signal averages. The two points with error bars were obtained by simultaneous upstream and downstream measurements at 800 MHz of the deliberately excited beam-breakup mode.

laser beam area was 0.2 cm^2 (small channel) and the fluence was 0.4 J/cm^2 with a calculated benzene ionization fraction of 0.03. The transport of the beam pulse by the ion channel over a distance of 4 m in the absence of any guiding magnetic field is clearly apparent. Without the channel, the beam does not propagate. Significant beam transport was observed at benzene pressures as low as 0.01 mT and over the entire ionization-fraction range studied.

The timing of the 27-ns laser pulse with respect to the 20-ns beam pulse was not critical because of the low ion-recombination rate. Advancing the laser pulse 1 μsec with respect to the beam pulse produced about 5% less charge transport down the channel. At 4-μsec advanced timing, 20% of the input charge was still transported at a pressure of 2 mT and a laser fluence of 0.8 J/cm^2.

Damping of transverse beam sweep due both to "natural" causes and to deliberate excitation of the 800-MHz beam-breakup mode[17] over a 2-m-long channel is shown in Fig. 3. These data were recorded by a spectrum analyzer using input from rf-loop probes upstream and downstream of the experimental zone. 2 min or more of data were averaged from each probe. Simultaneous upstream and downstream measurements in the time domain were made for the clearly discernible 800-MHz signal. By comparing downstream to upstream signal ratios using laser-channel transport to those obtained using solenoidal transport in vacuum, relative damping rates could be determined. Damping rates of up to 3 dB/m over a wide range of frequencies are evident in the small channel (wirelike) experiments. As expected, less damping occurred in the large-channel experiments, and, for a given channel size, damping increased with benzene pressure.

The equilibrium electron density profile of an ion channel guided beam may be derived if we make the following assumptions: (1) The ion channel is a uniform cylinder of radius a; (2) all channel electrons are expelled[18]; (3) the e beam is highly relativistic so that its electric and magnetic self-forces cancel to order $\gamma^{-2} \ll 1$ where γ is the usual Lorentz factor; and (4) the beam can be regarded as an isothermal fluid of temperature T. This is equivalent to the assumption of a Maxwellian distribution for the beam transverse velocities. At equilibrium we have $\nabla P = \rho \mathbf{E}$ or

$$k_B T(\partial n_b/\partial r) = -n_b e E_r, \tag{1}$$

where E_r is the channel radial electric field due to the channel ions and k_B is the Boltzmann constant. If λ is the channel linear charge density, then

$$\begin{aligned} E_r &= 2\lambda r/a^2, \quad r \leq a, \\ &= 2\lambda r, \quad r > a. \end{aligned} \tag{2}$$

Solving Eqs. (1) and (2) we have

$$\begin{aligned} n_b &= n_0 \exp(-xr^2/a^2), \quad r \leq a, \\ &= n_0 \exp(-x)(a/r)^{2x}, \quad r > a, \end{aligned} \tag{3}$$

where $x = e\lambda/kT$.

The rms beam radius R may then be found from the equilibrium condition of the beam-envelope equation[19]

$$E^2/R^2 = 2e\langle\lambda\rangle/\gamma mc^2 \tag{4}$$

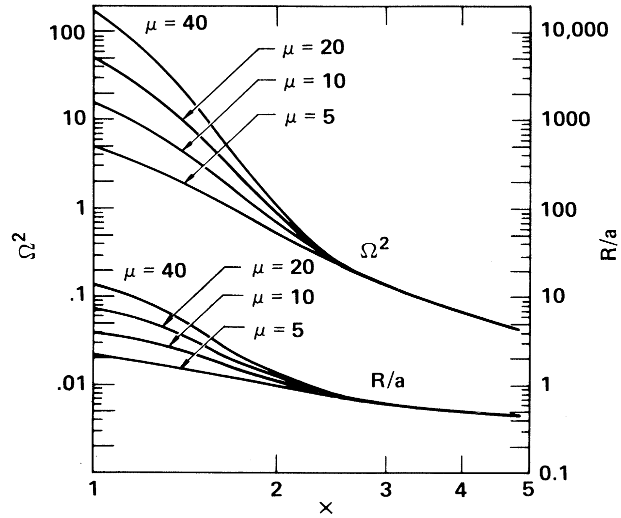

FIG. 4. The functional dependence of Ω^2 and R/a upon x and μ.

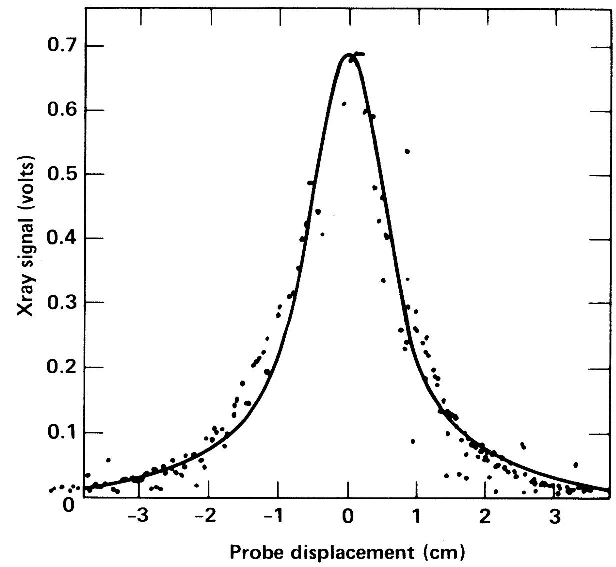

FIG. 5. X-ray wire-probe data (points) and fitted beam profile (line) at monitor $7B$ (2.4 m from entrance foil) for large-channel beam transport, $a \simeq 0.83$ cm, $P = 1$ mT. Each point is one beam pulse. The curve parameters are $x = 1.15$, $\mu = 5$.

where $\langle\lambda\rangle$ is the channel charge density averaged over the beam profile, and E is the unnormalized rms beam emittance. From the definition of x and Eq. (4), one may show that $\lambda = x\langle\lambda\rangle$ and $x \geqslant 1$.

For $x \leqslant 2$, the rms radius is not finite. If we truncate the profile[20] at radius b, and define $\mu = b/a$, we can solve the resulting transcendental equation in x as a function of μ and $\Omega^2 = E^2\gamma mc^2/(2e\lambda a^2) = R^2/xa^2$. Small Ω corresponds to large x and a small beam-to-channel radius ratio, while a large Ω corresponds to $x \simeq 1$ and a large beam-to-channel radius ratio. Our experiment was in the large-Ω regime for even the largest channel that was produced. In Fig. 4, we plot Ω^2 and R/a versus the dimensionless quantity x for various values of μ.

To determine Ω^2 and thus E^2/λ, we used beam-profile data produced by an x-ray-generating wire probe placed 2.4 m downstream of the entrance foil. The probe produces a signal which is proportional to a one-dimensional integration through the beam cross section. Figure 5 shows a typical data set. For comparison, the profiles of Eq. (3) were integrated along one Cartesian axis. For a laser-channel radius $a \simeq 0.83$ cm, the best fit to the profile of Fig. 5 is found to be $x = 1.15$, $\mu = 5$. This gives $\Omega^2 \simeq 3.5$ and $R \simeq 1.67$ cm which implies $E^2/\lambda = 3.0 \times 10^{-4}$. The beam emittance was dominated by foil scattering[21] and was approximately 0.186 rad cm, implying a $\lambda_\beta \approx 94$ cm. The inferred charge density is then $\lambda = 115$ esu/cm as compared with 98 esu/cm obtained from the rate-equation model.[15]

In summary, we have shown that laser-ionized channels in low-pressure gas can guide and focus a high-current REB and can also damp its coherent transverse motion. We have presented a simple model for calculation of the beam profile that is found to be in good agreement with the data. This transport technique should prove particularly useful for high-density long-pulse-length REB's where there will be difficulties in using electrostatically charged wires[9] due to short material lifetimes.

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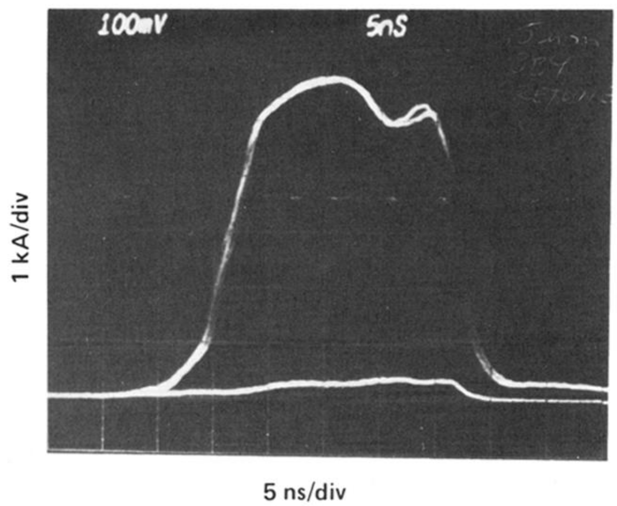

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