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Abstract. A high-energy CO_2 laser is channeled in a capillary discharge. Occurrence of guiding conditions at a relatively low plasma density ($<10^{18}$ cm^{-3}) is confirmed by MHD simulations. Divergence of relativistic electron beam changes depending on the plasma density. Counter-propagation of the electron and laser beams inside the plasma channel results in intense x-ray generation.

INTRODUCTION

High-power CO_2 laser guided in a plasma channel is a prospective driver for the next-generation high-gradient electron accelerators where electrons pick up momentum from the laser photons moving collinear with the laser beam.

When the laser and electron beam motion is changed to counter-propagation, electrons lose energy producing intense x-ray pulses via Thomson scattering. This process can benefit from optical guiding as well allowing efficient use of relatively long laser pulses [1,2].

A number of fundamental and technical problems are to be solved in order to put plasma channel technology to work for the laser/e-beam interaction schemes. Final solutions to these problems are still ahead. Reported here, important steps to this end have been taken during the first plasma-guided laser/e-beam interaction tests conducted at the Brookhaven Accelerator Test Facility (ATF).

Below we describe the capillary discharge technology used to produce a plasma channel, simulations of plasma profiles and laser channeling, demonstration of the CO_2 laser guiding through the capillary discharge, effects of e-beam manipulation by the plasma and the laser, and observation of intense x-rays upon counter-propagation of the electron and laser beams through a plasma channel.

PLASMA CHANNEL FOR CO_2 LASER

Until now, plasma channel experiments have been performed using primarily picosecond solid state lasers. However, the condition for plasma channeling

$$\Delta n_e\left[cm^{-3}\right] \cong 10^{20}/w_L^2\left[\mu m\right], \qquad (1)$$

where w_L is the radius of the laser focus and Δn_e is the radial increase in the electron plasma density from r=0 to r=w_L, is not sensitive to the laser wavelength.

In choosing a laser guiding method applicable to the ATF laser/e-beam interaction experiment, we apply the following selection rules: First, the plasma density needs to be lower than 10^{19} cm^{-3} which is the critical density for the 10-μm beam. Second, to be useful for Thomson scattering observation, the channel shall not obscure the produced x-ray cone. These requirements eliminate the use of a narrow micro-capillary and practically rule out methods based on optical breakdown in gas.

We select the capillary discharge scheme [3] that allows control of the plasma density. It has been demonstrated previously that the laser beam can be confined in a plasma core ~10 times smaller than the physical diameter of the discharge tube. This allows interaction between the laser and electron beam and extraction of the Thomson scattered x-rays without obstruction by the tube walls.

The on-axis plasma density obtained in the previous capillary discharge experiments is $(3\div5)\times10^{18}$ cm^{-3}. That is in proximity to the critical electron plasma density $n_{cr}=10^{19}$ cm^{-3} for the $\lambda=10$ μm radiation to compare with 10^{21} cm^{-3} for $\lambda=1$ μm.

CO_2 laser pulse propagating in subcritical plasma will lose its energy due to inverse bremsstrahlung over a distance

$$L_D = \frac{\omega_0^2}{\omega_p^2}\frac{c}{\nu_{ei}}, \qquad (2)$$

where ω_0 is the laser angular frequency and ω_p is the plasma frequency; $\nu_{ei} = N_i v \sigma$ is the electron-ion collision frequency, v is the electron velocity and σ is the cross section for momentum transfer collisions.

Understanding that both ω_p^2 and ν_{ei} are ultimately proportional to the electron plasma density n_e we see that L_D scales with n_e^{-2}. To calculate L_D at $n_e<n_{cr}$ we need an estimate for ν_{ei}, which is a function of the atomic content, degree of ionization, electron and ion temperature. For typical conditions of hydrogen plasma, $v\sigma\approx1.6\times10^{-7}$ cm^{-3}s^{-1} and $L_D\approx2$ cm @ $n_e=10^{18}$ cm^{-3}.

Thus, in order to adopt the plasma channel technique to a CO_2 laser, the plasma density needs to be downscaled by 1-2 orders of magnitude to compare with that previously demonstrated in capillary discharges. Fortunately, the plasma density is a strong function of the discharge current and the inner radius of the capillary tube, $n_e \sim IR_{cap}^{-2}$ [3]. Following this algorithm, the increase of the capillary radius to 1 mm shall make the plasma density range of $n_e=10^{17}\div10^{18}$ cm^{-3} accessible.

Simulations of CO_2 Laser Channeling in Capillary Discharge

Spatial and time dependence of plasma electron density and temperature in the electrical capillary discharge has been evaluated by one-dimensional MHD simulation.

The discharge plasma is originated via the capillary wall ablation. The plasma-wall interaction is modeled by considering the material of the wall as a cold neutral gas with atomic number $Z=7$, average atomic weight $A=14$, and initial density $\rho_0 = 1$ g/cm^3 that corresponds to the actual chemical composition CH_2 for the capillary material. The capillary plasma is driven by a current pulse approximated by the empirical formula that corresponds to the actual electrical parameters of the discharge used in the experiment.

The MHD simulation results shown in Fig.1 predict obtaining plasma channel conditions (radial increase of the plasma density) in the range of $n_{eo}=(1\div4)\times10^{17}$ cm^{-3}. Fitting the parabolic approximation

$$n_e = n_{e0}(r=0)\left[1+\frac{r^2}{R_{ch}^2}\right] \qquad (3)$$

to the simulated plasma profiles, we obtain the channel radius $R_{ch}=425\div450$ μm. The focal radius is matched to the channel radius and plasma density by the condition $R_{ch} = k_{p0}w_L^2$ [4], where $k_{po} = \omega_{p0}/c$. The best fit of Eq. (3) to the simulated profiles produces $w_L = 55\div75$ μm. Simulations of laser channeling in the same moderately dense plasma $n_e=(1\div4)\times10^{17}$ cm^{-3} confirm a possibility of the CO_2 laser pulses confinement inside the capillary discharge [5]. Together with the parabolic plasma profile produced in the capillary discharge, the model considered plasma response to the relatively long laser pulse that leads to the radial ponderomotive plasma expulsion and ponderomotive self-focusing of the laser beam. The simulations show that under the present experimental conditions (linear regime) the matched laser beam propagates along the channel without oscillations and distortions.

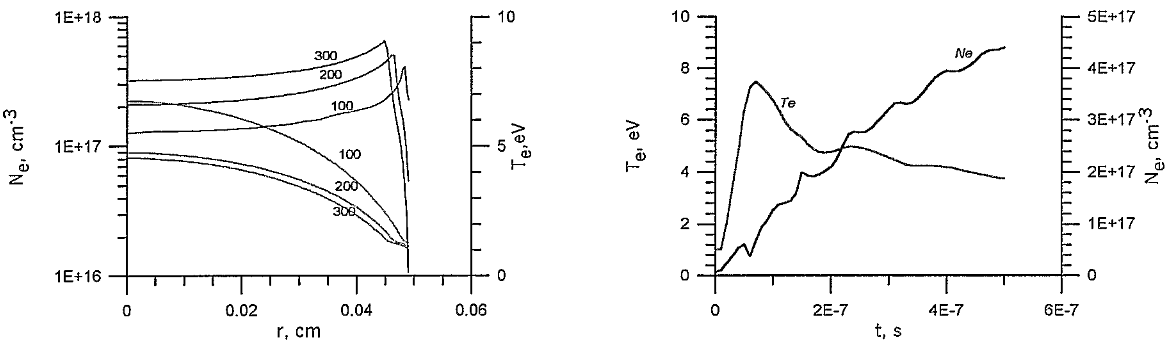


FIGURE 1. MHD simulations of the plasma channel formation in the capillary discharge

Observation of CO_2 Laser Channeling

The interaction cell used in the experiment (see Fig.2) incorporates focusing parabolic laser mirrors, a capillary setup, and in-vacuum high-voltage PFN. A polypropylene capillary tube of the 1 mm inner diameter and 18 mm length is mounted on a combination of translation and tilt manipulators. Standard electrical feedthroughs transmit high-voltage potentials to the PFN. The cell is pumped down to 10^{-5} torr.

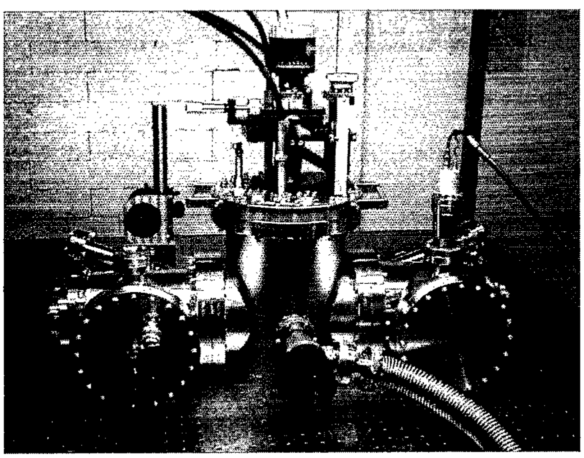


FIGURE 2. Picture of the interaction cell

The 200-ps, 100-mJ CO_2 laser pulse was focused at the entrance of the capillary. The output laser beam has been imaged with the 8X magnification to the pyroelectric video-camera. Intensity distributions shown in Fig. 3a and 3b are obtained in "free space" (capillary retracted). Note that in order to stay within a linear response of the camera and the frame-grabber, images 3a and 3b are obtained with different attenuation. This permits measurement of the beam size that, as we see, expands approximately 6 times in diameter between the observation points spaced by ~$6z_L$. The best channeling condition is obtained at the 17 kV voltage applied to the capillary, peak current ~400 A, and the laser pulse delayed by ~120 ns relative to the first current peak. We see in Fig.3c how the laser beam at the output of the capillary is kept confined close to the input focal size.

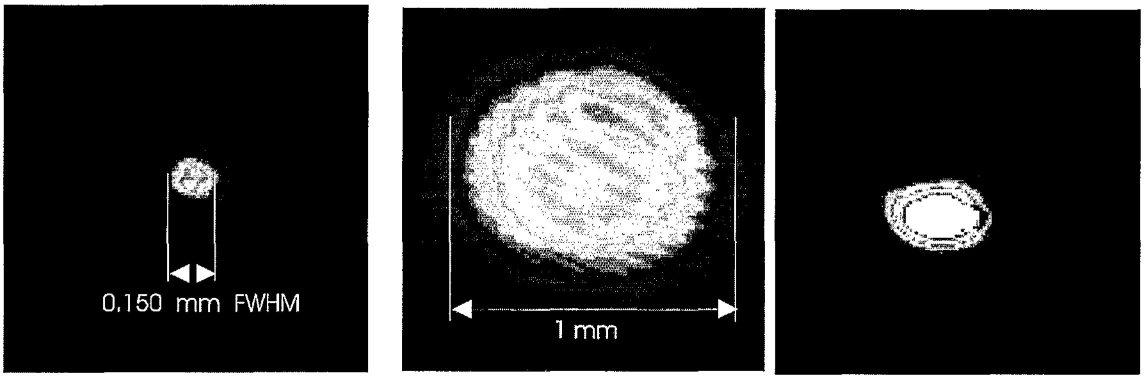
LASER/E-BEAM INTERACTION IN A PLASMA CHANNEL

The 60 MeV, 0.5 nC, 5 ps electron beam and 5 J, 180 ps CO_2 laser beam have been brought in counter-interaction within a capillary discharge. The prime diagnostics used included: two e-beam profile monitors (BPM) located after and below the 90-deg dipole that is a part of a high-resolution electron spectrometer, x-ray detector placed at the beamline exit behind the 250 um Be window, and IR camera that images the CO_2 laser. The location of the interaction cell in the electron beamline and x-ray diagnostics is shown on Fig. 4.

Fig. 5 shows smearing of the e-beam profiles on both BPM screens in the presence of plasma. The effect gradually disappears over the 5 μs after the discharge. This behavior can be explained by the "plasma lens" effect.

Observing interaction of the e-beam with the laser we set synchronization to the "zero" of the discharge current to eliminate effects of the magnetic field. Synchronization of the laser and electron bunch was independently verified by maximizing the Thomson signal that results from the free-space interaction between the laser and electrons. This does not effect the e-beam profiles shown in Fig.5. However, when the laser interacts with the e-beam inside the plasma capillary the e-beam practically disappears from both screens. Simultaneously, we observed strong x-ray signal. Although a part of this signal may be due to the

Thomson scattering effect, a significant contribution is due to enhanced bremsstrahlung. This indicates that the e-beam is strongly manipulated by the laser beam in plasma and is partially lost inside the capillary or on the mirror. This can be explained by the strong e-beam focusing in the course of ponderomotive expulsion of the plasma electrons by the intense laser beam.



(a) (b) (c)

FIGURE 3. CO_2 laser beam profiles:
a) at the focal point; b) 18 mm downstream from the focus in the free space propagation; c) at the exit of the 18 mm long plasma discharge with the capillary entrance placed at the focal point

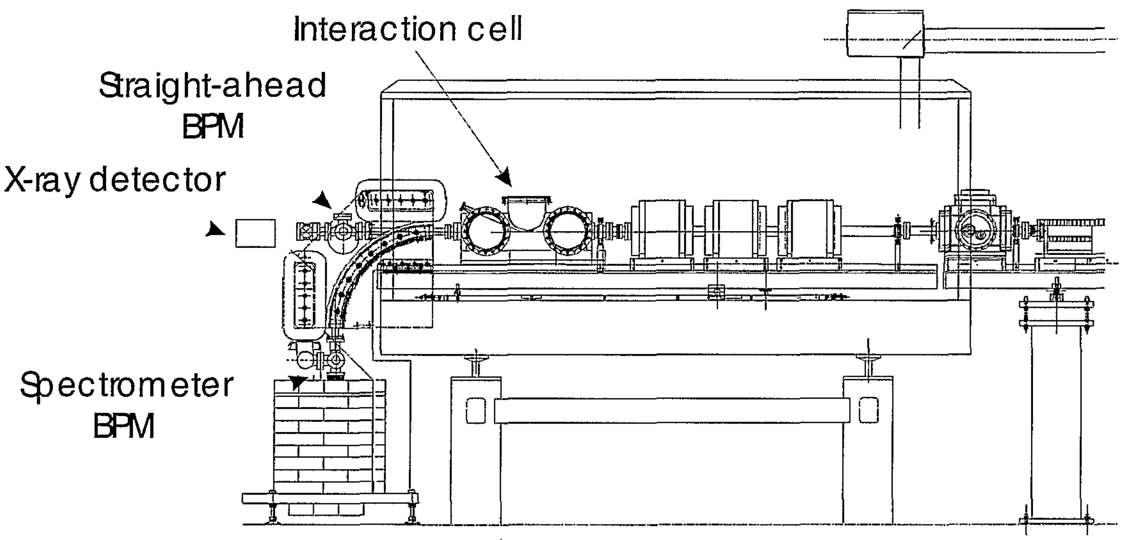


FIGURE 4. Diagram of the laser/e-beam interaction experiment

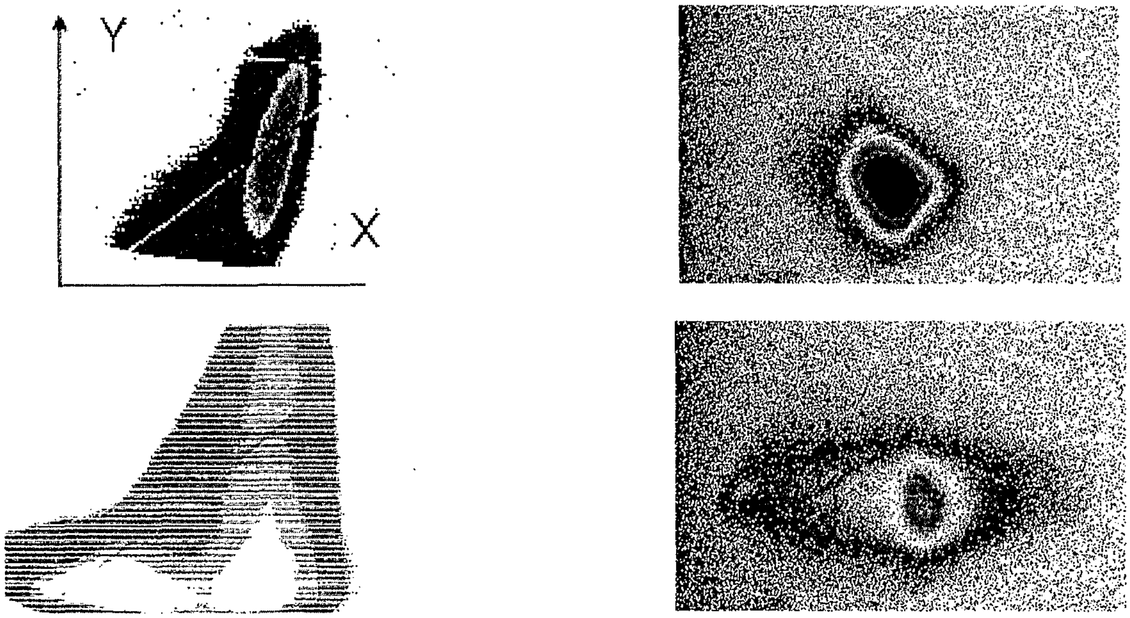


FIGURE 5. Left - spectrometer BPM images (X axis - beam energy), Y –horizontal profile of e-beam; Right - straight ahead BPM images. Top – no plasma; Bottom – 1 μs after discharge.

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