Highly ionized Ar plasma waveguides generated by a fast capillary discharge

B. M. Luther, Y. Wang, M.Berrill, D. Alessi, M. C. Marconi, M. A. Larotonda, and J. J. Rocca, Fellow IEEE

Abstract - **Highly ionized Ar plasma channels were created by a fast capillary discharge and used to guide laser pulses with peak intensities up to 2.2 x10^{17} W/cm^2 over a 5.5 cm distance. These plasmas are of interest for the generation of efficient soft x-ray lasers by longitudinal laser excitation. The guides were characterized using plasma interferometry, modeling and near field imaging.**

The guiding of intense laser beams in plasmas has attracted significant attention [1-7]. This is motivated by the need of extending the interaction length between intense laser pulses and plasmas beyond the limitations set by diffractive defocusing and ionization-induced refraction. An application of considerable interest for plasma waveguides is the longitudinal excitation of soft x-ray lasers that can potentially result in saturated amplifiers with reduced laser pump energy and increased efficiency.

Herein we report images related to the characterization of multiply ionized plasma waveguides created by a fast Ar capillary discharge of the type used to develop collisional soft x-ray lasers [8]. The experiments used ~ 2.5 ps, 800nm Ti:Sa laser pulses, except for the demonstration of high intensity beam guiding that was done using ~100 fs pulses. The discharge utilized 3.2 mm diameter, 5.5 to 11 cm long Al_2O_3 capillaries filled with 180 to 250 mTorr of Ar. The discharge current pulses had a peak amplitude of 15 to 21 kA and a half-period of ~ 120 ns. Interferometry of the plasma shows the evolution of an annular plasma shell with density minimum at the center that constitutes a waveguide of continuously decreasing diameter and increasing density until it collapses on axis (Fig 1). The plasma compression is accompanied by an increase in the degree of ionization, reaching Z = 8 shortly before the collapse, as corroborated during these experiments by the observation of lasing at 46.9 nm in Ne-like Ar.

The guiding properties of a 5.5 cm long capillaries were investigated by imaging the output of the capillary (Fig. 2, right) and by modeling the beam propagation using the Kirchhoff-Fresnel integral inputing the radially dependent phase delay determined from the interferometrically measured density profile (Fig.2 left). For times less than 30 ns with respect to beginning of the current pulse the plasma density is low and the peak of the electron density is far from the axis, resulting in no guiding of the beam. When the plasma column compresses to ~800 μm in diameter the wings of the laser pulse begin to experience a phase shift that results in output modes with concentric circles as shown in Fig. 2a. As the column continues to compress a variety of lower order modes, such as that illustrated in Fig 2b, are seen. Fig 2c shows an approximately gaussian output mode with a FWHM of ~ 50 μm. Subsequently the guide is lost as the plasma pinches and the electron density profile becomes convex, resulting in the beam being strongly refracted as shown in Fig. 2d. The development of a second guiding phase was observed to take place during the first few ns of the expansion that follows the pinch, as seen in Fig. 2e. However the post-pinch guides are significantly more leaky.

Channels composed of Ar VIII or Ar IX ions are immune to tunnel ionization for intensities < 3 x10^{16} Wcm^{-2} and < 1.5x10^{18} Wcm^{-2} respectively. We verified that the pre-pinch matched guides are maintained at high intensities by injecting pulses with a measured average energy of 500 mJ and pulse duration of 112 fs, corresponding to a peak input intensity of 2.2x10^{17} Wcm^{-2}. Full details are given in ref. [6].

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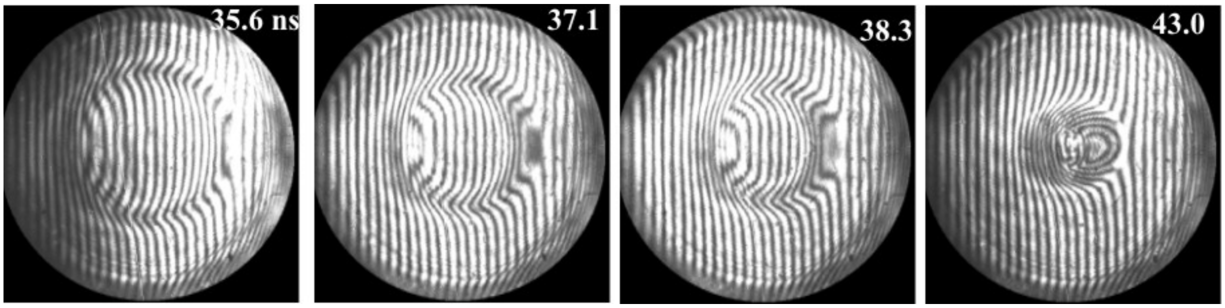

Figure 1. Time progression of interferograms showing the plasma column compression and waveguide development for a 250 mTorr Ar discharge in a 3.2mm diameter, 11cm long capillary. Times are measured with respect to the current pulse.

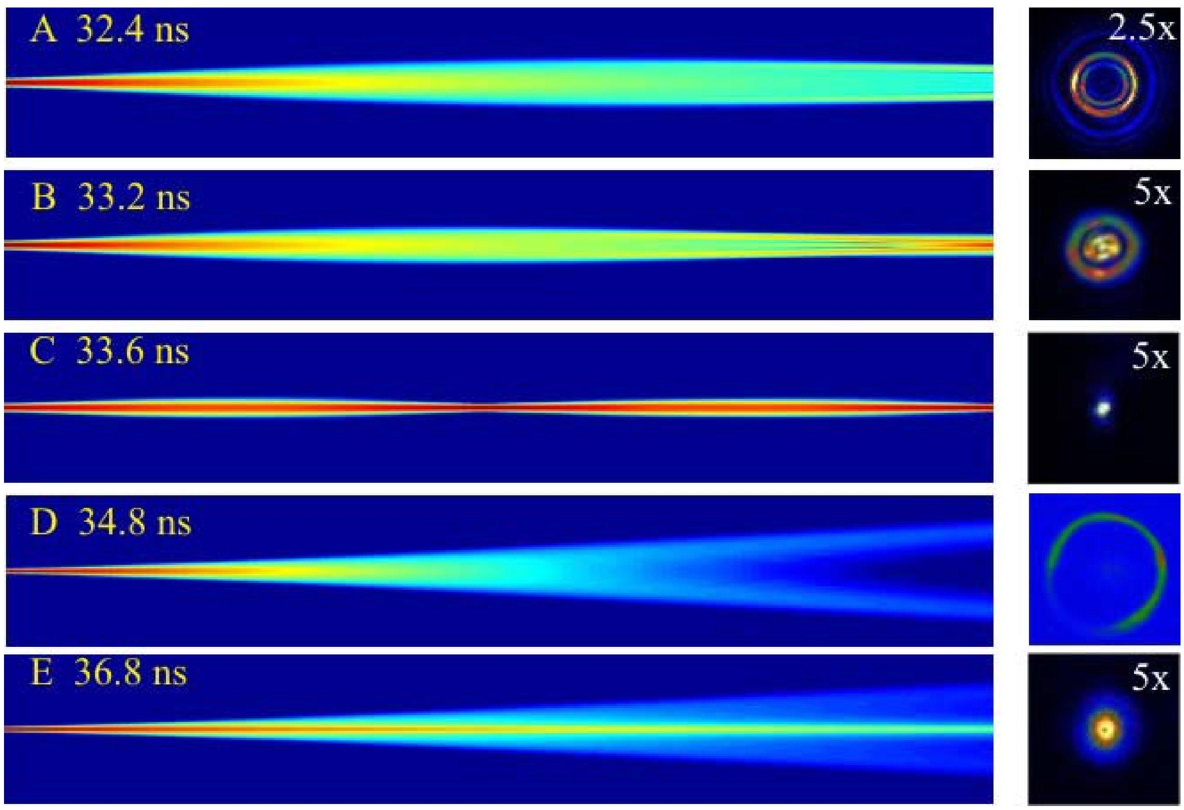

Figure 2. Modeled cross sections showing the calculated guided beam propagation in a 5.5 cm capillary (left), and corresponding experimental exit mode images (right, with magnification given).

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