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Telecentric viewing system for light collection from a z-pinch plasma

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As part of a Doppler spectroscopy system to measure the radial variation of ion flow and temperature, a pair of telecentric viewing telescopes has been installed on the ZaP *z*-pinch plasma device. Each telescope simultaneously collects 20 chords of light (200–1200 nm) emitted by impurities in the plasma, and images the chords on a fiber optic bundle for transport to a spectrometer. The center-to-center spacing of adjacent chords in the plasma is 1.24 mm, thus radial variation across the $r=10-15$ mm ZaP plasma is completely recorded. In this telecentric imaging system, all object chords and image points, including those laterally displaced from the optical axis, are formed by ray bundles whose chief ray is parallel to the optical axis. Thus all 20 light collection chords passing through the ZaP plasma are parallel, and all 20 image points fill the optical fibers with an identical cone. This maximizes system efficiency and measurement precision, and simplifies calibration and data analysis. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1353188]

The ZaP *z*-pinch plasma device[1] at the University of Washington produces a small diameter (20–30 mm) dense *z*-pinch plasma with typical electron density $10^{22}-10^{23}\,\mathrm{m}^{-3}$ and ion plus electron temperature 100–200 eV. The plasma is stable, with relatively low magnetic mode activity, for tens of microseconds.[2] This is orders of magnitude longer than predicted by a simple ideal magnetohydrodynamic calculation. Radial shear in the axial plasma flow has been proposed as a potential stabilizing mechanism,[3–5] thus accurate measurement of the magnitude and radial variation of the axial flow will provide critical input to theory.

Plasma flow is being passively measured in ZaP by recording the Doppler shift of UV and visible lines emitted by intrinsic carbon and oxygen impurities in the majority hydrogen plasma.[6] Useful lines are C III at 229.687 nm and O V at 278.101 nm, similar to what has been observed in a gas-puff *z* pinch.[7,8] To obtain radially resolved profiles of the axial flow velocity in ZaP, the plasma is viewed through two telescopes (Fig. 1). The radial telescope views perpendicular to the axis of the ZaP plasma, and thus provides the non-Doppler-shifted reference spectra (radial and poloidal flows are small relative to axial flow). The oblique telescope views 35° off the ZaP axis, and is sensitive to Doppler shifts induced by axial flows. These viewing telescopes are telecentric[9] (Fig. 2), meaning that the object and image lenses are separated by the sum of their focal lengths, with an aperture stop at the conjugate focal plane to place the pupils of the two lenses at infinity. This insures that all object chords in the plasma and image points on the fiber bundle, including those laterally displaced from the optical axis, are formed by ray bundles whose chief ray is parallel to the optical axis. Two advantages result from this: First, all 20 light collection chords passing through the ZaP plasma are parallel and equally spaced, simplifying calibration and data reduction, particularly inversion of the chord-average profile to local flow velocities.[10,11] Second, all 20 image points on the fiber bundle are formed by identical cones whose chief ray is perpendicular to the fiber face; thus each individual optical fiber is efficiently filled at an identical $f/7$.

The 20 image points from the telescope collection chords are formed on 20 individual fused silica core/clad multimode fibers. These 400 μm core diameter fibers are mounted in a line, 0.62 mm center-to-center spacing, in custom fixtures that preserve one-to-one mapping. Light from each collection chord is mapped to a specific vertical location on the entrance slit by simply butting the fiber bundle fixture (and thus the fiber faces) directly to the slit face, with a typical slit width of 25 μm. If not bent in an excessively tight radius, the 4 m long large core optical fibers effectively preserve the $f/7$ cone with which they were filled, so no matching optics are necessary to fill the $f/7$ acceptance of the

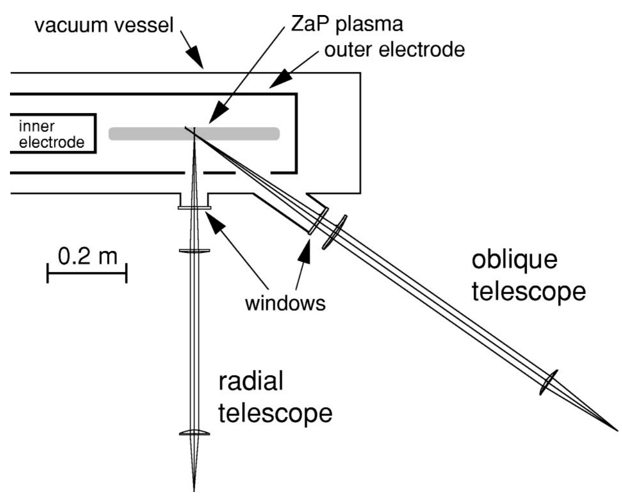

FIG. 1. Side view of the ZaP device and two viewing telescopes in schematic form.

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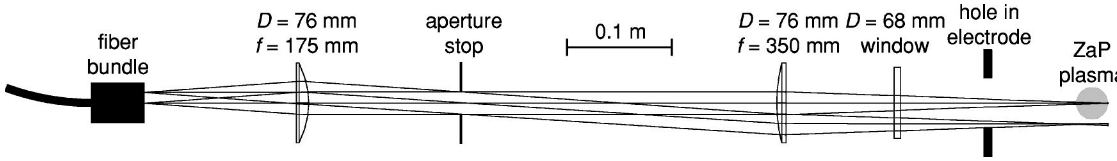

FIG. 2. Top view of radial viewing telescope, illustrating the telecentricity of the object chords and image points. Only central and extreme edge ray bundles are shown.

0.5 m spectrometer (Acton Research SpectraPro 500i). This spectrometer is corrected for astigmatism, thus the image of each of the fibers butted up to the entrance slit is preserved and light from each fiber is dispersed across a distinct horizontal strip of the spectrometer exit plane. Each horizontal strip then contains the Doppler broadened and shifted spectra from a specific collection chord in the plasma. All 20 of these spectra are simultaneously recorded by a gated ($\geqslant$100 ns) intensified CCD camera (Roper Scientific PI-MAX) and are stripped out of the two-dimensional camera image by an analysis program. Thus the entire radial profile of the plasma flow velocity is captured at a specific timepoint during the ZaP discharge; temporal development of the profile is recorded by firing reproducible discharges and moving the gate time.

In order to simplify telescope design, the lenses were fixed in place, but the fiber bundle fixture is mounted on two translation stages to provide fine adjustability both parallel and perpendicular to the optical axis. The radial telescope has two lenses of 175 and 350 mm focal length, while the oblique telescope has lenses of 250 and 500 mm focal length. Both telescopes magnify the plasma light collection chords by a factor of -0.5 onto the fiber bundle faces. The center-to-center spacing of adjacent chords in the plasma is 1.24 mm. Therefore, the 23.6 mm wide line of chords in the plasma appears as an 11.8 mm line of image points on the bundle face, and the line image is inverted. The line of chords in the plasma does not need to be centered on the plasma $r=0$, as the perpendicular translation stage allows the edge chord to move out to $r=20\,\mathrm{mm}$ for the radial telescope and to $r=17\,\mathrm{mm}$ for the oblique telescope (these limits are determined by the diameter of the viewing hole in the ZaP outer electrode). Thus it is possible to position the edge chords outside the edge of the ZaP plasma ($r=10-15\,\mathrm{mm}$) and clearly record the behavior of the edge plasma, an important requirement for successful inversion of the chord-integrated profiles.

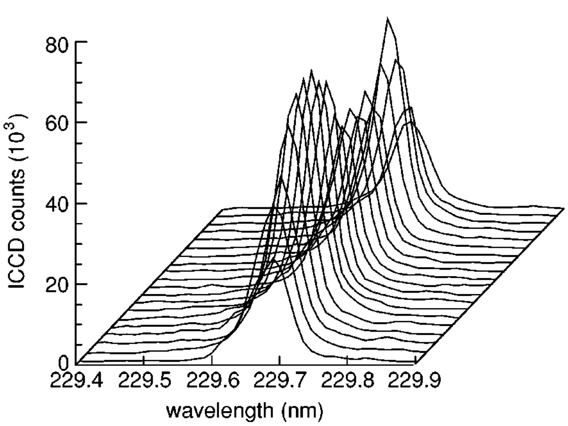

FIG. 3. Sample Doppler-broadened spectra (C III line at 229.687 nm) from the 20 chords through the radial viewing telescope.

During design, the telecentricity of the viewing telescopes was optimized for the 200–250 nm wavelength range. Refractive power of the lenses falls at longer wavelengths, but this is partially compensated by installing a slightly larger aperture stop and moving it toward the longer focal length lens, and translating the face of the fiber bundle fixture away from the shorter focal length lens (see Fig. 2). With these adjustments, degradation of image quality is minor, and magnification changes by only a few percent. Since the windows, telescope lenses, and optical fibers are UV-grade fused silica, the system is useful from 200 to 1200 nm.

Although the ability to record spectra from the two telescopes simultaneously would be ideal, doing so would require two separate spectrometers. As a cost effective alternative, each of the viewing telescopes is connected to a separate entrance slit on the spectrometer, designated the ''side'' and ''front'' slits. The front slit looks directly at the collimating mirror, while the side slit is remotely engaged by precisely flipping a mirror driven by a stepper motor into the optical path. When this mirror is engaged, light is blocked from the front slit, therefore data can be recorded from only one slit (and one telescope) during a ZaP shot. Therefore, the usual operating procedure requires a shot to obtain spectra from the radial view to provide the baseline calibration of the non-Doppler-shifted emission line (typical data shown in Fig. 3) then spectra are recorded from the oblique telescope to measure the radial variation of the plasma flow profile.

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