An optical probe for local measurements of fast plasma ion dynamics

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A novel insertable probe for local measurements of equilibrium and fluctuating plasma ion flow velocity and temperature via Doppler spectroscopy is described. Optical radiation is collected by two fused silica fiber optic bundles with perpendicular viewlines. Spatial resolution of about 5 cm is achieved by terminating each view with an optical dump. The collected light is transported by the fiber bundles to a high-resolution spectrometer. Two components of the velocity are measured simultaneously—the radial along the insertion of the probe and a perpendicular component (which can be varied by simply rotating the probe by 90°). The accuracy of the velocity measurements is better than 1 km/s. The probe is armored by a boron nitride enclosure and is inserted into a high temperature plasma to obtain radial profiles of the equilibrium and fluctuating plasma velocity. Initial measurements have been done in Madison Symmetric Torus reversed field pinch. © *1998 American Institute of Physics.* [S0034-6748(98)04305-6]

I. INTRODUCTION

Spatially and temporally resolved information on plasma ion flow and temperature is critical in many areas of plasma studies. The list of pertinent phenomena includes changes in the radial profile of plasma flow during the *L* to *H* confinement transition,[1] the MHD dynamo which is driven by nonzero correlation of the fluctuations of plasma velocity and magnetic field,[2] fast anomalous ion heating during discrete dynamo events in the reversed field pinch (RFP),[3] and fluctuation driven (via Reynolds stress) plasma flow.[4]

Passive Doppler spectroscopy remains one of the principal tools for studies of plasma ion flow and temperature. Several years ago we constructed an instrument which we call the ion dynamics spectrometer[5] (IDS). The IDS, a short description of which can be found in the next section, measures the wavelength spectra of intrinsic plasma impurities along a chordal view. Ion temperature and flow velocity are obtained from Doppler broadening and shift of line spectra. The time resolution of the instrument is high (250 kHz), but the spatial resolution is low due to the averaging along the chordal view. In this article we describe a simple and inexpensive extension to the IDS, which we call the ion dynamics spectrometer probe (IDSP), which circumvents this limitation. The device is arranged in the form of an insertable probe which collects light from a small plasma volume. The light is then transported via optical fibers into the IDS, thus obtaining locally resolved ion temperature and velocity.

II. THE APPARATUS

A. Ion dynamics spectrometer (IDS)

We present here only a brief synopsis of the IDS since a detailed description of the device can be found elsewhere.[5] The instrument is a *duo* spectrometer: it simultaneously records two chordal views of the plasma, each with 16 spectral wavelength channels. The key features of the instrument are a high signal throughput and a high time resolution. All 32 channels are read out and digitized at 1 MHz in parallel. The line broadening of the plasma intrinsic impurities is mainly determined by Doppler thermal broadening, thus the ion temperature can be determined. The chordal views are normally arranged so they are opposite to each other, thus the relative Doppler shift between the two is proportional to the component of the ion flow velocity in that direction. Very extensive calibration and testing of the device have been made[5,6] and software routines for deducing the ion temperature and flow have been developed. The accuracy of velocity measurement was found to be better than 1 km/s.

B. Ion dynamics spectrometer probe (IDSP)

A disadvantage of the passive spectroscopy is poor spatial localization due to the signal averaging along the chordal line of sight. Active spectroscopic methods, like charge exchange recombination spectroscopy (CHERS)[7] or laser induced florescence (LIF),[8] circumvent this limitation by using a cross view technique and employing a spatially localized neutral particle beam or a laser beam.

While these techniques are widely accepted they are usually quite expensive and require significant investment in hardware. We have built a simple extension to the IDS which we call the IDSP, arranged in the form of an insertable probe. A schematic view of the IDSP is shown in Fig. 1. Plasma radiation is observed with the lines of view crossing at 90°—Fig. 1(a). Each view line is collimated by a cylindrical entrance aperture with a diameter of 0.2 cm and a length of 2 cm, and is terminated by a view dump, thus achieving spatial localization of the accepted radiation. The spatial resolution is about $5\times5\times1$ cm as determined by the size of the light collection volume. (This could be reduced by further miniaturization of the probe.) The light, after reflection from a small fused silica prism, is transported through fused silica fiber optic bundles. The prism protects the fiber optic

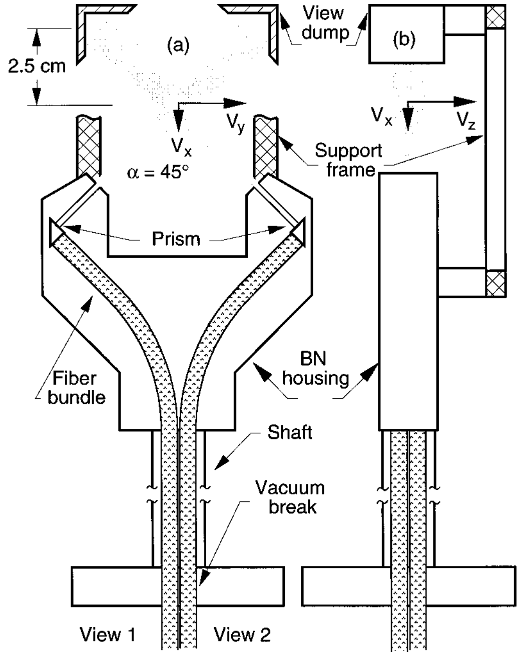

FIG. 1. A schematic view of the IDSP. (a) Top view. Optical radiation is collected by two fused silica fiber optic bundles with perpendicular viewlines. The light collection volume is shown. Spatial resolution of about 5 cm is achieved by terminating each view with an optical dump. The collected light is transported by the fiber bundles (view 1 and view 2) to a high-resolution spectrometer. The plasma ion flow velocity and the temperature are determined from the Doppler shifts and the broadening of the radiation spectra. (b) Side view. The support frame has a ''hole'' and is offset from the probe housing, thus minimizing obstruction to the plasma flow.

from plasma and is inexpensive and easily replaceable. The fibers are then fed into the entrance ports of the IDS, and the plasma ion flow velocity and the temperature are determined from the Doppler shifts and the broadening of the radiation spectra.

Two components of the velocity that are parallel to the probe's plane (see Fig. 1), v_x and v_y produce the Doppler shift:

$$\Delta\lambda_1 c/\lambda = -v_x \sin(\alpha) + v_y \cos(\alpha),$$

$$\Delta\lambda_2 c/\lambda = -v_x \sin(\alpha) - v_y \cos(\alpha),$$

where $\Delta\lambda_1$ and $\Delta\lambda_2$ are the corresponding (view 1 and view 2) Doppler shifts, λ is the unshifted wavelength, and $\alpha = 45°$. Therefore two components of the velocity can be simultaneously determined from:

$$v_x = -c(\Delta\lambda_1 + \Delta\lambda_2)/(2\lambda \sin\alpha),$$

$$v_y = c(\Delta\lambda_1 - \Delta\lambda_2)/(2\lambda \cos\alpha).$$

The third component v_z which is perpendicular to the probe's plane, cannot measured simultaneously with the other two but can be measured independently by simply rotating the probe by 90°.

An important feature of the probe is its ''transparency'' to the plasma flow at the observation point. A thin support frame with a ''hole'' in the middle allows the plasma to flow through it in the z direction and minimizes disturbance of the plasma—Fig. 1(b). The frame itself is offset from the observation plane so it does not shadow the observation area, which minimizes the obstruction to the plasma flow in the y direction.

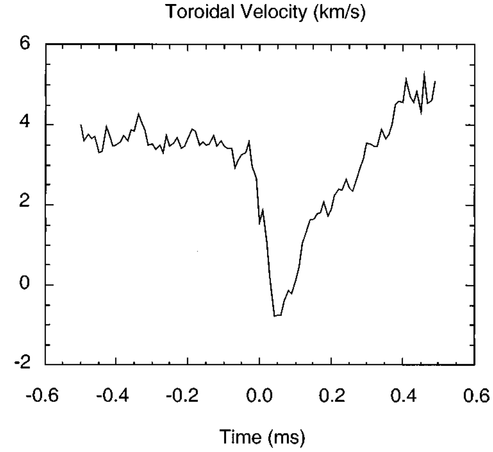

FIG. 2. Plasma braking during a sawtooth event. The plasma toroidal velocity was measured at an insertion point (as determined by the crossing of the view lines) of 5 cm from the wall. The rotation velocity was determined by Doppler shift of the He II 468.6 nm.

All the probe parts that are exposed to plasma—probe housing, the view dumps, and their support frame are made from boron nitride. The fiber bundles run inside the stainless-steel shaft which supports the probe housing and exit outside through a vacuum tight seal. The bundles are custom made by Fiberguide Industries, Stirling, NJ. Each bundle consists of 135 thermocoat jacketed fused silica fibers with a core diameter of 200 μm. The vacuum side (1 m) has a fiber glass sleeve, and the air side (2 m) has a monocoil stainless-steel sleeve. The probe can be moved radially into the plasma through a sliding vacuum seal. In addition, the probe can be rotated around the shaft axis to measure all three components of the velocity.

III. MEASUREMENTS

Measurements of plasma velocity were made in the Madison Symmetric Torus (MST)[9] RFP. MST is a toroidal plasma confinement device operated as a reversed-field pinch. The major radius is $R = 1.5$ m and the minor radius is $a = 0.52$ m. For the measurements described here the plasma current was $I_p = 220$ kA and the central line density $\overline{n_e} = 10^{13}$ cm^{-3}.

Special care was taken to establish that the probe did not perturb the plasma. We monitored the plasma global parameters-line density, radiation, loop voltage, etc. The rotation velocity of magnetic perturbations in the plasma which is a good indicator of core plasma rotation was monitored as well. In addition, we monitored the local plasma density and potential with a Langmuir probe located near our optical probe. In the future we are planning to use two optical probes inserted near each other and measure perturbation in the local plasma velocity. Meanwhile, measurements with smaller in size probes inserted near the IDSP showed that the local plasma velocity was not perturbed.

In order to have a better signal-to-background ratio we doped the plasma with a small controlled amount of helium using a pulsed piezovalve. Monitoring helium radiation rather than carbon or other intrinsic plasma impurities has the advantage of a lower contribution of radiation from the probe material or surface contamination. Another advantage is an independent control of the signal intensity. The He II 468.6 nm line radiation was measured, taking into account the approximately 0.05 nm of fine structure of this transition. A Gaussian curve was fit to the raw data, as the fine structure does not grossly distort the general shape of the Doppler broadened spectrum. This broadening does not affect the velocity measurements since it is determined by the relative Doppler shift between the two lines of view. It does make temperature measurement more difficult, as the thermal broadening and the fine structure broadening are about the same size.

Figure 2 illustrates the plasma ''braking'' during a sawtooth crash. The plasma toroidal velocity was measured at an insertion (as determined by the crossing of the view lines) of 5 cm from the wall. The ensemble average from 20 shots is shown. The crash occurs at $t=0$ at the plasma slows down with a typical deceleration time of 50–100 μs. These results agree with the previous IDS measurements of the edge toroidal plasma velocity using the C III 229.7 nm line radiation which is localized within a several cm from the wall.[10]

ACKNOWLEDGMENTS

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