Local measurements of plasma ion dynamics with optical probes

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Two insertable optical probes have been constructed to measure local ion temperature and flow velocity using the idea proposed by Fiksel *et al.* [Rev. Sci. Instrum. **69**, 2024 (1998)]. The light from plasma is collected by an optical fiber bundle and transported to a high resolution spectrometer. Spatial resolution of a few centimeters is achieved by using a collimator and a view dump. One ion dynamics spectroscopy (IDS) probe is employed in the edge plasma of Madison Symmetric Torus reversed field pinch in combination with the high throughput ($f/4.5$) and high resolution (0.15 nm/mm) IDS-II spectrometer. It has provided local ion temperature measurements of carbon and helium impurities with temporal resolution of 10 μs and accuracy of about 5 eV. The second instrument is used on the Magnetic Reconnection eXperiment, where the local temperature of helium ions (~10 eV) has been measured with 1 eV accuracy. Details of the designs, calibrations, and data analysis are described. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2220017]

I. INTRODUCTION

Spatially and temporally resolved measurements of the ion temperature and flow velocity are essential for understanding many key questions in the field of plasma physics, for example, mechanisms of ion heating during magnetic reconnection and self-organization in reversed field pinches (RFPs),[1] magnetohydrodynamic dynamo,[2] etc.

Doppler spectroscopy is a conventional tool for the ion temperature and flow velocity measurements in plasmas. Passive measurements are relatively easy to carry out, but they are lacking spatial localization since the signal is averaged along the line of sight. The localization can be achieved by using active diagnostics employing either neutral beam (charge exchange recombination spectroscopy and Rutherford scattering[3]) or laser beam (laser induced fluorescence[4]); however, these techniques are fairly expensive.

In this article we describe two inexpensive instruments for local measurements of the ion dynamics [called ion dynamics spectroscopy (IDS) probes] developed using the idea proposed by Fiksel *et al.*[5] The light is collected by a fiber bundle inserted into the plasma and spatial localization is achieved by placing a view dump in front of the fiber bundle. This approach allows for light collection locally, thus, avoiding problems with reconstructing profiles from line-integrated quantities.

II. PRINCIPLES OF DOPPLER SPECTROSCOPY

Thermal ion (or neutral) motion results in the Doppler broadening and shift of the emission line.[6] If the Doppler broadening is the dominant effect on the spectral line shape, then the resultant wavelength spectrum will be Gaussian and the temperature in eV can be expressed as

$$T(\mathrm{eV}) = 1.69 \times 10^8 \mu \left(\frac{\Delta\lambda_{\mathrm{FWHM}}}{\lambda_0} \right)^2, \tag{1}$$

where $\Delta\lambda_{\mathrm{FWHM}}$ is the full width of the spectral line at the half maximum level, λ_0 is the unshifted wavelength of the spectral line, and $\mu = M_i/M_p$ is the ratio of the ion neutral mass to the proton mass.

For the species with uniform velocity along the line of sight the emission spectrum will be shifted, and the ion velocity is given by

$$V = c\left(\frac{\lambda_0' - \lambda_0}{\lambda_0} \right), \tag{2}$$

where c is the speed of light and λ_0' is the shifted wavelength. $V > 0$ means that the flow is directed away from the observer.

In many situations this simple description can be complicated by effects like the fine structure of the emission line spectra, spectral line overlapping, instrumental broadening, pressure broadening, etc. Therefore, they need to be accurately taken into account to properly evaluate the ion temperature and flow velocity.

III. MST IDS PROBE

Initial studies of the ion dynamics in the edge plasma of the Madison Symmetric Torus (MST) RFP[7] were performed by the original IDS probe[5,8] which was coupled to the IDS-I spectrometer.[9] This spectrometer was useful for ion flow velocity measurements, but did not provide enough spectral resolution to conduct the ion temperature measurements in the edge plasma of MST.

The IDS probe, shown in Fig. 1, is based on the same concept as the one described in Ref. 5. The probe is inserted radially into the vacuum vessel through a double O-ring seal

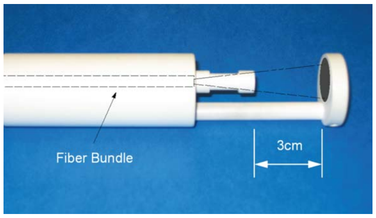

FIG. 1. (Color online) Photograph of the MST IDS probe tip.

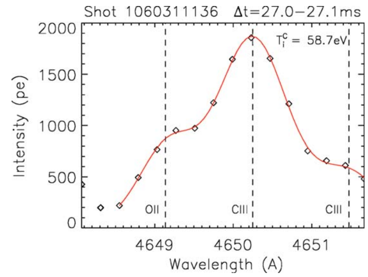

FIG. 2. (Color online) Sample spectrum at 4650 Å (diamonds) and fit function (solid line). The line centers are represented by dashed lines.

and allows for measurement of the radial flow speed V_r and the ion temperature T_i. A few modifications were done to the design of the old system. First of all, it is more compact and can fit through a 1.5 in. port hole, thus allowing more flexibility in positioning on the machine since these ports are readily available. Secondly, it is used in conjunction with the IDS-II spectrometer,[10] which provides a higher spectral resolution. The probe consists of a 3.2 mm diameter fused silica fiber bundle, composed of 135 thermocoat jacketed fused silica fibers with a core diameter of 200 μm. The bundle is custom made by Fiberguide Industries (Stirling, NJ). It is covered by a boron nitride shroud. A 5 mm diameter fused silica window is placed in front of the bundle to protect the spectrometer from hard UV light and to prevent the fibers from solarization. A spatial localization of 3 cm is achieved by placing a view dump and a collimator in front of the fiber bundle. The IDS fiber bundle is coupled to the IDS-II spectrometer fiber by a telescope coupler composed of a pair of lenses.

The IDS-II spectrometer is a custom high throughput ($f/4.5$) and high resolution ($\sim$0.15 nm/mm) double grating Czerny-Turner duospectrometer.[10] The light is continuously detected by 16×2 channels of photomultipler tubes (PMTs) and amplifiers with 100 kHz bandwidth. The spectrometer has several advantages with respect to the IDS-I spectrometer, which are very important for T_i measurements in the edge plasma of MST. Firstly, it has a wider entrance slit than the IDS-I (500 vs 200 μm), while the output detector size is the same. This provides a wider instrumental function. As a result, a typical measured emission line width from the edge plasma is $\geqslant$5 PMT channels. (For comparison, emission lines from the plasma edge dispersed by the IDS-I spectrometer were only about two channels wide, which hindered the ion temperature measurements.) Secondly, the IDS-II has about factor of 100 higher throughput, which improves the statistics and allows more reliable fits to the data. The instrumental broadening can then be subtracted, since the instrumental line width can be determined very precisely.

The calibration of the system is done in two steps. Firstly, the relative PMT gains and the dispersion are measured by slowly rotating the grating at constant speed (to illuminate different PMT channels) while looking at a pair of lines from a calibration lamp. A typical dispersion is $\sim$0.25 Å/channel. Then, the instrumental function is measured at a fixed grating location. It appears to be well described by a Gaussian. This simplifies calculations of the instrumental broadening effect on T_i, since it simply adds in quadrature. The instrumental temperature for He (C) ions in the 465 nm wavelength range is $\sim$18 eV (55 eV), respectively.

Several ionic spectral lines have been tested for T_i and V_r measurements in I_p=200 kA standard MST discharges with the line averaged density of 10^{13} cm^{-3}. The experiments have demonstrated that special care has to be taken when selecting a spectral line and analyzing the data, since most of the conventional lines typically used for T_i measurements (C III 2296.87 Å, C III 4647.42 Å, and C III 4650.25 Å) are contaminated by parasitic impurity lines. Surprisingly, many of these lines are not documented in the NIST database,[11] but are reported in Ref. 12. (In particular, the later database shows several O and N lines in the vicinity of the popular C V 2270.91 Å line.) These polluting lines are small during quiescent plasma, but get pronounced during internal reconnection events, when a sizable population of energetic electrons appears in the edge. These electrons strike the probe, resulting in the emission of the polluting radiation. Since the probe is made of boron nitride the parasitic lines are mainly represented by partially striped ionic lines of nitrogen, boron, and oxygen. To take this effect into account these lines have to be fitted together with the line of interest. Figure 2 shows an example of such fit, where lines fitted are O II(4649.135 Å) and C III (4650.246 and 4651.473 Å). The relative wavelength spacings between the lines were fixed during the fit. The relative amplitudes of the C III lines are well known[12] and their broadening was assumed to be the same. However, the amplitude and width of the O II line were free parameters.

For accurate velocity measurements absolute calibration of the system is required. Since the spectrometer has a second spare spatial channel it is planned to use a hollow cathode lamp to record the unshifted wavelength position in real time.

IV. MRX IDS PROBE

Magnetic Reconnection eXperiment (MRX) IDS probe is utilizing the same principles as the MST IDS probes outlined above. Since MRX[13] has a shorter discharge time ($\sim$100 μs) and lower plasma temperature ($\leqslant$20 eV) than MST, a lighter probe design was incorporated.

A photograph of the probe is displayed in Fig. 3. It combines two pairs of collimating optics with two pairs of view dumps in a compact package. The probe is introduced into the plasma radially. Each pair views the plasma along the

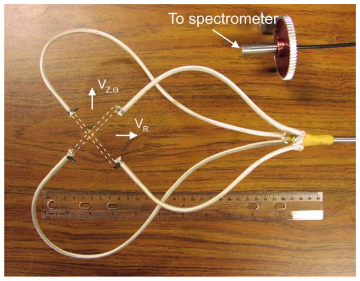

FIG. 3. (Color online) Photograph of the MRX IDS probe.

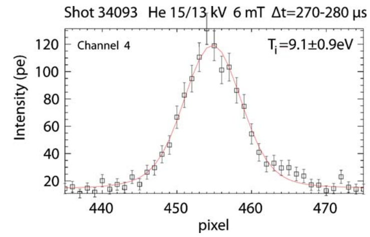

FIG. 4. (Color online) Profile of the O II 4685.7 Å spectral line and the fit function (solid line), which is a convolution of a Gaussian with an instrumental function.

same line but in the opposite directions. The spatial resolution of the probe is about $4\times4\times1$ cm^3. The light is coupled via optical fibers custom made by Fiberguide Industries to a spectrometer. At the end facing the plasma, the fibers are grouped in four bundles with circular cross section [one bundle per IDSP channel, seven fibers (200 μm diameter) in each bundle]. The bundles can slide along stainless steal tubes (covered by a fiberglass sleave to reduce interaction with plasma) right to the probe tips and can be taken out for calibration without breaking the vacuum. A small fused silica lens (3 mm diameter, 15 mm focal length) is positioned at the tip of each probe channel to collimate the plasma light, and the end of the fiber bundle stops right at the focal plane of this lens. At the other end, all 28 fibers are arranged in a linear array (8.2 mm high) and are attached to a spectrometer. This arrangement fills the entrance slit completely.

The spectrometer is a 1 m McPherson Model 2061 monochromator spectrometer of the Czerny-Turner type (2400 lines/mm grating, $\sim$0.05 Å resolution, $f/8.7$, wavelength range of 185–650 nm). The light output from the spectrometer is imaged by a gated, intensified charge-coupled device (CCD) camera PI-MAX:512SB from Princeton Instruments (512x512 pixels, effective pixel size of 24 μm, quantum efficiency of 15–30%) allowing one frame acquisition per MRX discharge. Each of the four spatial channels covers 70 CCD rows vertically (they are later binned in software). The horizontal direction on CCD represents wavelength axis. The camera calibration with a stable uniform light source demonstrated that it has the lowest noise level at the image intensifier gain of 150. At this gain, each photoelectron which strikes the microchannel plate results in 14 counts on CCD detector.

Measurements were done in helium plasma with a typical plasma density of $(2-10)\times10^{13}$ cm^{-3}. The overall resolution of the system at He II 4685.7 Å, used for T_i measurements, was calibrated using the known spectra of a neon lamp, and is equal to 0.074 Å/CCD pixel. The slit width of the spectrometer was set to be 100 μm, which corresponds to the instrumental width of 5 pixels on the CCD. This gives an effective instrumental temperature of $\sim$5 eV for helium. Since typical ion temperatures were measured to be 5–15 eV, it was necessary to do deconvolution and "subtract" the instrumental effect from the line width. A typical signal level was $\sim$100 photoelectrons for a 10 μs integration time window, which provided good Poisson statistics and an uncertainty in T_i measurements was less than 1 eV (see example of the data in Fig. 4). The line has a fine structure which consists of 14 components and spans over 0.5 Å.[12] However, since the spectrum is dominated by two components 0.1 Å apart, modeling with a multi-Gaussian fit showed that the single Gaussian fit overestimates T_i only by 10%–15%. The availability of four channels independently measuring T_i in the same plasma volume allowed a further reduction in the uncertainty by computing the weighted average.

All three components of the flow velocity can be measured by properly orienting the IDS probe. The availability of four channels also eliminates the need for an absolute wavelength calibration. However, since the CCD camera always had a slight unavoidable tilt, which was also found to vary with pixel number due to CCD chip imperfections, the unshifted value λ_0 differed from channel to channel. Thus, for accurate velocity measurements, the unshifted relative positions of all four spatial channels on the CCD were determined using Ne I 4687.6 Å line from a calibration lamp, which is very close to the He II line of interest. The IDS probe was also used for absolute calibration of the velocity profiles obtained by the Mach probe.[14,15]

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