First charge exchange recombination spectroscopy and motional Stark effect results from the Madison Symmetric Torus reversed field pinch

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We report on the first results of charge exchange recombination spectroscopy (CHERS) and motional Stark effect (MSE) measurements in the Madison Symmetric Torus reversed field pinch. A 30 keV, 4 A neutral H beam is used in combination with visible and ultraviolet spectroscopy to make the measurements. For CHERS, we find that the C VI line at 3433.69 Å yields the largest charge-exchange signal/background ratio and is most clearly resolved from other nearby lines. Equilibrium ion temperature measurements have been made with an existing fast Doppler spectrometer and a higher throughput spectrometer is being designed to do velocity and temperature fluctuation measurements. MSE measurements are made by recording the Doppler shifted H_α spectrum emitted by the beam with a charge coupled device and imaging spectrometer. We have observed separation of the π components of the Stark manifold at magnetic fields of about 0.5 T and are considering options for increasing measurement accuracy. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1319606]

I. INTRODUCTION

The plasma in the Madison Symmetric Torus (MST)[1] is characterized by low magnetic field (~0.1–0.5 T), moderate electron and ion temperatures (0.1–1.0 keV), moderate density ($\sim 10^{19}\,\mathrm{m}^{-3}$), and large levels of both magnetic and electrostatic fluctuations. The magnetic configuration is maintained both by externally applied inductive electric fields and by fluctuation-driven electric fields (magnetohydrodynamic dynamo) resulting from coupled magnetic and velocity fluctuations. The fluctuations are driven primarily by free energy in the current density profile. Although the fluctuations assist in creating the magnetic configuration, they enhance radial transport of particles and energy and hence degrade confinement. A major part of the MST program is to study the fluctuation-driven transport and dynamo due to these fluctuations and to develop control techniques to maintain the magnetic configuration without large radial transport.

In light of this, it is of great importance to have direct measurements of the current density profile, particle and energy fluxes, and fluctuations throughout the plasma. Probes have examined these extensively in the plasma edge.[2–4] In the core, passive spectroscopy[5] and interferometery[6] have provided information on large spatial scales. However, localized measurements of ion dynamics and magnetic fields have awaited improvements in diagnostic capabilities. In this article, we describe the first results of charge exchange recombination spectroscopy (CHERS) and motional Stark effect (MSE) measurements as applied to MST for localized measurement of ion dynamics and magnetic field.

II. EXPERIMENTAL SETUP

Both CHERS and MSE rely upon a neutral beam; a diagnostic neutral hydrogen beam is operating on MST for this purpose. The beam, purchased from the Budker Institute of Nuclear Physics, has an energy of 30 keV, a high current density (total current of 4 A is focused to 4 cm diameter), low divergence (<15 mrad), and 3 ms duration. As shown in Fig. 1, the beam is injected through the center of the discharge at a 22.5° angle to the midplane. The beam trajectory lies in a vertical plane (i.e., there is no toroidal component).

Also shown in Fig. 1 are several viewing locations. A set of 2 in. diam portholes oriented perpendicular to the beam provide for profile measurements from $r/a = 0.0$–0.9 and are used for CHERS measurements. The measurement volume is limited to the intersection of the light collection cone and the neutral beam (i.e., a radial extent of about 1 cm). A central view which crosses the beam at a 22.5° angle is also shown in Fig. 1. This view intercepts a larger beam volume than the perpendicular views and is useful for enhancing weak CHERS signals relative to the background. This view is also used for the MSE measurements reported below.

III. CHERS RESULTS

The CHERS technique has been exploited for impurity ion diagnosis extensively in recent years.[7–9] The basic task is to measure the shape, wavelength shift, and intensity of line emission from the two-step process $H^0 + A^{z+} \rightarrow H^+ + A^{(Z-1)+}(n,1) \rightarrow A^{(Z-1)+}(n',1') + h\nu$ which yields information on the density, velocity, and temperature of species A^{Z+}. A is usually an intrinsic impurity such as He, C, or O and Z is the nuclear charge. Most implementations of CHERS have used fiber-coupled spectrometers with array

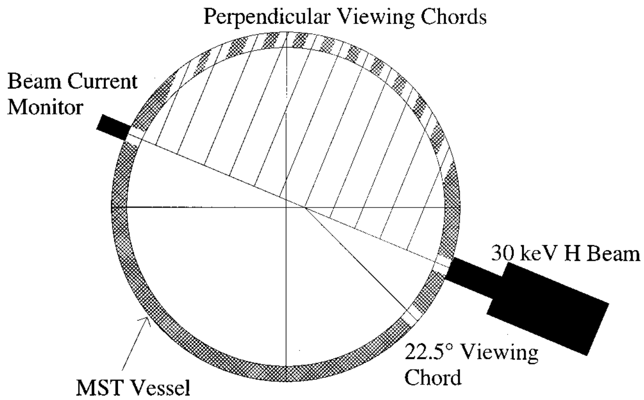

FIG. 1. Poloidal cross section of MST showing location of diagnostic neutral beam and several viewing locations.

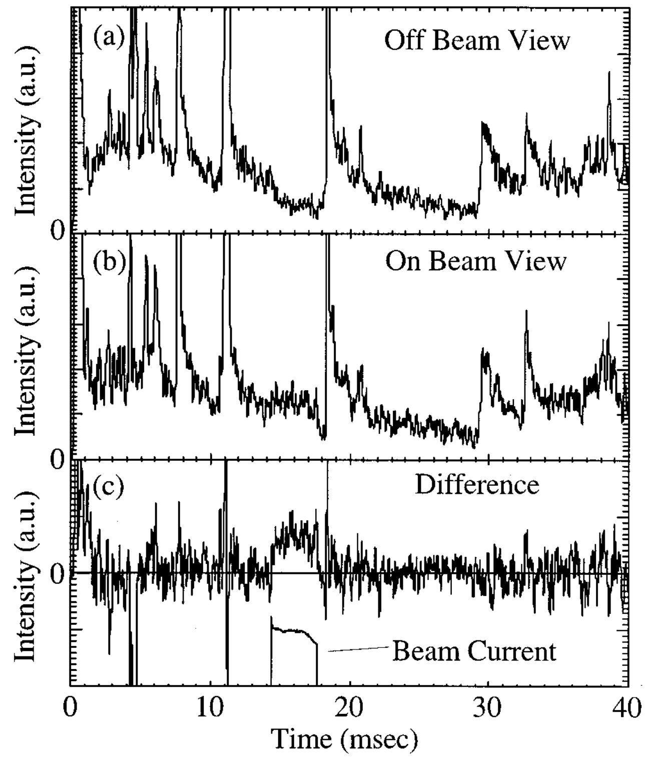

FIG. 2. Measured C VI (3433.69 Å) emission intensity for central views: (a) just to the side of and (b) intersecting the beam and (c) the difference of the two views.

detectors such as charge coupled devices (CCDs) to get good wavelength resolution and facilitate simultaneous measurement of multiple spatial points. Time resolution in these schemes is typically 1 ms or less, appropriate for measurement of equilibrium ion characteristics. For our application, we require time resolution of 10 μs or better coupled with good spatial resolution for resolving fluctuations in ion quantities. High speed CHERS has been successfully implemented previously[10] but is not yet widely available.

An important requirement for good time resolution is that enough light be collected to achieve sufficient signal-to-noise ratios despite short integration times. This requirement can be met in part by choosing a bright transition and also by using a very efficient collection and detection system. We have conducted a survey of ultra violet and visible transitions in MST to find an appropriate candidate for CHERS measurements. We considered He II (4685.24 Å), B V (4944.7 and 2981.4 Å), C VI (5290.53 and 3433.69 Å), and O VII (4340.58 and 2975.83 Å). The C VI transition at 3433.69 Å appears to be best for our application. This transition is relatively strong, gives the largest charge-exchange signal/background ratio of any line surveyed, and is well isolated in MST. Some possibility of ''contamination'' due to O VI emission at 3434 Å exists but measurement of nearby O VI lines at 3426 and 3438 Å indicate that this should not be a severe problem.

Although the C VI emission from charge exchange with the beam is strong, the background signal from the plasma is still of the same order or larger in most circumstances. This is apparently due in large part to the high background neutral density in MST which causes charge exchange of C^{6+} with thermal neutrals. In fact, we observe a clear anticorrelation of beam-induced charge-exchange emission with thermal neutral density and a strong correlation of background signal with the neutral density. By operating in heavier gases, like deuterium, the signal/background ratio is greater—presumably because the penetration depth of edge neutrals is less and core neutral densities are therefore lower. During periods of improved confinement[11] in MST, when neutral densities are quite low in the core, the beam-induced signal can be a factor of 5 above the background on a central chord.

In order to distinguish between beam-induced and background emission, we will implement a dynamic background subtraction technique with two optical views through each viewing port: one intersecting the beam and one to the side. The background signal in both views will be similar and the difference of the two views is then dominated by charge-exchange emission from the beam. We have tested this in MST using two fiber-coupled monochromators with photomultiplier detectors. One views the beam along a perpendicular viewing chord passing through the center of the beam. The other views it along a parallel chord displaced by 2 cm in the plasma (the beam has a radius of about 1.5 cm). The results are shown in Fig. 2. A normalization factor is applied to match the two monochromator signals when the beam is off and the difference between the signals is shown in Fig. 2(b). In the future, we plan to use a duo-spectrometer for the subtraction with on-beam and off-beam views coupled to the top and bottom halves of the spectrometer entrance slit. This will provide for a more accurate subtraction at each wavelength.

We have used an existing high speed Doppler spectrometer[12] to make a preliminary CHERS measurement without the dynamic background subtraction. The system is capable of 10 μs time resolution if light levels permit. Data from 16 wavelength channels are shown in Fig. 3 for a typical MST discharge with the spectrometer viewing along the 22.5° viewing chord (see Fig. 1) in order to have maximum sensitivity to beam-induced emission. The 16 channels cover a 6.7 Å wavelength range centered on 3433.69 Å. One observes enhanced intensity with beam injection for channels

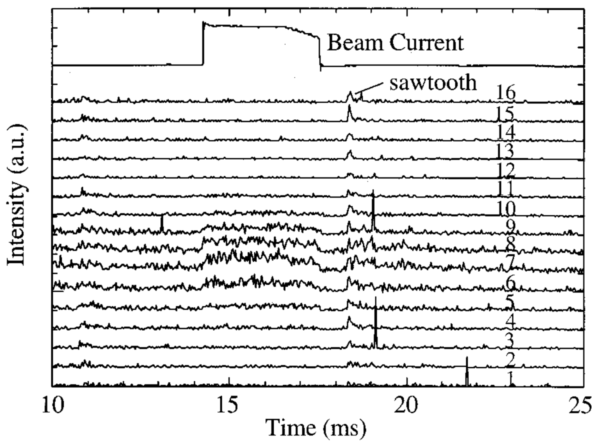

FIG. 3. Measured emission in 16 wavelength channels centered on the C VI emission at 3433.69 Å.

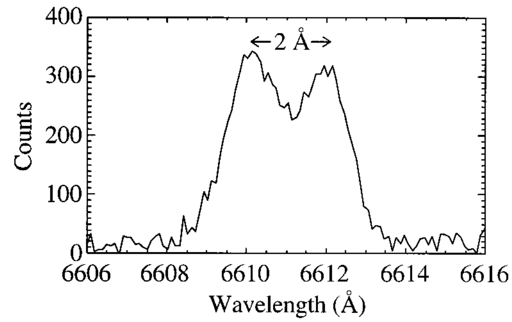

FIG. 4. Measured spectrum of Doppler shifted H_α emission from beam using vertical polarizer showing Stark splitting of π^+ and π^- components.

5–10 which cover the C VI line. A simple Gaussian fit to the data yields an ion temperature of about 300 eV for this case. Atomic fine structure and 1-mixing[7] will have an impact on the observed line shape at these temperatures and will need to be taken into account in future analysis. It is expected that this will reduce the apparent temperature by about 10%–20%.

The existing system is not efficient enough to allow fluctuation measurements. A new spectrometer is being designed with increased throughput, higher grating efficiency at the wavelengths of interest, and improved detector sensitivity. It is anticipated that an improvement of about 50 times in system efficiency can be realized. This should allow localized core ion fluctuation measurements to be made for the first time in the reversed field pinch.

IV. MSE RESULTS

MSE has become an important and widespread tool for making internal magnetic field measurements in high temperature plasmas.[13,14] The measurement relies upon the wavelength separation of the different components in the beam H_α emission which are Stark split due to the $\mathbf{v}\times\mathbf{B}$ electric field experienced in the beam atom's rest frame. The different components are polarized relative to this electric field and most implementations of MSE at present use some form of polarimetry to obtain information on the magnetic field direction and magnitude.

This works well provided the different polarizations do not overlap in wavelength space. The individual lines in the Stark manifold are broadened primarily by two effects: finite beam temperature and finite light collection volume which gives a spread of observation angles. For high magnetic fields (>1 T), this broadening is small enough compared to the Stark splitting to keep the different polarizations separated but this is not typically the case in low magnetic field devices like MST ($B\sim 0.1-0.5\,\mathrm{T}$). In low field cases, either the geometrical smearing must be significantly reduced [e.g., by use of a laser and laser induced fluorescence (LIF) to effectively collimate the beam][15] or the whole Stark spectrum must be measured and fit to a theoretical model with B as a parameter. LIF is being considered for use in MST. Initially, however, we plan to measure the toroidal magnetic field at the magnetic axis by direct observation of the Stark spectrum.

We have used the 22.5° viewing chord to measure the spectrum of H_α emission from the 30 keV neutral H beam on MST (Fig. 4). Light from the plasma is passed through a vertical polarizer to select primarily the π components which are polarized parallel to the $\mathbf{v}\times\mathbf{B}$ electric field. A CCD detector on a 0.5 m spectrometer integrates over the whole beam injection period of 3 ms.

The emission is Doppler shifted from the background thermal H_α emission by an amount $\lambda\cdot(v_{\mathrm{beam}}/c)\cdot\cos(22.5°) = 48.5\,\text{Å}$ making it easily distinguishable. The individual Stark components are fully blended together into three peaks representing the π^+, π^-, and σ components. (Only the π components are visible in Fig. 4 because of the polarization.) The smearing is dominantly from the large 1.5 in. diam collection lens which accepts light with an angular spread of about 5° corresponding to a width of about 1.8 Å for each component. Since the separation between adjacent components is only 0.33 Å, all components are blended together. In the future, we will better collimate both the viewing optics and the beam to reduce this smearing so that the features of the spectrum become more pronounced. A model for the relative intensity of each component will be needed to extract the magnitude of the magnetic field.

As an estimate, we suppose that the maximum of the blended π components coincides roughly with the 3π transition. The separation between the π^+ and π^- peaks is about 2 Å corresponding to a toroidal magnetic field of 0.5 T. This is consistent with the predictions of magnetic equilibrium models. A measurement accuracy of less than 10% is needed to discriminate between different magnetic field profiles which give the same external magnetic measurements.

V. SUMMARY

We have made the first CHERS and MSE measurements in a reversed field pinch configuration. The measurements rely upon a 30 keV diagnostic neutral hydrogen beam with low divergence and high current density. A survey of possible CHERS line candidates indicates that C VI emission at 3433.69 Å is best suited to our needs for a bright transition which will allow fluctuation measurements. Initial measurements of the Stark splitting of the H_α emission from the beam indicate that it should be possible to measure the magnetic field in the core provided the relative intensities of the individual Stark components can be accurately predicted.

ACKNOWLEDGMENTS

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