A diagnostic neutral beam system for the MST reversed-field pinch

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A diagnostic neutral beam system has been developed for the Madison symmetric torus (MST) reversed-field pinch. The system is primarily used: (1) for measurement of the majority ion equilibrium and fluctuating velocity and temperature by Rutherford scattering (RS); (2) for measurement of the impurity ion velocity and temperature, both equilibrium and fluctuating, by charge-exchange recombination spectroscopy (CHERS); and (3) for magnetic field measurement via motional Stark effect (MSE). The system consists of two neutral beam injectors, and two neutral particle analyzers. One injector creates a 20 keV, 4 A helium beam for RS. The energy spectra of the helium beam atoms scattered from the plasma ions is measured with two 12-channel, 45° electrostatic energy analyzers equipped with a hydrogen stripping cell. A second injector creates a 30 keV, 4 A hydrogen beam, which is used for the CHERS and MSE diagnostics. In each injector ions are extracted from a plasma created by an arc discharge source and, after acceleration and focusing, neutralized in a gaseous target. A low ion perpendicular temperature at the plasma emission surface, achieved via plasma expansion cooling, results in a low (0.016 rad) intrinsic beam divergence. A hallmark of the beam design is the focusing ion optical system that consists of four multiaperture spherically curved electrodes. The geometric focusing, together with a low intrinsic beam divergence, provides a small beam size—5 cm in diameter-on the MST axis and a high neutral current density (0.4 equivalent A/cm^2). A beam injector is compact in size—30 cm in diameter and 70 cm in length—and weighs about 70 kg. In this article we present details of the beam and analyzer designs and first results of their tests on the MST.
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I. INTRODUCTION

Diagnostic neutral beams have become extremely valuable tools in fusion plasma diagnosis. By studying interaction of the beam with the plasma various plasma parameters can be measured. For example, the plasma *impurity* ion temperature can be measured with charge exchange recombination spectroscopy (CHERS).[1,2] The temperature of impurity ions is deduced from the Doppler broadening of line radiation resulting from charge exchange collisions of the ions with the beam neutrals—$H^0+A^Z\rightarrow H^+ + A^{Z-1*}\rightarrow H^+ + A^{Z-1} + h\nu$. The CHERS measurements described in the article are done with a hydrogen beam with the energy of 30 keV and the atomic current of 4 equivalent A.

To measure the *majority* ion temperature, the Rutherford scattering (RS) diagnostic[3,4] can be used. The energy spectrum of the beam neutral atoms undergoing small angle collisions with the plasma ions is measured with a neutral particle analyzer (NPA). The ion temperature is deduced from the width of the energy spectra. In both cases the locality of the measurements is achieved from the intersection of the beam line and the optical spectrometer or the NPA lines of view. The RS measurements described in the article are done with a helium beam with an energy of 20 keV and atomic current of 4 equivalent A.

II. INJECTOR DESCRIPTION

The DINA-5F injector for the Madison symmetric torus (MST)[5] is essentially a modification of the DINA-5[6] injector developed for applications for the GDT mirror machine.[7] The injector consists of an ion source and a neutralizer. The ion source and neutralizer are mounted inside a cylindrical soft-iron magnetic screen which reduces the stray magnetic field to a tolerable value. The ion source forms an intense focused ion beam that is neutralized in a gas target. A unique approach to the formation of a low-divergence, high-brightness ion beam via plasma expansion cooling is used. Figure 1 shows a schematic view of the injector ion source. A cold cathode arc discharge plasma generator produces a highly ionized plasma stream. As a result of collisionless expansion, the transverse ion temperature in the diverging plasma stream is reduced from the initial ~3–5 eV down to ~0.2 eV,[8] which results in a small beam divergence.

In order to maintain a small magnetic field error, the diameter of the portholes on the MST vacuum vessel avail-

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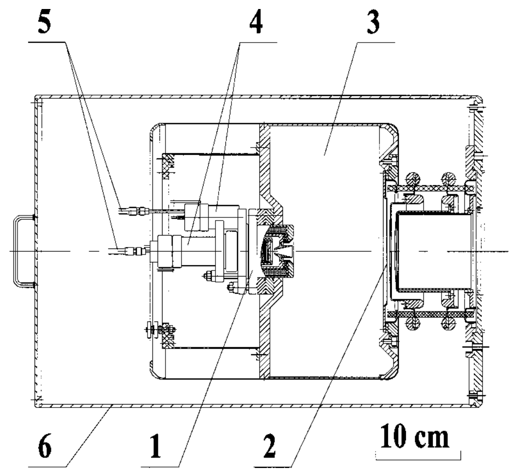

FIG. 1. Schematic of the plasma source and the ion optical system: (1) plasma generator, (2) electrodes of the optical system, (3) plasma expansion volume, (4) gas puffing valves, (5) HV feedtroughs, and (6) magnetic screen.

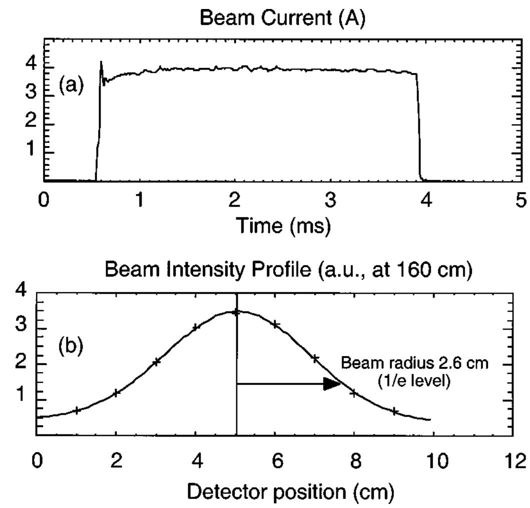

FIG. 2. Wave form (a) and current density profile (b) of the 30 keV hydrogen beam at 160 cm from the plasma electrode.

able for the beams is small—5 cm. On the other hand, a preliminary analysis of required beam parameters indicated that the initial beam diameter should be as large as 8 cm in order to provide for the necessary total beam current of 4 A. Therefore, to completely utilize the high beam current the beam has to be focused to pass through the small portholes.

The ion extraction, acceleration, and focusing are achieved with a four-electrode multiaperture ion optical system with a geometrical focusing which is accomplished by spherical shaping of the electrodes. To determine the optimal properties of an ion optical system at a given geometry it is necessary to take into account a number of factors: the radii of the electrodes, the shape and position of the plasma boundary near each aperture, the initial velocity of the ions in the plasma emitter, etc. These factors were analyzed in a three-dimensional (3D) numerical simulation of the ion optical system using Whealton's code[9] and the results of these calculations were used to refine the geometry of the electrodes.

In the final implementation each electrode has 547 circular apertures with diameter 2.5 mm arranged in a hexagonal structure with the distance between centers 3.2 mm and the outer diameter 8 cm. The electrodes are made of 0.5 mm thick 99.9% molybdenum. Photoetching technology[10] was used for the formation of the holes, after which the grids were press-shaped by high temperature recrystallization in vacuum. The curvature radius varies from 1.5 m for the inner, plasma electrode, to 0.5 m for the outer, grounded electrode. The calculated focal distance of the optical system is 130 cm (measured from the plasma electrode).

The time duration of the beam is limited by its power supply, the choice of which was strongly affected by the cost/benefit analysis. The pulse forming networks used for the arc discharge plasma source and for the high voltage ion optics provide the beam duration of 3 ms. This duration is quite adequate for the equilibrium and fluctuation studies of the MST plasma. A longer pulse duration can be provided using different (and more expensive) power supplies. As far as the source mechanical and thermal properties, a time duration up to 0.1 can be sustained without changing the source design and without external cooling. More details can be found in Ref. 6.

III. NEUTRAL PARTICLE ANALYZERS

The neutral particle analyzers are similar to a design successfully employed for RS on the gas dynamic trap (GDT) mirror machine.[11,12] The neutral particle analyzer comprises a gas stripping cell, a 45° electrostatic energy analyzer, and 12-channel MCP detector. An important feature of the analyzer is that the entrance slit of the analyzer is biased to some positive potential. Therefore, the retarding electric field slows down the ions entering the analyzer prior to the analysis, which allows one to match precisely the energy range of scattered atoms and the analyzer energy range.

IV. BEAM PROPERTIES

Characteristics of the formed hydrogen and helium beams were studied both in Novosibirsk and Madison. The wave form of the hydrogen beam current is shown in Fig. 2(a). The beam current density profiles were measured by an array of secondary emission detectors and a movable miniature calorimeter. Figure 2(b) shows the intensity profile of the 30 keV hydrogen beam measured at a distance of 160 cm from the source. The measured profile can be approximated by a Gaussian $j = j_0 \exp(-r^2/r_0^2)$ with the value of the beam radius $r_0 \approx 2.6$ cm. That corresponds to the beam intrinsic angular distribution at the plasma electrode proportional to $\exp(-\theta^2/\theta_0^2)^8$ with $\theta_0 = 0.016$ rad at the ion optics focal length 130 cm. The beam is positioned so the plasma electrode is at 140 cm from the MST plasma axis.

The composition of the hydrogen neutral beam was measured by a magnetic analyzer equipped with a stripping He target. Figure 3 demonstrates the results of the measurements at the beam energy of 30 keV. The measured fraction of hydrogen atoms with the full energy exceeds 90%. This is attributed to a high electron temperature and plasma density in the plasma source and a low concentration of molecular

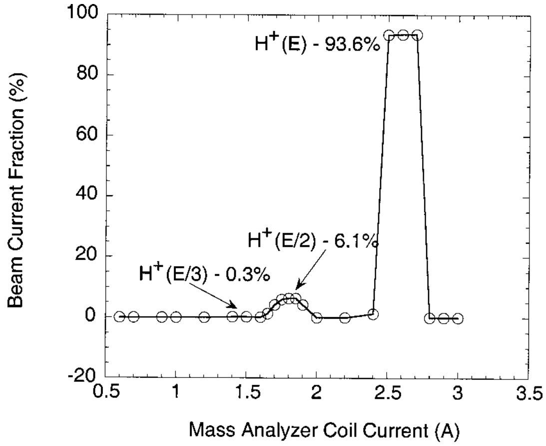

FIG. 3. Energy composition of the hydrogen beam.

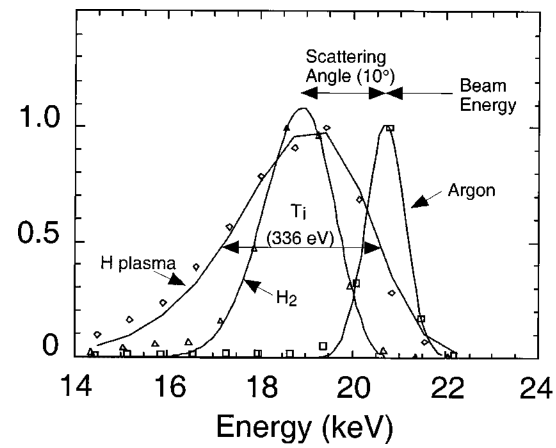

FIG. 5. Results of RS measurements with 20 keV helium beam in hydrogen plasma. The plasma scattered peak analysis gives $T_i = 336$ eV.

ions. Notice also that the full energy component is narrower in the energy space than the half-energy component.

V. MST RESULTS

To illustrate the beam application for the MST we show examples of measurements with the CHERS and RS diagnostics. More details can be found in Refs. 13 and 14.

The CHERS hydrogen 4 A/30 keV diagnostic neutral beam (DNB) propagates along the minor radius and the recombination radiation is collected from a small volume at the plasma center. A wave form of C VI radiation at 343.37 nm measured with a ISA-H20 monochromator (Instruments SA, Inc.) with a photomultiplier tube (PMT) is shown in Fig. 4(a). One can clearly see the enhancement of the signal over the background (which is the signal level before and after the beam) during the beam operation. The irregular spikes come from so-called sawtooth crashes and for analysis we select shots with the beam between the crashes. The light emitted during the beam operation was spectrally analyzed with an existing high speed Doppler spectrometer.[15] This device has 16 fiber bundles on the exit plane of a 1 m focal length spectrometer which couple light to 16 PMTs to be read out in parallel. Data from these 16 channels are shown in Fig. 4(b) for a typical MST discharge. The 16 channels cover a 0.67 nm wavelength range centered on 343.37 nm and a simple Gaussian fit to the data yields an ion temperature of about 300 eV for this case.

The RS helium 4 A/20 keV DNB also propagates along the minor radius and the scattered atoms are collected from an area near the axis at $\theta = 10°$ scattering angle. The results of scattering on room temperature argon and hydrogen, and on hydrogen plasma ions are shown in Fig. 5. Scattering on the heavy Ar results in a peak at the beam energy with the width approximately equal to the beam initial energy spread. Scattering on the room temperature H_2 results in the peak shift equal to $E_{\mathrm{beam}} m_{\mathrm{He}} / m_{\mathrm{H}} \theta^2$.[3] The beam spectra widens in comparison to the argon case due to the finite angular spread of the DNB. Scattering on the plasma ions results in additional broadening of the spectra which is related to the plasma ion temperature [3] $\Delta E_{\mathrm{HWFM}} = 8\,\theta (E_{\mathrm{beam}} T_i \ln 2)^{1/2}$. The plasma ion temperature, calculated using this formula is $T_i = 336$ eV, which agrees with the CHERS results. The spectra also become somewhat asymmetric due the finite angular spread of the DNB.

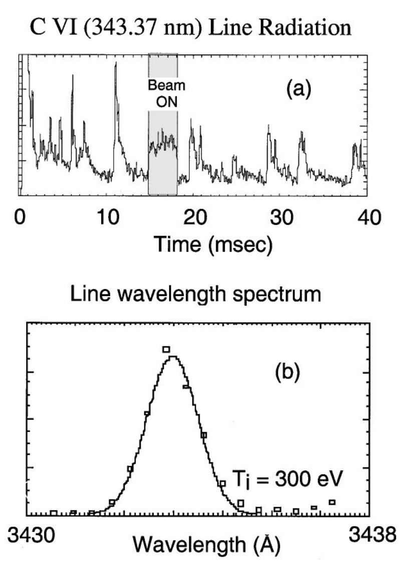

FIG. 4. Results of CHERS measurements with 30 keV hydrogen beam. (a) Wave form of C VI radiation at 343.37 nm. (b) Doppler resolved spectra gives $T_i = 300$ eV.

VI. CONCLUSIONS

The DNB system developed and fabricated by the Budker Institute of Nuclear Physics for the MST is completely operational and the beam and the analyzers' parameters are entirely within the specified range. Preliminary measurements using the Rutherford scattering, CHERS, and motional Stark effect diagnostics are very encouraging.[13,14] The direction of work on the MST now is to improve the sensitivity, increase the signal-to-noise ratio, and to improve the time resolution of the diagnostics.

ACKNOWLEDGMENTS

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