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Calibration of an advanced neutral particle analyzer for the Madison Symmetric Torus reversed-field pinch[a)]

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A new **E**||**B** neutral particle analyzer, which has recently been installed on Madison Symmetric Torus (MST) reversed-field pinch (RFP), has now been calibrated, allowing the measurement of the fast ion density and energy distribution. This diagnostic, dubbed the advanced neutral particle analyzer (ANPA), can simultaneously produce time resolved measurements of the efflux of both hydrogen and deuterium ions from the plasma over a 35 keV energy range with an energy resolution of 2–4 keV and a time resolution of 10 μs. These capabilities are needed to measure both majority ion heating that occurs during magnetic reconnection events in MST and the behavior of the fast ions from the 1 MW hydrogen neutral beam injector on MST. Calibration of the ANPA was performed using a custom ion source that resides in the flight tube between the MST and the ANPA. In this work, the ANPA will be described, the calibration procedure and results will be discussed, and initial measurements of the time evolution of 25 keV neutral beam injection-born fast ions will be presented. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4729493]

I. INTRODUCTION

The recent addition of a 1 MW, tangential neutral beam injector[1,2] on the Madison Symmetric Torus (MST)[3] has facilitated the study of fast ion dynamics and momentum transport in the reversed-field pinch (RFP). While acceleration of thermal ions and the generation of non-Maxwellian ion distributions during magnetic reconnection events have been studied in the RFP in the past, it is only now, with the installation of high power neutral beams on multiple RFPs, that the behavior of fast beam-born ions can be investigated in the RFP configuration. To that end, the advanced neutral particle analyzer (ANPA) has been added to the diagnostic set of MST. This diagnostic is capable of simultaneously measuring hydrogen and deuterium fast neutrals with energies up to 45 keV and an energy range of 35 keV. The flexible design of the ANPA also allows this 35 keV energy range to be shifted down in order to detect thermal neutrals and the 25 keV beam neutrals at the same time. This diagnostic greatly enhances our ability to measure the time evolution of both the beam-generated fast hydrogen distribution and a fast deuterium population that is generated during global reconnection events that occur in standard MST discharges. While there is a great deal of physics that can, and soon will, be studied with this diagnostic, this work focuses on the calibration of the diagnostic, which is critical to gaining a quantitative understanding of the fast ion population in MST.

II. HARDWARE

Designed at the Budker Institute of Nuclear Physics (BINP) in Russia, details of the ANPA design have appeared elsewhere,[4,5] but specifics of the device implemented on MST will be presented here. The ANPA is compact, measuring just 28 cm across, which allows the diagnostic to be moved with relative ease between radial and tangential views. This is significant as it makes it possible to measure both the parallel and perpendicular components of the distribution function with a single diagnostic. The ANPA, shown in Fig. 1, consists of five primary components: the electron stripping foil, the electrostatic focusing lens, the magnet for energy separation, the capacitor for mass separation, and the secondary electron multipliers (SEMs) used to detect the incident ions at 10 locations for each species (for a total of 20 channels). The vacuum housing, lens, capacitor, and 0.6 T magnet were provided by BINP. The stripping foil is made by the Lebow company and consists of a 10 nm thick carbon foil on a Ni mesh support. The foil is mounted on an Al ring with a 5 mm inner diameter which provides the limiting aperture for the field of view of the diagnostic. The SEMs selected for this diagnostic are the MAGNUM 5900 from Photonis. The stripping foil bias, SEM bias, lens, and capacitor voltages are provided by high voltage power supplies from UltraVolt Inc. All of the high voltage supplies are controlled over ethernet via the analogue output of a pocket PLC (Galil RIO-47100).

In addition to the ANPA itself, the BINP design includes an integrated ion source for *in situ* calibration (see Fig. 1). The operating principle of the ion source is similar to the Bayard-Alpert high vacuum gauge. The source consists of a thoriated tungsten filament that is biased −200 V with respect to a

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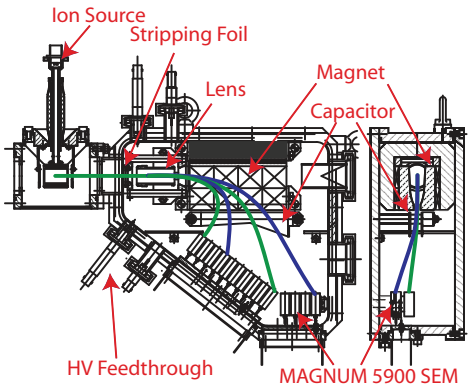

FIG. 1. This figure shows a schematic view of the major components of the ANPA including the ion source. MST is off the figure to the left. The green lines show the hydrogen trajectories while the blue show the deuterium trajectories for the lowest and highest energy channels.

can shaped cylindrical mesh that is held at high potential with respect to a set of grounded grids about 1 cm from the ends of the mesh can. The mesh can and the grounded grids are nearly transparent to neutrals and so the entire apparatus resides in the beam line during operation. The energy of the ions produced by the source is fundamentally limited by the three conductor vacuum feedthrough, but in practice is limited by the high voltage bias supply (UltraVolt 40A-12-P4-C) at 43 kV.

III. CALIBRATION

The ion source provides a straightforward way to calibrate the ANPA. The energy calibration can be done in place by continuously scanning the voltage on the ion source from 43 kV to 0 V. Performing an absolute calibration is somewhat more involved as the total number of each species of ion incident on the foil must be known as well. To this end, the absolute calibration of the ANPA was performed on the bench with a faraday cup (Beam Imaging Solutions model FC-1) placed on what is normally the MST side of the ion source (see Fig. 2). The faraday cup is biased to +18 V in order to avoid secondary emission current. Since the source design is symmetric, the current output from the SEMs for each of the 10 hydrogen detectors is compared to the total current measured by the faraday cup. In practice, the source is not perfectly symmetric, but the output from one side is generally proportional to the other and has been accounted for in the following analysis.

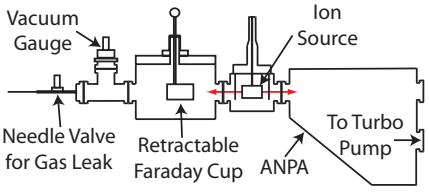

FIG. 2. Schematic view of the calibration setup. A gas bottle attached to the needle valve on the left side can provide a controlled leak of a particular gas if desired. The faraday cup is retractable for possible *in situ* absolute calibration in the future.

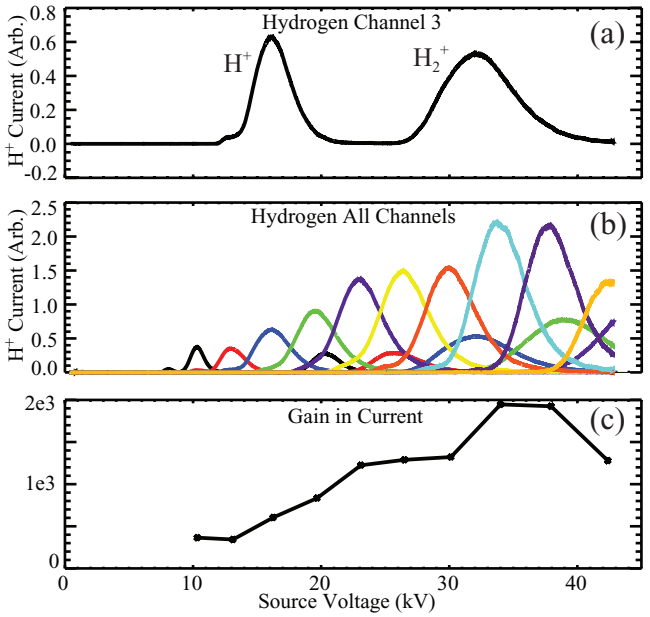

FIG. 3. Panel (a) shows one of the lower energy channels in which the H^+ and H_2^+ peaks can be seen clearly. Panel (b) shows all 10 of the hydrogen channels. Panel (c) shows the absolute gain in current of the ANPA.

In order to perform the absolute calibration of the hydrogen channels, which will only detect H^+ ions, with the faraday cup, which will measure the total incident ion current, the relative contribution of each species of ion generated by the ion source must be determined. The H^+ ions were generated by electron impact ionization of the residual water vapor in the ion source. This process generates two products that can be measured by the ANPA, H^+ and H_2^+. It is assumed that these ions dominate the faraday cup signal; however, work is ongoing to properly quantify the contributions from heavier ions such as H_2O^+ and OH^+. Sweeping the voltage over the full range of the source shows two clear peaks in each of the lower energy hydrogen channels (see Fig. 3(a)). The first peak is due to H^+ ions which have passed through the stripping foil and continued to the detectors. The second is due to H_2^+ molecular ions which split upon hitting the foil to become a pair of hydrogen ions moving at half the velocity of the primary hydrogen ions. It should be noted that there is also a small contribution from hydrogen ions that neutralize (H_0) before they reach the stripping foil and are then ionized. The three species can be easily distinguished by biasing the stripping foil with respect to ground. The H^+ ions decelerate towards and accelerate away from the foil in equal amounts, and thus the central energy for this peak will not change with changing foil bias. The H_2^+ signal will shift towards the H^+ peak with increasing foil bias as they will see twice as much acceleration as deceleration. The H_0 peak will shift to lower energy, away from the H^+ peak, as it will see no deceleration and the full acceleration due to the foil bias. For this setup used here, the H_0 contribution is negligible.

The relative contribution of the H_2^+ and H^+ species to the faraday cup current is determined by comparing the relative heights of their respective peaks seen in the SEM signals during a voltage sweep. The H_2^+ peak is generally about 25%

smaller than the H^+ peak and the SEM will register twice as much current from the H_2^+ than the faraday cup will because the SEM registers two H^+ ions for each H_2^+. Given this information, the H^+ current is found to be roughly 72% of the current measured by the faraday cup. Combining this information with the differences in area of the stripping foil and the faraday cup as well as the asymmetry of the ion source, the absolute gain for each channel can be determined. Figure 3(b) shows the calibration scan for the full set of 10 hydrogen channels. While the peaks are distinct, there is significant channel to channel overlap indicating that the ion beam, after passing through the carbon foil, is poorly focused. Work is ongoing to optimize the focusing optics to minimize this overlap. Figure 3(c) shows the gain coefficients relating the SEM current output to the current incident on the stripping foil.

While ionization of residual gas works well for the relative calibration of the hydrogen channels, it does not work for calibration of the deuterium channels as there is very little residual deuterium in the diagnostic. For calibrating the deuterium channels, a 2×10^{-5} torr deuterium leak was supplied through the needle valve shown on the left side of Fig. 2 (the nominal base pressure was 2×10^{-6} torr). However, electron impact ionization of D_2 preferentially generates D_2^+, and thus the much smaller D^+ signal was nearly washed out. An alternate approach is to use a fill gas that does not produce as much molecular deuterium. Deuterated methane, which is available from Cambridge Isotope, is one such molecule and will be pursued in the near future. Despite this difficulty, an initial relative calibration of the deuterium channels has been performed by identifying and fitting the D^+ peak for each channel.

IV. INITIAL DATA

This diagnostic has now been used on MST to measure two different components of the fast ion distribution. The first is a radial view which is primarily sensitive to fast ions with high $v_\perp$. The second is a toroidal view which measures fast ions from the core with high $v_\parallel$ and in the edge with high $v_\perp$. A more detailed discussion of this analysis can be found in S. Eilerman *et al.*[6] Figure 4 shows ANPA data from a standard MST discharge taken on the tangential view. The fast ion distribution is very dynamic in time with clear indications of ion acceleration at sawteeth. After the beam turns off, the signal decays in a way that is consistent with classical slowing of the fast ions, suggesting that the fast ions are well confined in MST plasmas.

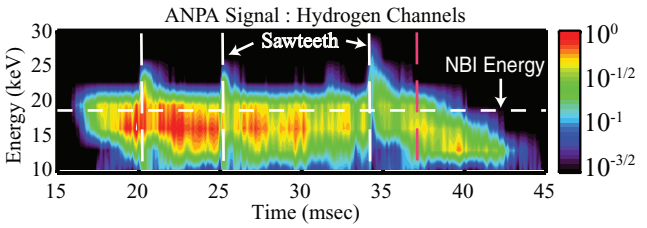

FIG. 4. ANPA data from neutral beam injection (NBI) into a standard MST discharge. The NBI turns on at 15 ms and turns off at 37 ms (red dashed line). The beam, run at 19 kV for this experiment, is clearly visible as is the fast ion acceleration at sawtooth events.

V. CONCLUSIONS

The addition of the ANPA to the diagnostic set on MST has greatly enhanced our ability to understand the time dynamics of fast ions traveling both parallel and perpendicular to the magnetic field. Absolute calibration of this diagnostic not only allows the characterization of the shape of the fast ion distribution, but also the fast ion density. This makes it possible to study fast ion confinement and β values (which TRANSP modeling suggests may be as high as 10%) as well as acceleration and heating mechanisms believed to be active during global magnetic reconnection events that occur in standard discharges in MST.[7]

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