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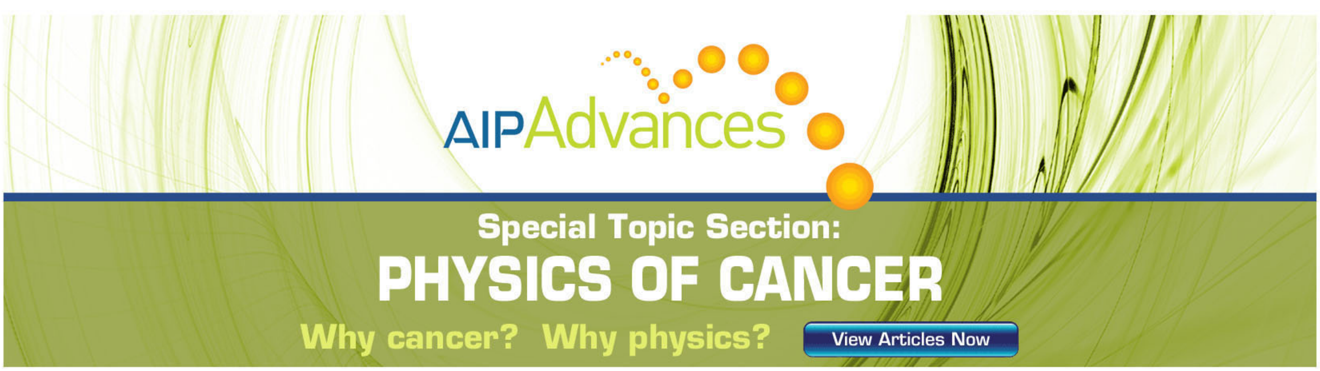

Time-resolved ion energy distribution measurements using an advanced neutral particle analyzer on the MST reversed-field pinch[a)]

S. Eilerman,[1,b)] J. K. Anderson,[1] J. A. Reusch,[1] D. Liu,[2] G. Fiksel,[3] S. Polosatkin,[4] and V. Belykh[4]

[1]*University of Wisconsin–Madison, Madison, Wisconsin 53706, USA*
[2]*University of California–Irvine, Irvine, California 92697, USA*
[3]*University of Rochester, Rochester, New York 14623, USA*
[4]*Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia*

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An advanced neutral particle analyzer (ANPA) capable of simultaneously measuring hydrogen and deuterium ions of energies up to 45 keV has recently been developed for use on the Madison Symmetric Torus. The charge-to-mass separation allows for separate analysis of bulk deuterium ions and hydrogen ions injected with a 1 MW, 25 keV neutral beam. Orientation of the ANPA allows sampling of different regions of ion velocity space; a radial viewport favors collection of ions with high $v_{\perp}/|v|$ while a recently installed tangential viewport favors ions with high $v_{||}/|v|$, such as those from the core-localized fast ion population created by the neutral beam. Signals are observed in the ANPA's highest energy channels during periodic magnetic reconnection events, which are drivers of anisotropic, non-Maxwellian ion energization in the reversed-field pinch. ANPA signal strength is dependent on the background neutral density, which also increases during magnetic reconnection events, so careful analysis must be performed to identify the true change in the ion distribution. A Monte Carlo neutral particle tracing code (NENE) is used to reconstruct neutral density profiles based on D_α line emission, which is measured using a 16-chord filtered photodiode array. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4728312]

I. INTRODUCTION

The Madison Symmetric Torus (MST) has recently added an advanced neutral particle analyzer[1] (ANPA) to its collection of diagnostics for studying the energetic ion distribution in the reversed-field pinch (RFP). The ANPA is an E‖B NPA with energy resolution of 2–4 keV, temporal resolution of 10 μs, and an energy range of ∼35 keV. It is able to separately measure hydrogen and deuterium ions, allowing independent measurements of thermal deuterium ions and hydrogen ions sourced by a 1 MW, 25 keV neutral beam injector (NBI). A more detailed discussion of the ANPA hardware and calibration can be found in Reusch *et al.*[2] This work outlines the analysis of the ion pitch profile and background neutral density which is required to extract information about the fast ion distribution from the ANPA signal.

II. CONTRIBUTIONS TO MEASURED SIGNAL

The ANPA measures the products of a fast ion population n_{fi} exchanging charge with a background neutral population n_0. However, only a fraction of the neutrals generated make it to the ANPA. Ions must have the correct pitch at the location of charge exchange such that the resulting neutral's straight path leads into the ANPA collection region. This pitch, γ_c, varies with the magnetic field structure and the orientation of the ANPA with respect to MST. Unlike in a tokamak, the poloidal and toroidal fields in the RFP are of comparable amplitude, with the toroidal field crossing zero and reversing near the plasma edge. Consequentially, ions near the edge with high pitch $\gamma \equiv v_{||}/|v|$ are actually traveling in the poloidal direction and would not be detected by a toroidally viewing NPA. Signal is further reduced by the chance of reionization before the neutral reaches the ANPA. The fraction that reionizes, f_r, is calculated from the sums of ion impact ionization, electron impact ionization, and ion-neutral charge exchange. Taking these effects into account, the measured neutral flux is

$$\Gamma_{meas} = \int_L n_0 n_{fi} \langle \sigma v \rangle_{cx} \, \delta(\gamma - \gamma_c)(1 - f_r) \, dl. \qquad (1)$$

TRANSP modeling[3] of the fast ion distribution generated by NBI[4] produces estimates of the pitch distribution and density of fast ions. The critical pitch γ_c and reionizing fraction f_r can be determined from equilibrium reconstructions, and the neutral density n_0 is calculated from modeling of the measured D_α line emission, which will be discussed in Sec. III. Due to the finite solid angle of the ANPA, the delta function in Eq. (1) will have a finite width around the critical pitch γ_c. The ANPA's solid angle has not yet been precisely characterized, but due to multiple apertures in the flight tube, it is well-collimated. For this model, ions with minor pitch deviations ($|\gamma - \gamma_c| \leq 0.04$) are considered. By combining these calculations, analysis of the signal contribution along the ANPA's line of sight can be performed (Fig. 1).

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[b)]eilerman@wisc.edu.

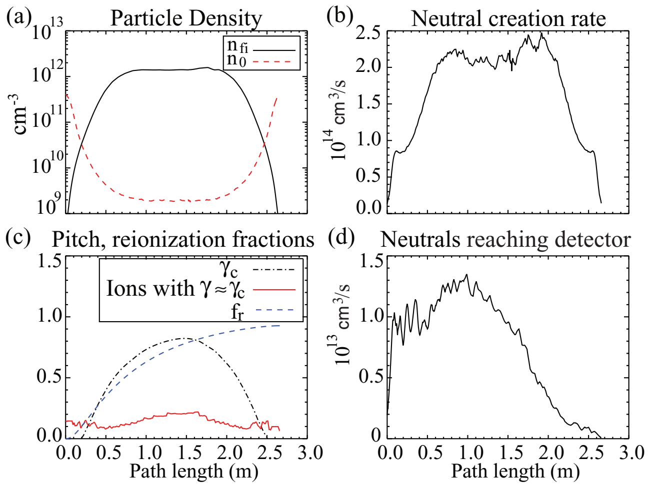

FIG. 1. Modeling of the total expected signal on the ANPA tangential viewport based on TRANSP estimates of NBI-injected ions. The fast ion and background neutral densities (a) generate a flux of neutrals (b). However, only a fraction of ions (c, red) have the correct pitch (c, black) to make it into the ANPA. Additionally, neutrals born further along the sightline have an increased probability of reionizing (c, blue). After accounting for the reduction factors in (c), a prediction of the measured signal is shown (d).

The ANPA has been mounted on two different MST viewports: a "radial" view that is perpendicular to MST's wall and looks radially through the plasma core, and a "tangential" view that is mounted at an angle and looks toroidally through the plasma core (Fig. 2(a)). These two views allow examination of different regions of the spatial and velocity spaces of the fast ion distribution function. Although the RFP is characterized by strong magnetic shear, a radially viewing chord is still perpendicular to the magnetic field along its entire sightline, while a toroidal view will sample parallel ions from the plasma core and perpendicular ions from the plasma edge. Based on the modeling technique shown in Fig. 1, the pitch distribution of the measured neutral flux for each viewport can be determined (Fig. 2(b)). Results confirm that the radial view receives most of its signal from low-pitch ions while the tangential view is weighted toward high-pitch ions but has a much wider distribution.

Due to the edge-peaked neutral density profile, small alterations to the edge fast ion density profile provided by TRANSP can lead to large changes in the expected signal. Errors in the profile may be expected due to TRANSP's use of toroidal flux as a radial coordinate, resulting in improper modeling of the edge of the RFP where the toroidal field becomes negative. Increased charge exchange at the plasma edge would contaminate the tangential view with large quantities of low-pitch ions; methods of sourcing additional neutrals in the plasma core with a radially injected hydrogen neutral beam or deuterium pellet injector are being explored to mitigate this effect. Another solution under consideration is an extension of the ANPA flight tube that could be inserted into the plasma to block out signal from the plasma edge.

III. MEASUREMENTS AND MODELING OF THE NEUTRAL DENSITY PROFILE

Accurately determining the background neutral density is crucial to ANPA signal analysis. Neutral density can be calculated from measurements of the flux of D_α line emission photons γ_{D_α} through the relationship

$$\gamma_{D_\alpha} = n_0 n_e \langle \sigma v \rangle_{excitation} . \tag{2}$$

Line-integrated D_α emission is measured using a 16-chord array of filtered photodiode detectors.[5] A two-dimensional emission profile can be reconstructed using an Abel inversion; however, due to the asymmetric and edge-localized nature of MST's emission profile, previous attempts at direct inversions led to unrealistic results. Instead, the Monte Carlo neutral particle tracing code NENE (Ref. 6) is used to model diffusion of neutral particles from the edge of MST to the core. NENE models are created with a variety of neutral source profiles and a synthetic replica of MST's D_α array is used to find a combination of models that match the line-integrated emission measurements. Results indicate typical neutral densities of 10^8–10^9 cm^{-3} in the core and 10^{11}–10^{12} cm^{-3} at the edge. More neutrals are sourced on the outboard wall of the machine due to plasma collision with a carbon limiter. This increased sourcing, along with asymmetry of n_e and T_e profiles due to the plasma's Shafranov shift, generate an overall asymmetry of the D_α emission that is consistent with measurements (Fig. 3).

To better characterize the fast ion distribution, raw ANPA signals can be normalized to the changing background neutral density; however, because of the equilibrium modeling required to calculate the neutral density and the non-local nature of the ANPA signal, the line-integrated D_α emission is used as a proxy for the spatially averaged change in neutral density. In Fig. 4, ANPA measurements of the hydrogen beam are shown with and without D_α normalization. Analysis of the

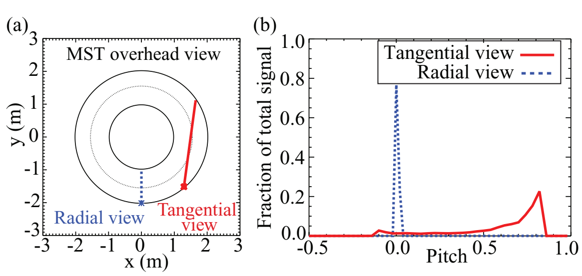

FIG. 2. The geometry of the ANPA viewports on MST (a) affects the pitch distribution sampled by the diagnostic (b).

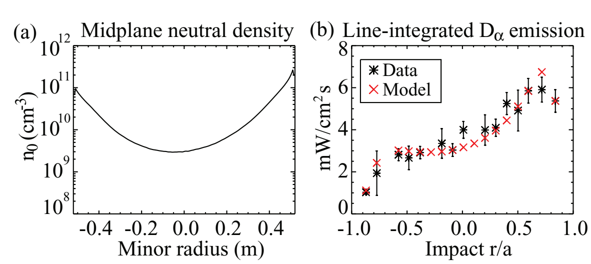

FIG. 3. (a) Midplane neutral density profile generated by NENE. (b) Simulated D_α emission from the NENE profile (red) agrees well with measurements (black).

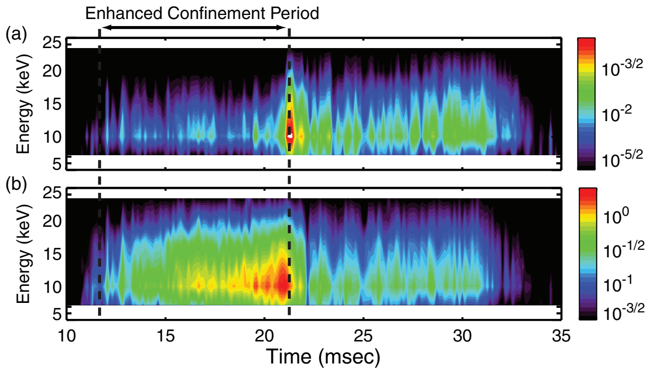

FIG. 4. (a) ANPA signal increases substantially after the end of an enhanced confinement period in which D_α emission is reduced. Neutral density also increases dramatically at the end of this period, and after normalizing (b), the fast ion density is seen to be reduced after loss of confinement.

data without correction would lead to improper conclusions about the generation of energetic ions during MHD activity at the end of the enhanced confinement period.[7]

IV. MEASUREMENTS OF ION ENERGIZATION DUE TO TEARING MODE RECONNECTION

Periodic magnetic reconnection events in the RFP known as sawteeth are drivers of ion energization. Magee *et al.*[8] measured a non-Maxwellian, anisotropic ion energy distribution (out to the previous diagnostic limit of 5 keV) after reconnection events. Measurements of D–D neutron flux indicate that the power-law tail should extend to even higher energies. With the addition of the ANPA to MST's diagnostic suite, reconnection-energized ions have now been measured as high as 25 keV (Fig. 5). Magnetic modes rise in amplitude until the sawtooth crash (coinciding with the sharp rise in $m = 0$ activity). This crash accelerates ions, creating a large neutron flux, and signal is seen in the highest ANPA energy channels.

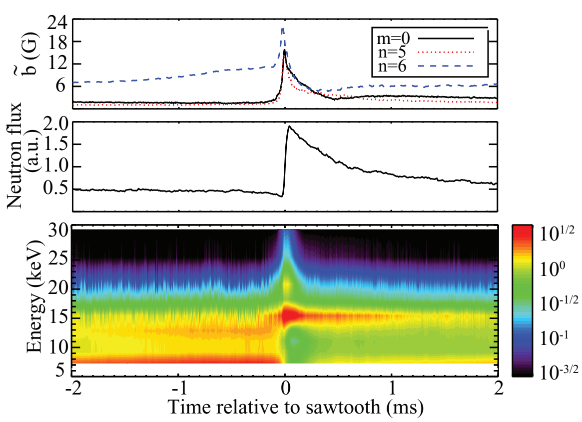

FIG. 5. After reduction of statistical noise by averaging 205 similar sawtooth events, energization of thermal deuterium ions during reconnection is observed on the ANPA. D–D neutron flux rises dramatically as signal moves into the higher ANPA D^+ energy channels. These data were taken on the radial viewport and are calibrated for relative detector efficiency.

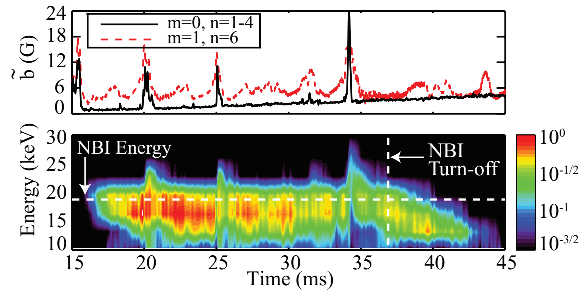

FIG. 6. Energization of the NBI hydrogen distribution is observed during sawtooth crashes, and decay of the distribution function can be measured after beam turn-off at 37 ms.

Energization of NBI-sourced ions above their injection energy has also been observed (Fig. 6). Magnetic activity energizes ions during the beam injection period, and ANPA signal falls off after beam turn-off. Decay of the ANPA signal along with neutron flux decay is being used to study the confinement of fast ions in the RFP.[4]

V. SUMMARY

The advanced neutral particle analyzer is a versatile addition to MST's diagnostic suite, enabling time-resolved measurements of the energy and phase distributions for hydrogen beam ions and bulk deuterium ions. However, careful analysis of ion pitch and background neutral density must be performed to ensure proper conclusions are drawn about the ion distribution. Using these techniques, ion energies as high as 25 keV have been observed after magnetic field reconnection, and further studies of ion distribution function dynamics and confinement are underway.

ACKNOWLEDGMENTS

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