Energetic Ion Generation and Confinement in the MST RFP

S. Eilerman[1], A.F. Almagri[1], J.K. Anderson[1], V.V. Belykh[2], B.E. Chapman[1], V.I. Davydenko[2], D.J. Den Hartog[1], W.X. Ding[3], G. Fiksel[1,4], C.B. Forest[1], A.A. Ivanov[2], J.J. Koliner[1], S.T.A. Kumar[1], L. Lin[3], D. Liu[1,5], R.M. Magee[1,6], V.V. Mirnov[1], M.D. Nornberg[1], S.V. Polosatkin[2], J.A. Reusch[1], J.S. Sarff[1], D.A. Spong[7], N. Stupishin[2], J. Waksman[1]

[1] *University of Wisconsin – Madison, Madison WI, USA*

[2] *Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia*

[3] *University of California – Los Angeles, Los Angeles CA, USA*

[4] *University of Rochester Laboratory for Laser Energetics, Rochester NY, USA*

[5] *University of California – Irvine, Irvine CA, USA*

[6] *West Virginia University, Morgantown WV, USA*

[7] *Oak Ridge National Laboratory, Oak Ridge TN, USA*

Recent diagnostic upgrades on the Madison Symmetric Torus (MST) have revealed many new features of energetic ion generation and confinement processes in the reversed-field pinch (RFP). MST [1] is a large-scale RFP (R/a = 1.5 m / 0.5 m) with moderate plasma current (200-600 kA) and density (0.5-1.5 10^{13} cm^{-3}), and temperatures up to 2 keV. Energetic ions can be sourced with a 1 MW, 25 keV hydrogen neutral beam injector (NBI) doped with up to 5% deuterium so that beam-target neutron flux (measured by a plastic scintillator) can be used as an indication of the presence of fast ions. A new advanced neutral particle analyzer (ANPA) [2] [3] is capable of measuring ions with energies of 0-45 keV with separate channels for bulk deuterium ions and hydrogen beam ions. Its compact size allows easy movement between radial and tangential viewports, allowing sampling of different areas of the ion velocity space [4]. MST is also equipped with a charge exchange recombination spectrometery (CHERS) system for measuring impurity ion temperature, a Rutherford scattering diagnostic for majority ion temperature, an 11-chord FIR interferometer, and a multipoint Thomson scattering diagnostic.

Although the mechanism for ion energization during tearing mode-driven magnetic reconnection has not yet been identified, previous studies have identified a number of features of the process. In MST, global reconnection events (known as sawteeth) have been shown to create a non-Maxwellian tail in the ion distribution out to the previous diagnostic limit of 5 keV [5]. Heating anisotropy ($T_\perp > T_{||}$) has been measured in C^{+6} impurity ions, and the heating efficiency increases with $\sqrt{m_i}$ [6]. Figure 1 shows the D-D neutron flux generated by high-energy ions created at sawtooth crashes. The amount of neutron flux generated by sawteeth implies the extension of the energetic ion tail to 25 keV or greater [5].

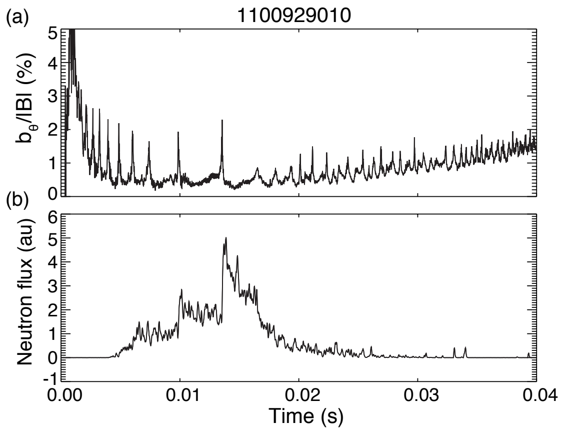

Figure 1: Magnetic fluctuations associated with sawteeth (a) rapidly energize ions, causing large, abrupt increases in the neutron flux (b).

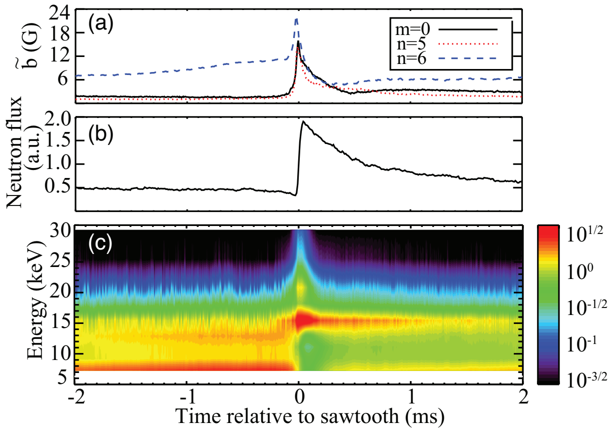

Figure 2: An ensemble of many sawtooth events (a) reveals ion acceleration through the D-D neutron flux (b) and neutral flux measured by the ANPA (c).

A well-resolved measurement of the non-Maxwellian energetic ion distribution created during sawtooth energization is now possible using the ANPA. By averaging many similar sawtooth events, signals are measured up to 30 keV without NBI (Fig. 2). Beam-injected ions are also energized above their injection energy during sawteeth (Fig. 3).

Neutral beam injection provides a reliable source of energetic ions for confinement studies. Using the "beam blip" technique, previous experiments have revealed that energetic ions are well-confined and obey classical slowing-down theory [7]. These experiments were conducted using the beam-target neutron flux as an indication of the fast ion population. Recent experiments using the ANPA to measure the fast ion population confirm these results. After NBI turn-off, measured ions in the energy channel corresponding to the beam injection energy descend into lower energy channels at a rate τ_{sl} that is roughly consistent with the estimated plasma temperature (Fig. 3). Longer slowing times are measured in higher-current, hotter plasmas.

Contrary to the full-energy component of the beam, which exhibits good confinement, the half-energy population appears to be lost shortly after beam turn-off. This is observed using the tangential ANPA view, which is sensitive to a combination of core-localized, high-pitch ions and edge-localized, low-pitch ions [4]. The half-energy component of the neutral beam is more likely to ionize in the outer portion of the plasma, giving it a higher perpendicular velocity component. This region has a much higher background neutral population than the core, leading to more charge exchange loss (and consequentially, more ANPA signal). Lower energy ions are also more prone to loss via stochastic diffusion.

The energetic ion population introduced by NBI has several macroscopic effects on the bulk

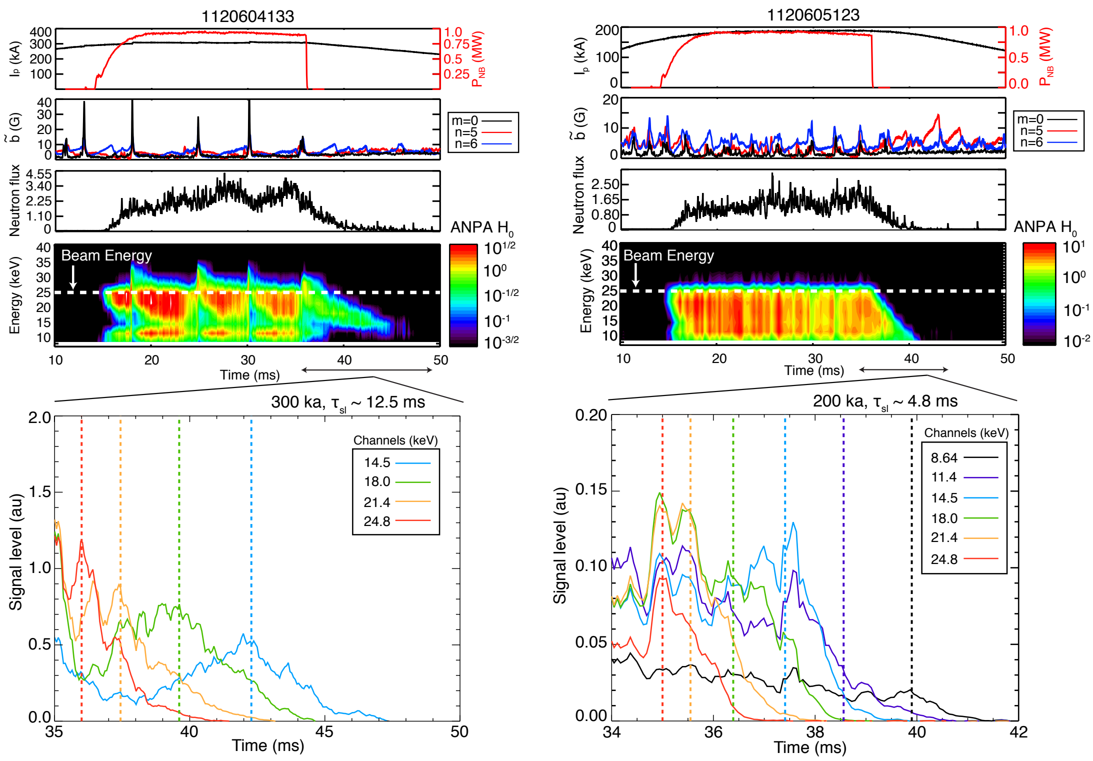

Figure 3: During the period directly after beam turn-off, ion slowing is observed as the neutral flux passes into lower ANPA energy channels. The vertical dashed lines indicate when the beam ions should be in the corresponding energy channel based on classical slowing theory. Shown left is a shot with $I_p \approx 300$ kA in which a slowing time of 12.5 ms best fits the ANPA data. Shown right is a 200 kA shot in which the ions slow at a much quicker rate ($\tau_{sl} \approx 4.8$ ms). Sawtooth energization of beam ions and rapid decay of the half-energy beam population is also observed in the left set of plots. The right set of plots are from a discharge in which sawtooth activity is intentionally suppressed, and the beam slows too quickly to distinctly observe the half-energy component.

plasma. When injected in the same direction as the plasma current, NBI substantially increases plasma rotation. Inversely, if NBI is injected counter-current, the plasma rotation decreases. Electron heating due to NBI has also been observed. During a study of 200 kA high-confinement PPCD plasmas [8], typical core electron temperatures without NBI increase from 200 to 800 eV during the PPCD period. With NBI, an additional 100 ($\pm$ 50) eV of heating is observed [9].

The energetic ion population also has a stabilizing effect on the plasma, significantly reducing the core-most tearing mode amplitude. The mechanism for the mode reduction is not yet fully understood, but possible explanations include modification of the $J_{||}$ profile, enhanced flow shear, or net perpendicular current stabilization of magnetic islands. Further study of mode stabilization is being explored by adjusting MST's q profile, thereby shifting the location of tearing mode resonant surfaces with respect to the beam ion population.

Several high-frequency bursting modes have also been observed for the first time in the RFP [10]. The modes are characterized by brief (∼0.06 ms) magnetic and density fluctuations with m=1, n=4-5 mode numbers. The n=5 mode occurs first and scales with beam injection energy, behavior reminiscent of energetic particle modes observed in tokamaks. The n=4 mode scales with plasma mass density and magnetic field, suggesting an Alfvénic nature. Using the FIR diagnostic, significant bicoherence is measured between these two modes and an m=0, n=−1 mode, strongly suggesting a three-wave coupling relation.

The amplitude of the bursting modes is correlated with the amount of core tearing mode suppression, and the amount of suppression decreases at each burst. This implies that larger energetic ion populations have a stronger effect on the tearing mode while also driving stronger bursting modes, and these modes cause fast ion loss or redistribution, which results in a weakening of the suppression effect. This is supported by an observed decrease in ANPA signal in the channels corresponding to the beam injection energy at the time of the bursts.

In summary, the generation, confinement, and effects of energetic ions is a rich field of study in the RFP. New diagnostic capabilities allow more detailed measurements of the non-Maxwellian energetic ion tail created by magnetic reconnection; neutral beam injection provides an excellent source of fast ions for confinement, momentum, heating, and mode suppression studies; and beam-driven instabilities have been observed for the first time in the RFP, providing a possible loss or redistribution mechanism for the energetic ion population.

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