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Development towards a fast ion loss detector for the reversed field pinch

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A fast ion loss detector has been constructed and implemented on the Madison Symmetric Torus (MST) to investigate energetic ion losses and transport due to energetic particle and MHD instabilities. The detector discriminates particle orbits solely on pitch and consists of two thin-foil, particle collecting plates that are symmetric with respect to the device aperture. One plate collects fast ion signal, while the second aids in the minimization of background and noise effects. Initial measurements are reported along with suggestions for the next design phase of the detector. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4959950]

I. INTRODUCTION

Understanding the confinement and transport of energetic particles is critical in a burning plasma. Fast ions are ubiquitous in fusion research through neutral beam injection, RF heating, and fusion products. Along with MHD activity, large populations of fast ions can subsequently drive instabilities and reduce heating efficiency, degrade confinement, and damage wall components. A full understanding of fast ion confinement and transport, however, is yet to be achieved.[1] Fast ion loss detectors (FILDs) aid in our understanding of confinement and transport by providing direct measurements of lost particles. Combining FILD signals with other diagnostic measurements, such as magnetic mode structure or density and temperature fluctuations, provides a powerful tool to examine transport processes.

The reversed field pinch (RFP) provides a unique environment to study fast ion confinement and transport. The RFP's large magnetic shear and high fast ion beta present a distinct regime from that of tokamaks or stellarators. While FILDs have been designed and implemented on various magnetic confinement devices,[2–6] a FILD has yet to be constructed that caters to the RFP. The magnetic topology of the RFP establishes $E \times B$, ∇B, and curvature drifts along flux surfaces, and the loss region for fast ions in phase space is remarkably small. In addition, the RFP has a very small vacuum region (~1 cm) between the last closed flux surface and the conducting shell.

MST ($R_0 = 1.5$ m, $a = 0.5$ m) produces RFP plasmas with I_p = 200–600 kA, $|B|$ = 0.2–0.5 T, and $T_e(0)$ = 200–300 eV that may be heated with 1 MW of neutral beam injection in addition to the dominant ohmic heating. The neutral beam is injected tangentially and produces core-localized, 25 keV hydrogen or deuterium ions. In recent years, MST has been a testbed for energetic particle physics for the RFP. Indeed, neutral particle analysis and measured fusion neutron flux indicate enhanced fast ion transport in the plasma core at the RFP's transition to a 3D state and with beam-driven, bursting magnetic modes.[7–9] By including a FILD in our diagnostic suite, we wish to gain further insight into these events.

This paper will discuss the design of a high-pitch FILD for a RFP in Section II and present the initial measurements and findings of the device in Section III. The paper will conclude with remarks on improving the detector design and point to future experimental goals.

II. FILD DESIGN

While other magnetic confinement devices employ wall mounted FILD designs,[3–6] the distance from the wall of MST to the last closed flux surface is ~1 cm. Therefore, to minimize plasma perturbation, a compact, probe-like design capable of being inserted through one of MST's standard 40 mm portholes was utilized. The probe is fully retractable and is capable of being rotated a full 360°. It is toroidally displaced 180° from the neutral beam so as to not be sensitive to prompt losses.

The FILD is a Faraday cup type design capable of measuring high-pitch ($v_{\parallel}/v$) fast ions in MST. It consists of two 5 μm thick Ni foils that act as current collectors for the 25 keV NBI ions. The FILD is inserted ~3–4 cm past the wall, so only ions at the "top" of their helical trajectory heading "down" may pass through the 3 mm circular aperture and be captured. The aperture size, depth, and plate locations are such that only particles with a pitch of 0.8–0.95 are collected. Figure 1 gives a representation of how the FILD functions.

A 4th order Runge-Kutta numerical model that replicated the 25 keV NBI hydrogen ion orbits aided in the design of the FILD. The magnetic field used was 0.2 T, which is comparable to the edge magnetic field in MST. The foils are housed in a cylindrical probe end that is composed of a grounded aluminum shell to eliminate electrostatic coupling to the plasma and a boron-nitride shielding to provide thermal protection.

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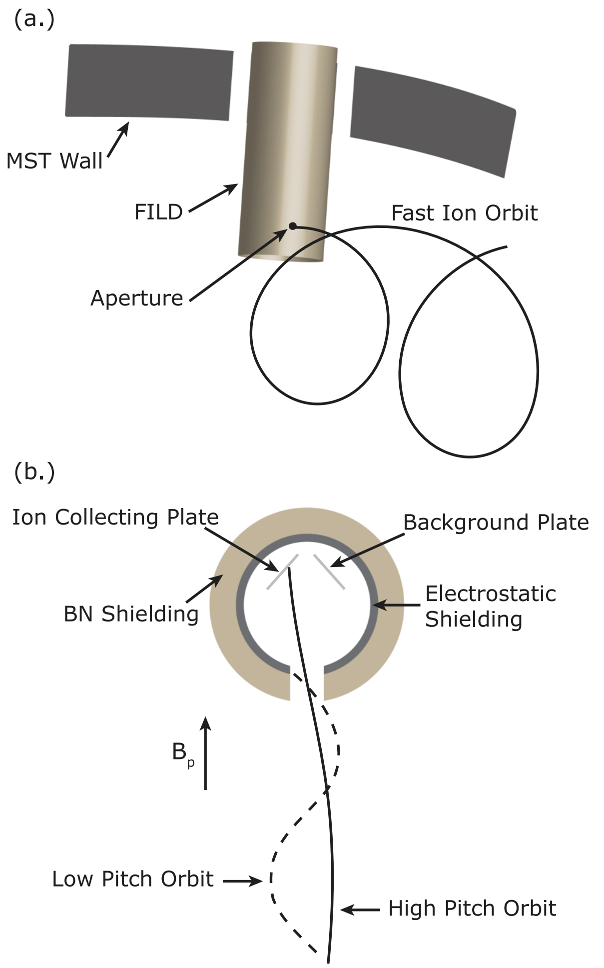

FIG. 1. Representative schematic of the high-pitch FILD. (a) Poloidal cross-cut view of the FILD through a MST porthole and an arbitrary fast ion orbit. (b) Top view along the axis of the FILD showing a rejected low-pitch orbit, an accepted high-pitch orbit, and the symmetrical plate design.

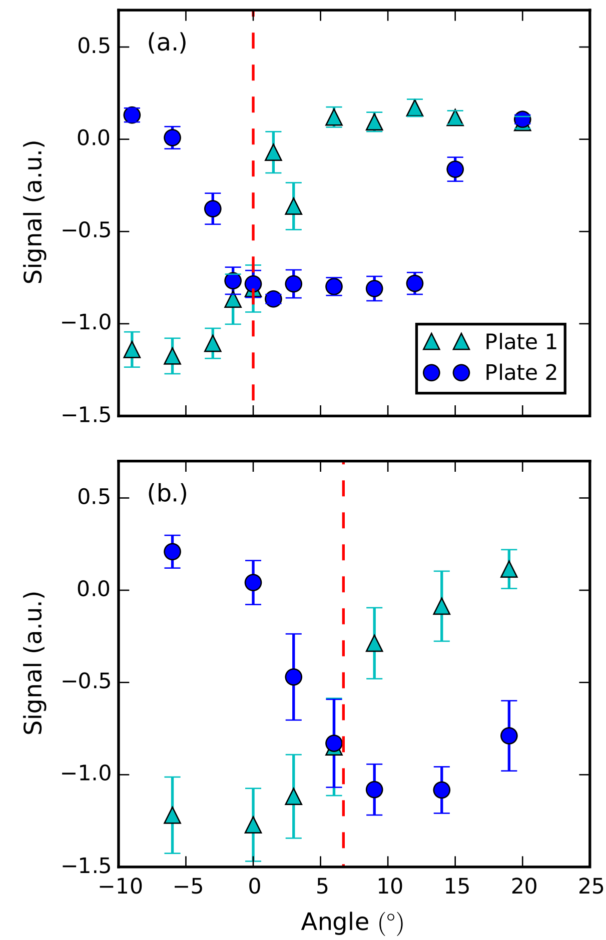

FIG. 2. Rotational scan of the FILD probe as a function of angle from the poloidal cross-section. The dashed vertical lines denote the equilibrium magnetic field line pitch at the wall. (a) $F = 0$ plasma. (b) $F = -0.2$ plasma.

One of the plates is removed from possible ion orbits by its position within the probe in order to collect any background signal present. A substantial background signal, larger than the expected fast ion loss current, is measured. (See Section III) Several possible contributors to the background are electron collection due to parallel motion along fluctuating field lines, photoelectric effect, and/or secondary electrons. Of note, we assume the background pollutes both plates equally.

Multiple observations of well-confined fast ions in MST[10] lead us to expect a small lost ion signal. To maximize our lost fast ion signal, the signal from the background plate is subtracted from the collected ion signal via a differential amplifier. The differential transimpedance amplifier has a 10^6 gain and 250 kHz cutoff frequency.

III. INITIAL RESULTS AND ANALYSIS

An angular scan of the FILD probe was first performed to find its optimal operating point. The goal of the scan was to find the location where both collecting plates measured the same signal in a plasma without NBI. Therefore, when the measurement was repeated with NBI, only the lost fast ion signal should be recorded when used with the differential amplifier. This calibration was performed in 250 kA plasmas with reversal parameters $F = 0$ and $F = -0.2$, where $F = \frac{B_\phi(a)}{\langle B_\phi \rangle}$. The results are shown in Figure 2.

In diagnosing the background signal, the collection electronics were modified to use single-channel transimpedance amplifiers for each plate instead of a single differential amplifier. As shown in Figure 2, the recorded signals have a strong dependence on the FILD's orientation with respect to the magnetic field. Notably, the two plates have equal signal when the aperture is aligned with the edge magnetic field pitch, given by $\frac{B_\phi(a)}{B_\theta(a)}$. While a complete understanding of all components of the background signal remains elusive, these measurements confirm a symmetrical (but not maximum) effect on the probe plates when aligned with $\vec{B}$.

Collected electrons appear to dominate the background signal based on this observation. The FILD has an aperture size of 3 mm, allowing electrons tightly tied to the field lines (gyroradius < 1 mm) to enter. Resistive tearing modes and porthole field error, however, result in an edge magnetic field and electron response that is not well known. The negative voltage measured provides further indication of detected electrons as well.

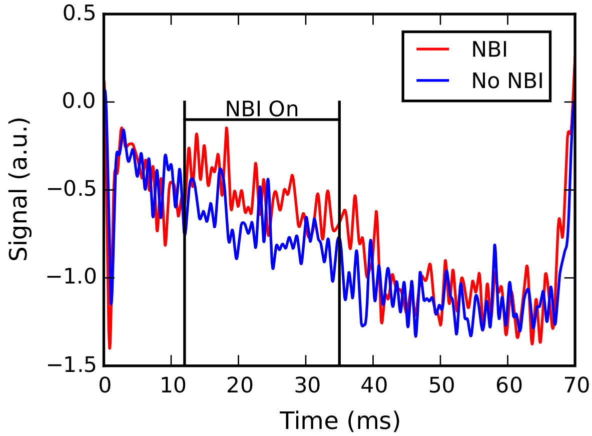

FIG. 3. FILD signal with and without NBI. The area denoted by the vertical bars is the time frame in which the neutral beam is fired.

After examining the background signal, the probe was aligned with the edge magnetic field and the differential amplifier was used in an attempt to measure fast ion losses. Neutral beam injection was used in half of a daylong campaign's shots to generate two sets of discharges: one with a significant fast ion population and one without. The results are shown in Figure 3.

A noticeable difference is discernable between the NBI and No NBI signals during the duration of the neutral beam. This is the first measured lost fast ion signal ever recorded in MST. Changes in ambient plasma parameters and fast electrons were ruled out as sources for this change by examining n_e, bolometer, and soft x-ray signals. Past work has also confirmed that NBI has little to no effect on the electron population.[11] The NBI signal persists after the duration of the neutral beam due to the well confined nature of fast ions in MST.

While the observed difference between NBI and No NBI signals is noticeable, several improvements are needed before the FILD can be used to probe the underlying physics of fast ion transport in the RFP. A higher gain could strengthen the signal but better understanding and mitigation of the background and noise are needed. Next phase efforts will be to maximize the signal-to-noise ratio of the FILD by rejecting electron signals and improving on the current circuitry design. In addition, these results have been smoothed to 1 kHz using fast Fourier transforms in order to highlight the difference between each case. No correlation between the FILD signal and energetic particle modes was found.

IV. CONCLUSION

In conclusion, we have presented our initial findings toward developing a FILD on MST in the hopes of better understanding fast ion transport in the RFP. Our high-pitch FILD is comprised of two collecting plates in a symmetric design. The simplified design discriminates high-pitch ions and allows for the minimization of background effects. A small, but appreciable, lost fast ion signal has been observed in MST but is hindered in part by unwanted electrons. Future versions of FILDs on MST will aim to eliminate any electron measurements, lower stray circuit noise, and improve resolution in both fast ion pitch and energy.

SUPPLEMENTARY MATERIAL

See supplementary material for the digital format of the data shown in this paper.

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[1] W. W. Heidbrink, Phys. Plasmas **15**, 055501 (2008).
[2] R. K. Fisher, D. C. Pace, M. Garcia-Munoz, W. W. Heidbrink, C. M. Muscatello, M. A. Van Zeeland, and Y. B. Zhu, Rev. Sci. Instrum. **81**, 10D307 (2010).
[3] D. S. Darrow, Rev. Sci. Instrum. **79**, 023502 (2008).
[4] D. S. Darrow, A. Werner, and A. Weller, Rev. Sci. Instrum. **72**, 2936 (2001).
[5] D. C. Pace, R. S. Granetz, R. Vieira, A. Bader, J. Bosco, D. S. Darrow, C. Fiore, J. Irby, R. R. Parker, W. Parkin, M. L. Reinke, J. L. Terry, S. M. Wolfe, S. J. Wukitch, and S. J. Zweben, Rev. Sci. Instrum. **83**, 073501 (2012).
[6] D. S. Darrow, S. Baumel, F. E. Cecil, R. Ellis, K. Fullard, K. Hill, A. Horton, V. Kiptily, L. Pedrick, M. Reiche, and A. Werner, Rev. Sci. Instrum. **77**, 10E701 (2006).
[7] J. K. Anderson, W. Capecchi, S. Eilerman, J. J. Koliner, M. D. Nornberg, J. A. Reusch, J. S. Sarff, and L. Lin, Plasma Phys. Controlled Fusion **56**, 094006 (2014).
[8] L. Lin, W. X. Ding, D. L. Brower, J. J. Koliner, S. Eilerman, J. A. Reusch, J. K. Anderson, M. D. Nornberg, J. S. Sarff, J. Waksman, and D. Liu, Phys. Plasmas **20**, 030701 (2013).
[9] L. Lin, J. K. Anderson, D. L. Brower, W. Capecchi, W. X. Ding, S. Eilerman, C. B. Forest, J. J. Koliner, D. Liu, M. D. Nornberg, J. Reusch, and J. S. Sarff, Phys. Plasmas **21**, 056104 (2014).
[10] G. Fiksel, B. Hudson, D. J. Den Hartog, R. M. Magee, R. O'Connell, and S. C. Prager, Phys. Rev. Lett. **95**, 125001 (2005).
[11] J. Waksman, Ph.D. thesis, Univeristy of Wisconsin–Madison, 2013.