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Analysis techniques for diagnosing runaway ion distributions in the reversed field pinch

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An advanced neutral particle analyzer (ANPA) on the Madison Symmetric Torus measures deuterium ions of energy ranges 8-45 keV with an energy resolution of 2-4 keV and time resolution of 10 μs. Three different experimental configurations measure distinct portions of the naturally occurring fast ion distributions: fast ions moving parallel, anti-parallel, or perpendicular to the plasma current. On a radial-facing port, fast ions moving perpendicular to the current have the necessary pitch to be measured by the ANPA. With the diagnostic positioned on a tangent line through the plasma core, a chord integration over fast ion density, background neutral density, and local appropriate pitch defines the measured sample. The plasma current can be reversed to measure anti-parallel fast ions in the same configuration. Comparisons of energy distributions for the three configurations show an anisotropic fast ion distribution favoring high pitch ions. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960422]

I. INTRODUCTION

The Advanced Neutral Particle Analyzer (ANPA) on Madison Symmetric Torus (MST) is used to measure fast ions in the 8-45 keV range,[1] shown in Fig. 1, most commonly used in experiments with neutral beam injection.[2,3] However, more recent experiments involve running MST at its highest current ($I_p = 500$ kA) and low density ($\overline{n_e} = 0.5 \times 10^{13}$ cm^{-3}) generate a substantial natural fast ion distribution along with a high fusion neutron signal on the order of 10^{11} s^{-1}. The distribution is anisotropic and asymmetric, with ions of energies as high as 30 keV. The anisotropy was measured along three sightlines into the MST vessel, which illustrated a distribution that favored ions traveling parallel to the plasma current in the core. Although initially surprising, as the RFP plasma is well-known to undergo primarily perpendicular ion heating at magnetic reconnection events,[4] recent work measured parallel runaway of sufficiently fast ions[5] and may explain the developed distribution.

II. MULTIPLE SIGHTLINE RECONSTRUCTION OF DISTRIBUTION

The ANPA can be placed on two different portholes and MST can be run with toroidal plasma current running clockwise or counter-clockwise, as shown in Fig. 2. Energy distributions were measured for ions traveling perpendicular to current, parallel to current, and anti-parallel to the current. On the radial view, the measured signal is reliably perpendicular to the current for either choice of plasma current direction. On the tangential view, the measured signal has a more complicated pitch distribution. The ANPA is used to measure fast ion content by deconvolution from the total line-averaged signal,

$$\Gamma_{fi} = \int n_o n_{fi} \langle \sigma v \rangle_{cx} \delta(1 - \gamma_c)(1 - f_r) dl. \qquad (1)$$

The contributing variables are the neutral density n_o, fast ion density n_{fi}, charge exchange cross section $\langle \sigma v \rangle_{cx}$, pitch parameter γ_c, and recombination rate f_r, which are line-averaged through the detector's line of sight. Most of these variables are well-characterized from equilibrium reconstructions. However, the neutral density varies strongly from the edge to the core, and it spikes during every reconnection event. The heating and runaway mechanism both occur during these reconnection events, in which an unstable $J_{\|}$ gradient relaxes to a flatter profile with a corresponding change in the equilibrium. This change in magnetic energy is the ultimate source of energy for ion energization. The most interesting physics occur during these events, and dynamic correction of average neutral density is critical in estimating the fast ion behavior.[6] An array of D_α detectors provide information on neutral density by

$$\Gamma_{D_\alpha} = \int n_o n_e \langle \sigma v \rangle_{excitation} dl. \qquad (2)$$

Background electron density n_e and excitation cross sections are known, so this diagnostic is a reliable source for line-averaged neutral density signals. A complicating factor is that the neutral density at the edge is 2-3 orders of magnitude higher than the neutral density at the core, which means the line-averaged D_α signals are mostly measurements of the edge, leaving higher uncertainty in core n_o estimates. The lack of certainty in core neutral density prevents quantitative comparison of the three sightlines. However, the temporal changes in edge neutral density are used as a proxy for changes in overall neutral density, allowing comparisons of the energy distributions measured at different sightlines.

The necessary pitch required for the proper trajectory to be measurable by the ANPA γ_c varies with position along the

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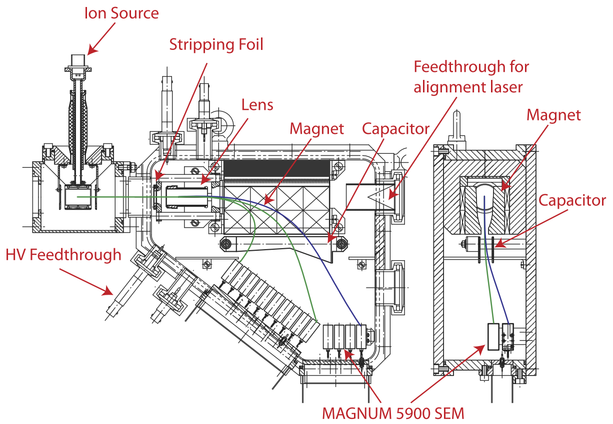

FIG. 1. Schematic of the ANPA shown with a calibrating ion source. Incoming neutrals are ionized by the stripping foil and decelerated by a target voltage of 1-3 keV to reduce noise before entering the field region. Deuterium and hydrogen ions are vertically separated by an electric field and measured by an array of 10 channeltrons for each species with 2-4 keV resolution.

line of sight for the tangential view, as shown in Fig. 3. The distribution of the naturally generated fast ions is not as well known as neutral beam injection (NBI) sourced ions, which have a known initial distribution. Nevertheless, it is reasonably certain that most of these fast ions are originating from the core. As a pollutant to the interesting ion distribution in the core, the tangential view collects a small number of low pitch ions near the edge in both normal and reversed current configurations. Experiments with reversing plasma current show ANPA signals two orders of magnitude below normal operation, which suggests that this low pitch contribution from the edge is small and most of the signal measured on the tangential view are ions parallel to the plasma current, originating from the core of the plasma.

III. DATA SHOWS ANISOTROPIC FAST ION DISTRIBUTION

Figure 4 is a set of ANPA measurements used to reconstruct the fast ion distribution to the best of our current ability. Ions moving parallel to current show discrete energization at reconnection events and are also observed to accelerate throughout the shot. Ions measured on the perpendicular view show a rapid energization to around 12 keV, but the large discrete steps are not apparent in the perpendicular energy distribution as they are in the total neutron flux. This is consistent with the working theory of a perpendicular bulk heating mechanism acting in conjunction with parallel runaway. The perpendicular mechanism becomes weak at higher energies. Ions moving counter to the direction of plasma current are briefly measured during reconnection events but they quickly dissipate.

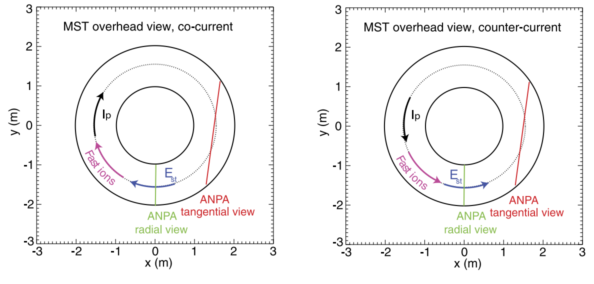

FIG. 2. Overhead view of the MST vessel showing the toroidal direction of current and position of ANPA ports. The ANPA can be placed on either the radial or tangential view to measure low or high pitch ions. The direction of plasma current can be reversed by reversing the poloidal magnetic field, allowing the tangential port to measure negative pitch ions.

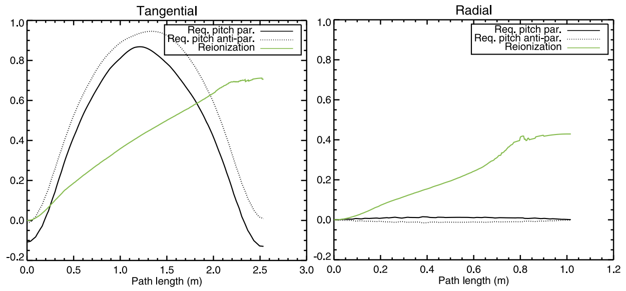

FIG. 3. The pitch required for an ion to be measured by the ANPA varies as a function of position along the tangential view but not the radial view. The radial view reliably measures low pitch ions, but the pitch measured by the tangential port depends on position of neutralization. Flipping the direction of plasma current does not significantly change the required pitch for either sightlines.

During reconnection events, a stochastic heating mechanism or a cyclotron heating mechanism heats thermal ions in the perpendicular direction. The same reconnection event also creates an inductive electric field that can only affect ions that are moving fast enough to separate themselves from the stochastic magnetic field. The combination of these two phenomena boosts a small percentage of perpendicularly heated fast ions into stable mostly parallel fast ion orbits. Confinement time for fast ions are high, allowing these fast ions to accelerate further at the next reconnection event. The three viewpoints are consistent with what would be predicted by this explanation. Since there are no more ports with which to measure more regions of the phase space, further validation studies require simulation work to fill in the gaps that cannot be physically measured.

IV. COMPUTATION

The primary code being used is CQL3D, a Fokker-Planck equation solver that in this application evolves a general ion distribution through a time varying electric field, shown in Fig. 5. An *ad hoc* perpendicular heating effect has been implemented to heat Maxwellian thermal ions, which is then put through an electric field that is responsible for fast ion runaway.[7] The electric field model is chosen to mimic the induced parallel field from change in equilibrium fields at the reconnection event.

When finished, the contours along the parallel, perpendicular, and anti-parallel directions should match the ANPA data. However, pitch- and energy-dependent confinement time information is required for best accuracy; the neutron flux is overestimated without a loss mechanism. Some confinement time information is already known from experiments, but since beam injection is limited in scope for energy range and

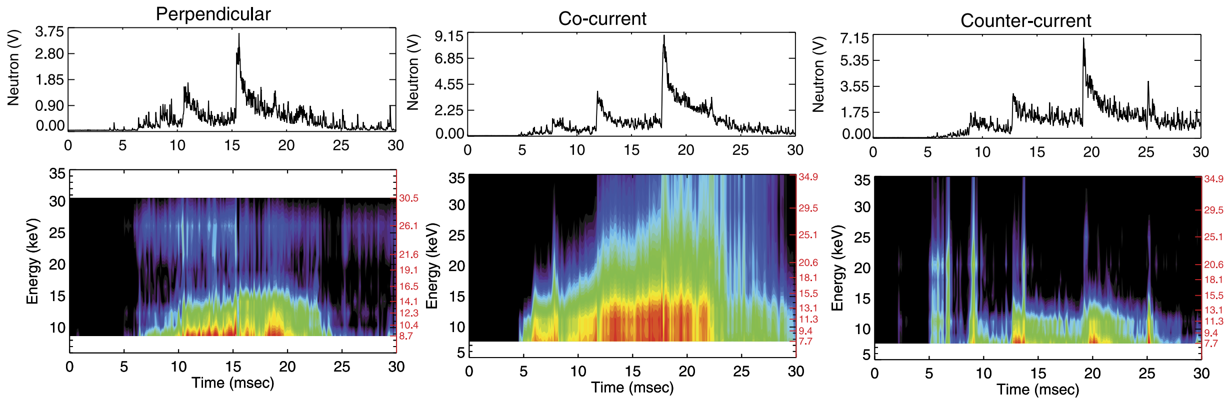

FIG. 4. Similar MST shots with high fusion neutron signals with the ANPA positioned to measure fast ions perpendicular, parallel, or anti-parallel to the plasma current. Ions perpendicular to current energize up to but not beyond 12 keV. Ions moving parallel to current continue to increase in energy after each reconnection event, indicating runaway. Ions anti-parallel to current are quickly lost.

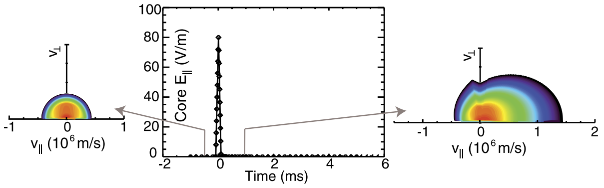

FIG. 5. CQL3D run in which a Maxwellian thermal distribution boosted with perpendicular heating is put through a parallel electric field. The combination of a perpendicular heating mechanism and parallel runaway appears to be a good model, but pitch-dependent confinement time information will improve it.

direction of injection, more information is required. A full orbit ion tracing code called RIO will be used to gather confinement information as a function of energy, pitch, and position.

V. CONCLUSION

Recent experiments with the ANPA have yielded data that support the theory of perpendicular heating combined with parallel runaway for ion energization in MST. Three sightlines were used to compare ANPA signals that look at different parts of the phase space: parallel, perpendicular, or anti-parallel to plasma current. Work with CQL3D is ongoing to validate this theory, and RIO is being used to fill in the gaps in confinement time where experimental data are not available.

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[8] See supplementary material at http://dx.doi.org/10.1063/1.4960422 for digital format of data.