Preferential Confinement and Field-Aligned Acceleration of Energetic Ions in a Reversed Field Pinch

J. K. Anderson[1,a)], J. Kim[1], J. S. Sarff[1], V. Belykh[2], V. I. Davydenko[2], A. A. Ivanov[2] and S. Polosatkin[2]

[1] *University of Wisconsin-Madison, Department of Physics, Madison WI 53706 USA*
[2] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*

[a)] Corresponding author: jkanders@wisc.edu

Abstract. Reconnection-driven heating of ions is a powerful process in many astrophysical and laboratory plasmas, including compact toroid (CT) merging and reversed-field pinch (RFP) discharges. The RFP is often characterized by rapid ion heating during impulsive reconnection, generating an ion distribution with an enhanced perpendicular bulk temperature. Two additional factors must be considered to explain the ion distribution measured in the Madison Symmetric Torus. First, ion runaway can occur in a strong parallel-to-B electric field induced by a rapid equilibrium change triggered by reconnection-based relaxation; this effect is particularly strong on sufficiently energetic ions whose guiding centers drift substantially from magnetic field lines. Second, the confinement of ions varies dramatically as a function of velocity. High energy ions traveling mainly in the direction of plasma current are nearly classically confined, much higher than counter-propagating energetic ions or thermal ions. The details of ion confinement tend to reinforce the asymmetric drive, resulting in a very asymmetric, anisotropic distribution.

INTRODUCTION

The reversed field pinch (RFP) provides an excellent terrestrial plasma for the study of reconnection-driven ion heating. Well-characterized perpendicular ion heating accompanies periodic bursts of driven reconnection[1, 2, 3] (called sawteeth) in the Madison Symmetric Torus (MST). In the subset of discharges at the upper end of MST operating range, five to six large sawteeth occur during a 30 ms period with strong relaxation of the current density profile (and a rapid change to the magnetic equilibrium) each time.

The developed deuterium ion distribution is very anisotropic with a strong parallel-to-B component and produces a fusion neutron flux several orders of magnitude above that expected for a Maxwellian distribution. This is attributed to parallel runaway of the sufficiently energetic ions, whose friction is reduced relative to thermal ions. Measured dynamics of test particles show acceleration in quantitative agreement with force balance between an electric field induced by the rapid equilibrium change (short duration of $\sim$100 μs) and drag on background particles.

While the confinement time of thermal particles is short compared to the spacing between successive sawtooth relaxations, a remarkable transition in confinement properties of sufficiently energetic ions leads to near classical confinement. Multiple accelerations are applied to these well confined particles allowing them to reach energies of up to 40keV within a thermal distribution of $T_i \sim 0.5$ keV.

A 25 keV tangentially-oriented neutral beam injector and advanced fast ion diagnostics[4] are used to probe the physics of ion runaway and confinement as a function of velocity in reversed field pinch plasmas. These principles are applied to the study of the natural RFP ion distribution following several impulsive sawteeth. Measurements on three slices through velocity phase space confirm the importance of confinement and acceleration asymmetries and resolve the difference between measured and expected fusion neutron flux.

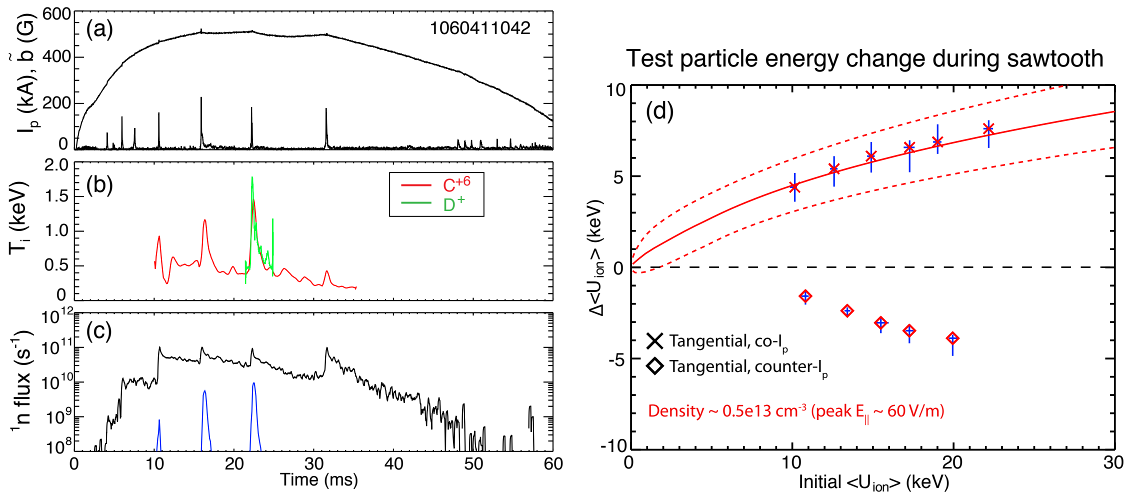

FIGURE 1. 500 kA MST discharge and magnetic fluctuations (a), clearly identify time points where measured ion temperature (b), (impurity and bulk) is enhanced. The measured neutron flux (c),(black line) dramatically exceeds that expected for a thermal distribution (blue curve). Runaway of test ions (d) is confirmed by varying initial energy through neutral beam injection. Important to note that the data match the simple model for ion runaway, which shows very small energy gain for thermal (< 1 keV) ions.

ION RUNAWAY IN THE RFP

Figure 1 is an example of the discharges studied herein. Toroidal plasma current just over 500 kA is plotted along with magnetic fluctuations (Figure 1(a)) to mark the times of impulsive reconnection. In Figure 1(b) perpendicular ion temperature from two diagnostics (one measuring a carbon impurity[5], the other the bulk deuterium [6]) is plotted. There is a measurable D-D fusion neutron flux (black line in Figure 1(c)) which exceeds the expected flux computed using a Maxwellian distribution at the measured temperature (blue line) by several orders of magnitude.

The sawtooth-induced equilibrium change generates a toroidally symmetric parallel electric field which can overcome the drag of Coulomb collisions. The sharp change in equilibrium magnetic field releases energy and induces a brief but strong electric field of up to 100V/m for ∼100μs. Figure 1(d) is a confirmation of the runaway process using test neutral beam injection (NBI) sourced H^+ within the deuterium plasma. The average energy of the test particles is measured with time and a step change is observed at the sawtooth[7]. Many measurements are averaged over similar sawteeth on three distinct neutral particle analyzer (NPA) views. In the default view, the NPA samples core-localized ions traveling nearly parallel to the toroidal plasma current. The second view is achieved by reversal of the toroidal plasma current and the NPA-sampled ions are traveling against I_p (and against the strong impulsive electric field accompanying the burst of reconnection). Finally, relocation of the NPA to a radial viewing port directs it to sample ions with a high perpendicular energy. In the parallel-to-I_p view a clear energy gain is observed at a sawtooth with peak $E_\parallel \sim 60\,V/m$. A scan of the beam injection voltage maps the increase of energy gain with initial energy. A test particle model computes the expected energy gain as a function of initial energy by simple force balance with electric field and friction. For injection parallel to I_p (solid red line), the model matches the data very well. The error bars (dotted lines) are estimated from an uncertainty in T_e and Z_{eff} of the plasmas. In the case of inverted plasma current, the sawtooth-driven $E_\parallel$ opposes the motion of the test ions and substantial deceleration is observed. Radial viewing NPA measurements show that high energy test particles are not accelerated perpendicular to B during reconnection.

ION CONFINEMENT VARIATION WITH VELOCITY

The radial magnetic field perturbations associated with tearing modes govern thermal confinement in the RFP. A substantial overlap of magnetic islands typically makes the magnetic field in the RFP stochastic and limits electron and thermal ion confinement times to around 1 ms[8]. The confinement of fast ions is insensitive to the stochastic field of the RFP and is understood from the decoupling of the fast ion orbits from the magnetic perturbations[9, 10]. In the RFP, with a magnetic field strongest at the magnetic axis and a dominant poloidal field over much of the minor

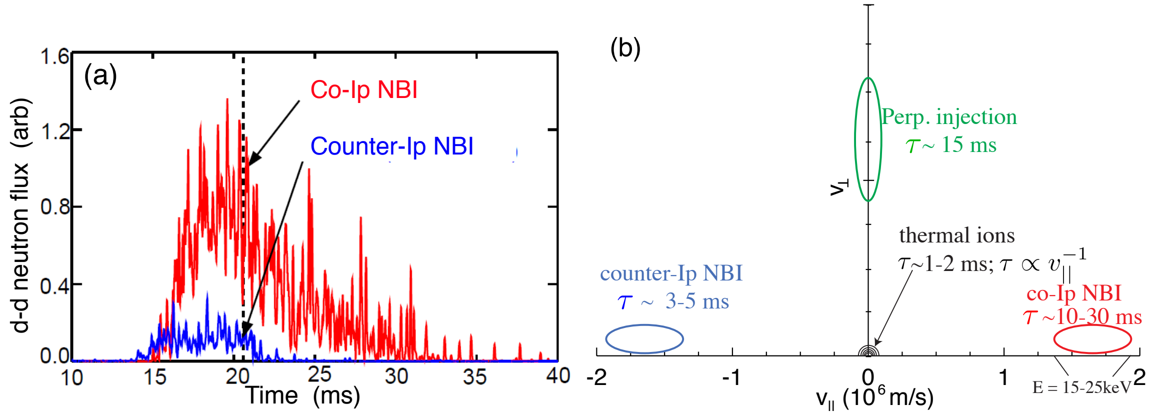

FIGURE 2. (a) NBI-sourced test ions show a confinement asymmetry. In red (blue), 25 keV D+ ions injected parallel (anti-parallel) to plasma current produce fusion neutron flux with different decay timescales. (b) Illustration of known ion confinement behavior as a function of position in $v_\perp/v_\parallel$ plane. A boundary between thermal and highly energetic ions must exist.

radius, the drift-altered fast ion guiding center remains on a flux surface. Although well confined, the guiding center can wander and islands can develop in the ion guiding center motion analogous to magnetic islands on the field lines.

The decay of neutron flux compared to the expected decay from classical slowing alone following turn-off of a short beam pulse of deuterium injection is used to infer the confinement of the fast ions, τ_{fi}. The beam blip technique keeps the total fast ion content small, and the possibly destabilizing effects of a large fast ion population are not relevant. In the example in Figure 2(a), the neutron flux shown in red is measured for beam injection of ions parallel to the toroidal plasma current. In this example, the computed confinement time is approximately 13 ms. Counter-propagating fast ions (measured by reversing the direction of plasma current) have much lower confinement. The neutron flux plotted in blue is a representative example; the overall flux is much lower than co-injection (due to a combination of higher prompt loss and lower confinement), and the flux decay at beam turnoff is considerably faster than classical slowing would predict. Fitting typically yields fast ion confinement times of 3-5 ms for counter-I_p traveling ions in these plasma conditions.

Figure 2(b) is a consolidation of core-localized ion confinement as a function of position in the $v_\perp/v_\parallel$ plane in MST; there is a strong variation. While this graph illustrates asymmetry in $v_\parallel = \frac{\mathbf{v}\cdot\mathbf{B}}{|B|}$ with respect to core magnetic field, the important physics lie with the direction of plasma current (and hence B_θ). The radial component of the Lorentz force from $v_\phi B_\theta$ creates the asymmetry between co-and counter- I_p passing fast ions. In addition to the two tangential NBI measurements, previous work on MST utilized a neutral beam mounted radially[11], injecting perpendicular to the magnetic field. Here the ∇B contribution dominates the guiding center drift of the fast ions and there is again a substantial deviation from the magnetic field lines; much better than thermal confinement is observed. Interestingly, thermal particles (near the origin) are least-well confined as motion along the stochastic field lines governs cross-field transport. Typical confinement times are on the order of a millisecond, and the confinement is expected to decrease with parallel speed. Clearly there exists a critical energy along the $v_\perp = 0$ axis where a transition in confinement occurs; it remains to be found experimentally as it is below the operating range of the injector.

The confinement variation and runaway process both play an important role in the development of the observed naturally occurring ion distribution[12]. Figure 3 is a measure of the core-localized energetic distribution of discharges without NBI by three NPA views: (a) anti-parallel, (b) perpendicular to and (c) parallel to I_p. The top panel of each is the neutron flux as a function of time, which shows a discrete step at each reconnection event, and the fast ion distribution is shown in the lower panel. Comparison of parallel to perpendicular reveals a strong anisotropy. The parallel-to-I_p energetic ions show a high energy tail, developed in discrete steps, with substantial particle count at energies above 30 keV. The steady particle flux between sawteeth is indicative of good confinement of these high $v_\parallel$ ions. The perpendicular view, where temperature increases at the reconnection event, shows a population that grows in energy to approximately 12 keV and stabilizes. Good confinement of these ions is surmised between events due to the time dependence. Of particular interest, note that the perpendicular distribution is not significantly altered at t=15 ms, where the neutron rate jumps sharply due to a strong reconnection event. In addition to the anisotropy, there is a strong asymmetry in the $v_\perp = 0$ ions. There is a smaller particle flux counter-I_p and the population steadily decreases

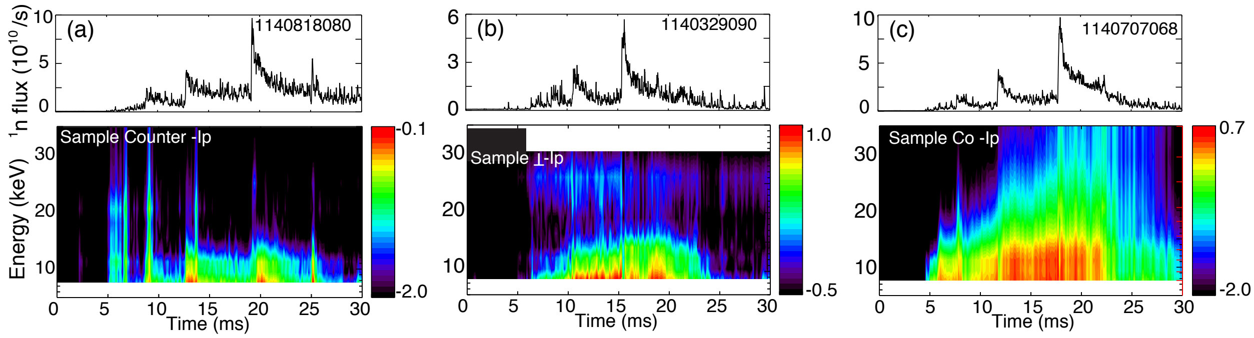

FIGURE 3. Three NPA views sample the natural fast deuterium distribution. In (a), (particles anti-I_p) an uptick observed at each reconnection event is followed by a steady decrease. In (b), (particles with perpendicular energy), a high energy population develops and remains steady between sawteeth; once established it is not further energized by subsequent reconnection events. In (c), (particles co-I_p) a well-confined, steadily increasing population is measured. The color scales are logarithmic with levels indicated by digits adjacent to the color bars.

following a burst. Pitch angle scattering is thought to be an important process in sourcing high energy particles into both the perpendicular and anti-I_p regions of phase space. The evolution of the distribution is affected by confinement, which tends to reinforce the asymmetry from one-directional field-aligned drive at the sawtooth.

SUMMARY AND ACKNOWLEDGMENTS

Energetic ions in the RFP do not obey a simple source and loss balance. There is a very strong variation of confinement with velocity, and a strong parallel energization mechanism. Both apply preferentially to high energy ions, leading to a very asymmetric anisotropic distribution which produces orders of magnitude more fusion neutrons than expected for a Maxwellian at the measured temperature.

This work is supported by the U.S.D.O.E. under Award Number DE-FC02-05ER54814. Portions of the work were accomplished with the use of infrastructure of Complex DOL (BINP, Russia). Data published here are available in digital format through http://plasma.physics.wisc.edu/publications.

REFERENCES

[1] E. Scime, S. Hokin, and N. Mattor, Phys. Rev. Letters **68** (1992).
[2] G. Fiksel, A. F. Almagri, B. E. Chapman, V. V. Mirnov, Y. Ren, J. S. Sarff, and P. W. Terry, Phys. Rev. Letters **103** (2009).
[3] R. M. Magee, D. J. Den Hartog, S. T. A. Kumar, A. F. Almagri, B. E. Chapman, G. Fiksel, V. V. Mirnov, E. D. Mezonlin, and J. B. Titus, Phys. Rev. Letters **107** (2011).
[4] S. V. Polosatkin, V. Belykh, and V. I. Davydenko, Nucl. Instrum. and Meth. Physics Research A (2012).
[5] D. Craig, D. J. Den Hartog, G. Fiksel, V. I. Davydenko, and A. A. Ivanov, Rev. Sci. Instrum. **72** (2001).
[6] J. C. Reardon, G. Fiksel, C. Forest, A. F. Abdrashitov, V. I. Davydenko, A. Ivanov, S. A. Korepanov, S. V. Murachtin, and G. I. Shulzhenko, Rev. Sci. Instrum. **72** (2001).
[7] S. Eilerman, J. K. Anderson, J. S. Sarff, C. B. Forest, J. A. Reusch, M. D. Nornberg, and J. Kim, Phys. Plasmas **22** (2015).
[8] G. Fiksel, A. F. Almagri, J. K. Anderson, A. D. Beklemishev, B. E. Chapman, D. Craig, V. I. Davydenko, D. J. Den Hartog, D. Ennis, S. Gangadhara, *et al.*, "Confinement of High Energy and High Temperature Ions in the MST RFP," in *21st IAEA Fusion Energy Conference* (Chengdu, 2006).
[9] G. Fiksel, B. Hudson, D. J. Den Hartog, R. M. Magee, R. O'Connell, S. C. Prager, A. Beklemishev, V. I. Davydenko, A. A. Ivanov, and Y. Tsidulko, Phys. Rev. Letters **95** (2005).
[10] J. A. Reusch, J. K. Anderson, and Y. Tsidulko, Nuclear Fusion **54** (2014).
[11] B. Hudson, "Fast Ion Confinement in The RFP," Ph.D. thesis, University of Wisconsin - Madison 2006.
[12] J. K. Anderson, J. Kim, P. J. Bonofiglo, W. Capecchi, S. Eilerman, M. D. Nornberg, J. S. Sarff, and S. H. Sears, Phys. Plasmas **23** (2016).