Classical confinement of impurity ions and fast NBI-born ions in the RFP

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

[1]University of Wisconsin, Madison WI, USA
[2]Wheaton College, Wheaton IL, USA
[3]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[4]University of California-Los Angeles, Los Angeles CA, USA
[5]Laboratory for Laser Energetics, Rochester NY, USA
[6]University of California-Irvine, Irvine CA, USA
[7]Oak Ridge National Laboratory, Oak Ridge, TN, USA

Corresponding Author: jkanders@wisc.edu

Abstract:

Classical behavior of two types of ions (impurity and NBI−born fast bulk) has recently been observed in the MST RFP plasma. Both have positive implications, as NBI−born fast ions (with normalized Larmor radius similar to that of fusion alphas in a reactor−sized plasma) are well confined and transfer their energy to the background plasma. Classical transport of impurities in this specific collisionality regime leads to a decrease in core impurity density thereby reducing bremsstrahlung losses in the dense core plasma. The confinement time and radial transport properties of carbon impurity ions are determined by classical theory during periods of suppressed magnetic turbulence in MST. The measured density of fully stripped carbon rapidly evolves to a hollow profile due to outward convection, consistent with the temperature screening mechanism in classical transport modeling. A confinement time is deduced from the decay of core carbon ions sourced by methane pellet injection and agrees with classical modeling. Classical behavior of NBI−born fast ions is also observed. A new 1 MW injector sources 25 kV hydrogen (and roughly 5% deuterium) atoms in the core of MST. The measured fast H distribution and time decay of beam−target neutron flux both indicate classical slowing without enhanced radial transport, even in a stochastic magnetic field. This leads to a substantial population of fast ions and has several effects on the bulk plasma including enhanced rotation, electron heating, and stabilization of the core resonant tearing mode. Beam driven instabilities in the RFP are observed for the first time, as both continuum energetic particle modes and discrete toroidal Alfven eigenmodes are excited by inverse Landau damping.

1 Introduction

Particle drifts play an important role in a toroidal magnetically confined plasma. Neoclassical transport– an enhancement of classical Coulomb-collisional transport due to these particle drifts– represents the lower bound a tokamak or stellarator can achieve. Indeed, for certain plasma conditions with low levels of turbulence, the measured ion confinement characteristics have matched the neoclassical value[1, and references therein]. The neoclassical enhancement of radial transport is small in the RFP, since ∇B points toward the magnetic axis. With the strength of the toroidal and poloidal magnetic field components being of the same order, the connection length between high and low field side of a magnetic flux surface is quite short, and the radial width of a banana orbit of a trapped particle is smaller than the particle gyroradius. The drift of thermal particles' guiding centers off a magnetic flux surface is therefore small, and in periods where turbulent transport is suppressed the theoretical lower limit should be governed by classical Coulomb collisions alone.

At the other end of the velocity spectrum, neutral beam injected fast ions have a substantial guiding center drift correction to their orbits. This alters the rotational transform which describes their motion within the plasma; no longer are they tied directly to the magnetic field lines. Still, when perturbed, the helical trajectories of the ion guiding centers can develop islands which can overlap and lead to rapid transport. This Rechester-Rosenbluth process dominates the electron confinement in standard RFP plasmas. Resonant perturbations to the ion-orbit guiding centers do not match the resonant perturbations to the magnetic field. Fast ions are confined as well as classically while the thermal confinement is limited to much lower values by magnetic stochasticity[2].

Presented herein are measurements of ion dynamics which show the attainment of classical transport levels[1]. The density profile of fully stripped carbon ions undergoes outward convection and a hollow profile develops. This agrees with classical confinement expectations due to the details of the density and temperature profiles. The behavior is verified by methane pellet injection experiments which source carbon directly in the plasma core, and a confinement time measured as a function of residual turbulence in the plasma extrapolates to classical levels.

Fast ions born of neutral beam injection are classically confined in plasmas with a range of magnetic turbulence. This includes standard RFP discharges with poor electron confinement and continues to the periods of reduced turbulence. MST routinely uses a 1MW, 25keV neutral beam injector with a 5% deuterium, 95% hydrogen fuel. The beam-target d-d fusion neutron rate is a measurement of the concentration of fast deuterium content, and after removing the source (e.g. turn-off NBI), the signal decay rate can be used to estimate confinement. Additionally, an advanced neutral particle analyzer (ANPA) separately measures the time resolved distribution (5-30keV) of both hydrogen and deuterium ions lost from the plasma via charge exchange. These time resolved measurements show that the fast NBI-born ions are insensitive to radial magnetic perturbations, and their dynamics are governed by classical slowing.

2 Classical Transport of Carbon Impurity Ions

Studies of impurity transport in MST focus on reduced-turbulence periods of the RFP discharge. Modeling of classical impurity transport which includes collisions with bulk and dominant impurity ions predicts the rapid formation of a hollow profile via the temperature screening mechanism in these plasmas. For classical impurity transport, outward convection is expected when the temperature profile is more peaked than the density profile.

2.1 Reduced Turbulence Conditions

The periods of suppressed magnetic turbulence in MST are induced by inductively driving parallel current near the plasma edge. The characteristics of a typical discharge are plotted in Fig. 1. Auxiliary drive is initiated at t=0.01s which reduces the magnetic fluctuation level (c) for a period that can last typically about 0.01s. The plasma current of about 500kA (a) and line averaged electron density (b) are nearly constant over this period, while there is a marked increase in SXR emission (d) and core electron temperature (e).

2.2 Carbon density profile evolution

The density of fully stripped carbon is measured with 2cm spatial and 10 μs temporal resolution by CHERS with a 50kV diagnostic neutral beam. There is a slow decay of fully stripped carbon in the plasma core, while the density at the mid-radius density increases. The profile becomes hollow on a roughly 10 ms timescale, and is plotted in Fig. 2 along with the predicted classical impurity flux versus time.[1]

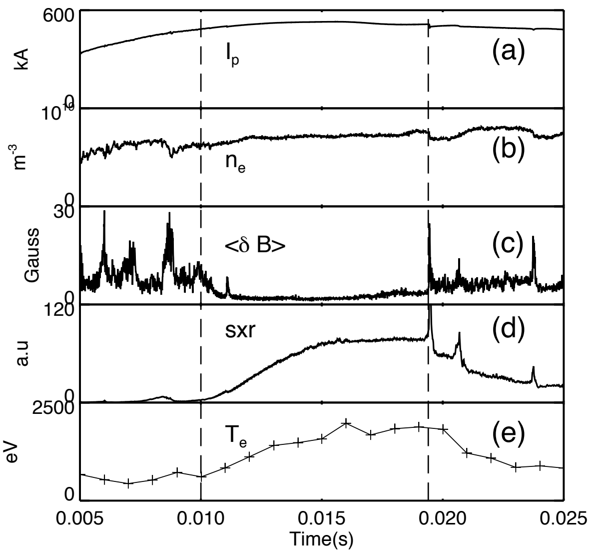

FIG. 1: Time evolution of a typical PPCD discharge.

The model[3] relies on time-resolved profile measurements of the bulk electron and impurity density and temperatures. The ion density profile in these discharges is nearly flat, which implies a weak drive for core impurity accumulation; the finite temperature gradient leads to impurity expulsion. Details on these fascinating measurements are in reference [1]. Hollow impurity ion profiles have been observed in tokamak and stellarator

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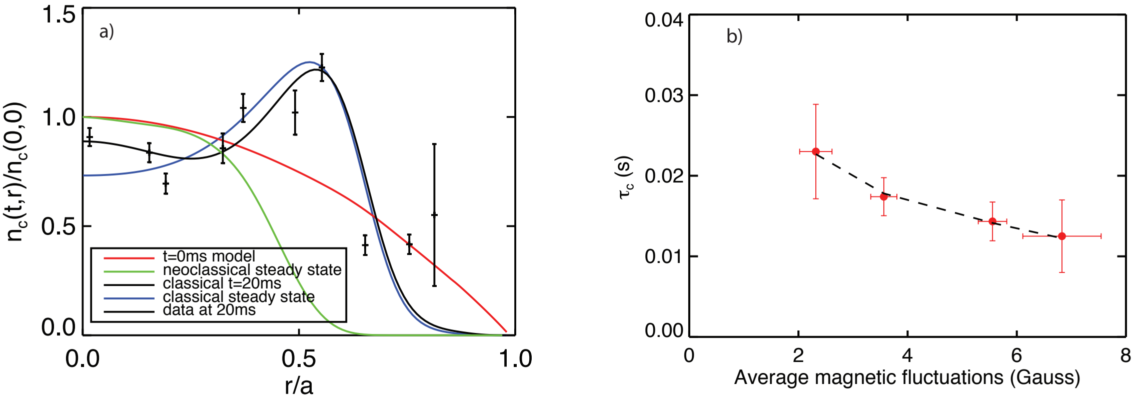

FIG. 2: a) Measurement and models of impurity density profile evolution. The initial state (red curve) evolves according to classical transport theory in ∼20 ms (black curve, data); plotted along with the steady state solution (blue curve). b) Confinement time of core sourced carbon increases as magnetic fluctuations are reduced. The zero fluctuation limit is consistent with the classical prediction.

plasmas, as well, dependent on particular conditions of the density and temperature profiles and collisionality regime. A tokamak plasma with parameters similar to these MST discharges would be in the plateau regime of neoclassical transport and a core-peaked impurity density is expected. With magnetic fluctuations suppressed, impurity expulsion is a natural consequence in the RFP.

In addition to studying the naturally occurring carbon from graphite plasma facing components, carbon is sourced directly in the core by pellet injection to study transport. Methane pellets were formed in a pellet injector designed for deuterium fueling and injected into the core of these reduced-turbulence discharges. The core carbon density initially rises quite rapidly, but begins to exponentially decay with a characteristic confinement time that is easily measured. The discharges with pellet injection typically have a higher residual magnetic turbulence than the discharges studied above; in Fig. 2(b) the confinement time is plotted versus magnetic fluctuation level. The graph extrapolates to zero magnetic turbulence and is consistent with the classical confinement time of about 30-45 ms.

3 Classical behavior of NBI-born fast ions

Fast NBI-born ions also behave classically[4], as evinced by time resolved measurements of the fast hydrogen distribution by neutral particle analysis and total fast deuterium content (a 5% dopant in beam fuel) by decay of d-d neutron flux (Fig. 3). The radial confinement is only weakly affected by magnetic turbulence and the dynamics are governed by classical slowing. This leads to a significant population of core-localized fast ions; TRANSP simulations predict a peaked fast ion profile in the core ($r \lesssim 10$cm) with density up to 20% of central electron density.

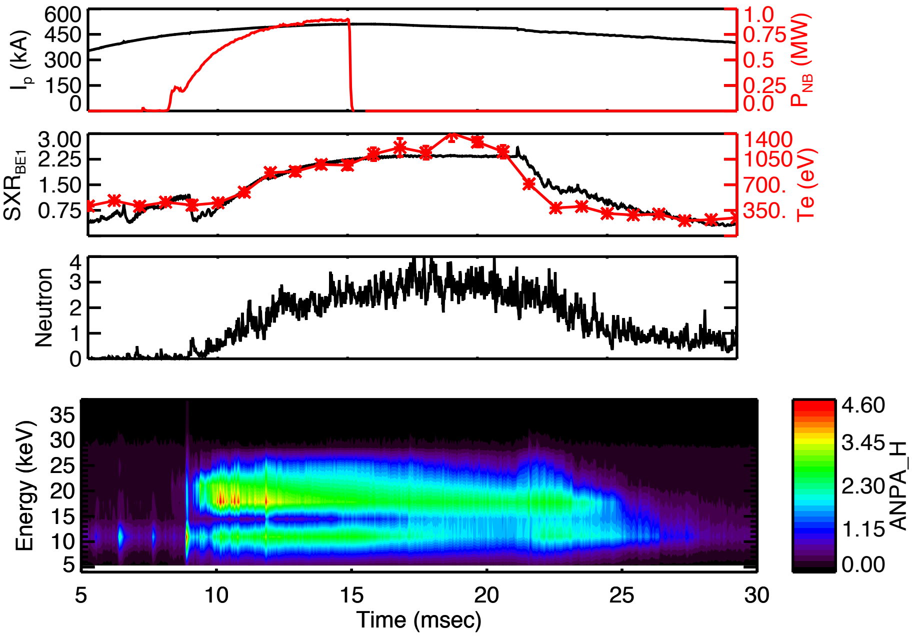

FIG. 3: NBI (95% H, 5% D) into a hot target discharge with $T_e(0) \sim$ 1keV. The time dependence of the neutron flux and concentration of 25keV H is consistent with classical slowing.

The ANPA data in Fig. 3 show classical fast ion behavior. The fast hydrogen ions at the injection energy of about 22 keV are confined after beam turn-off and slow down on a timescale of about 40 msec, which is the computed slowing time from the core plasma parameters. The confinement degrades after 22 ms when plasma-wall interactions induce an increase in the D_α emission and core neutral density; still consistent with classical slowing and fast ion loss due to charge exchange only. The half-energy component of injected fast ions are also observed to be well confined on this tangential viewing chord.

The neutron flux in panel 3.c) exhibits interesting behavior. Estimation of the fast deuteron confinement time is typically made by fitting an exponential to the decay of the flux after beam turn-off. In this case, however, the neutron flux increases with time following beam turn-off. This is likely a result of the impurity transport discussed previously. As impurities move outward the core deuterium density increases to maintain quasineutrality, leading to a higher fusion rate.

The fast ion confinement properties are investigated in a set of other MST discharges[5]. The neutron flux decay is correlated with the calculated fast ion slowing down time with measured plasma parameters spanning a wide range of magnetic turbulence. Plotted in Fig. 4 are the measured neutron flux decay time versus the classical slowing time (a) and versus the expected neutron flux decay time assuming classical slowing (b). That the data do not perfectly match the $y = x$ dashed line shows a finite fast ion confinement time, which can be estimated by comparison with the example dotted

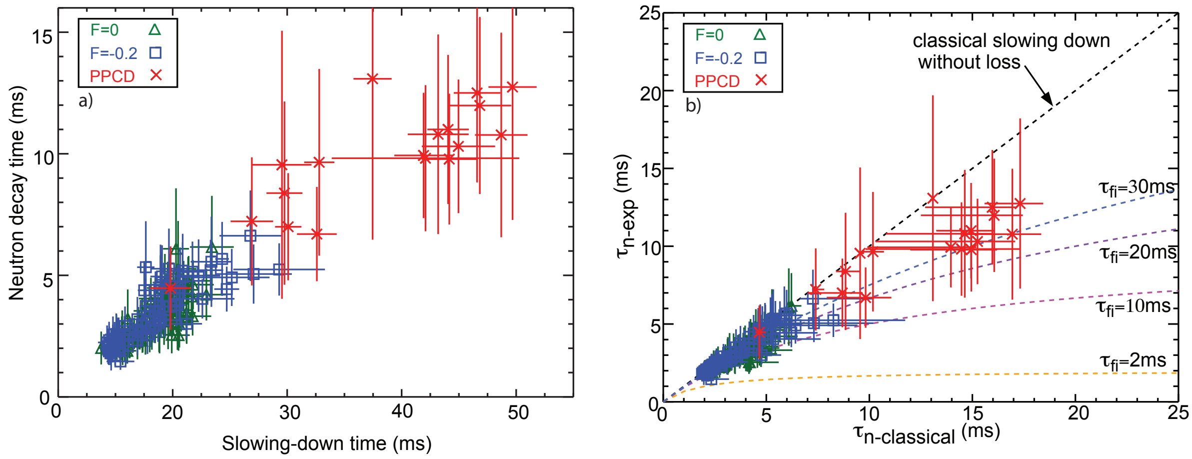

FIG. 4: a) Comparison of measured neutron flux decay time and calculated fast ion slowing time using core electron density and temperature. b) Comparison of experimental neutron flux decay time with the predictions of classical slowing down theory.

lines for varying τ_{fi}. In all cases, the implied τ_{fi} is much greater than the thermal particle and energy confinement time. The 10 to $\geq$ 30 ms confinement times are consistent with charge exchange losses: the implied core neutral density for these loss times is between 0.5 and 1.3 x10^9 cm^{-3}, consistent with lower bounds of estimates from MST discharges.

3.1 Fast particle effect on RFP stability

The expected NBI heating of the RFP discharge is small but measurable in periods when the thermal conductivity is suppressed (corresponding to reduced magnetic turbulence as studied above). While the temperature change is small, there is a strong effect of the substantial fast ion population on stability. Two such observations are demonstrated here.

It has been robustly observed that fast ions have a stabilizing influence on the core-most resonant tearing mode in MST. The discharges have an on-axis safety factor of just over 0.22 to 0.18, and with the negative shear of the RFP equilibrium, the core most tearing mode has a poloidal mode number m=1 and a toroidal mode number of either n=5 or n=6 depending on magnetic field boundary

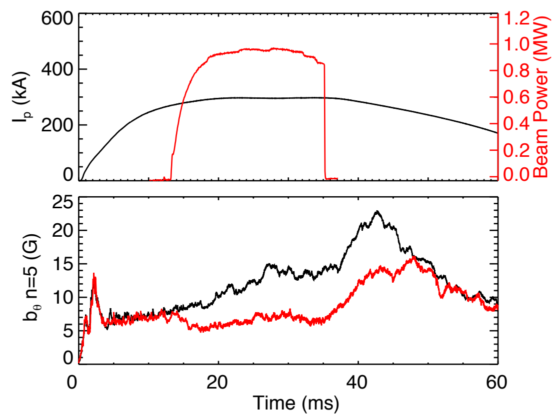

FIG. 5: The amplitude of the core tearing mode is suppressed during NBI. The black curve is the typical n=5 mode amplitude for the 300kA target discharge. Plotted in red is the mode amplitude for discharges with 1MW NBI.

conditions. Plotted in Fig. 5 is an example of n=5 core mode reduction by NBI.

Limited TRANSP modeling indicates the fast ions are strongly core localized, and an analytical model [6] predicts a stabilizing influence by finite Larmor radius effect when there is a strong gradient in fast ion density at the rational surface of the mode. While the core-most mode is substantially reduced, there is no effect on any higher-n tearing modes. This is in agreement with the picture of a fast ion density gradient at the rational surface being necessary for stabilization: the rational surfaces of other tearing modes are at radii greater than the region where fast ions accumulate.

While the tearing mode is reduced, the fast particles have a destabilizing effect on higher frequency Alfvenic modes. The NBI born fast ions are super-Alfvenic and have a significant $v_{||}$ gradient. Figure 6 shows an example of an NBI-heated discharge with bursting mode activity.[2] An initial investigation of the energetic particle driven modes is in reference [7].

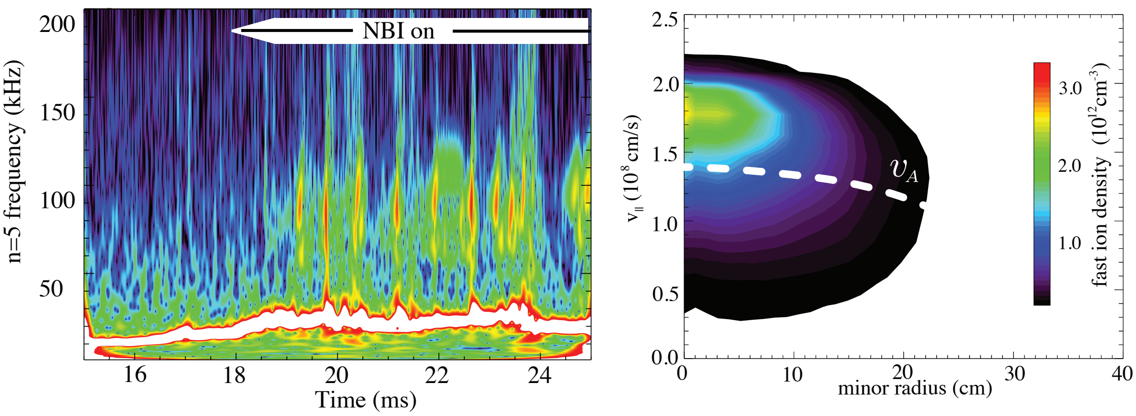

FIG. 6: Shortly after NBI onset, periodic bursts of Alfvenic activity are observed at ∼100kHz. These are driven by inverse Landau damping due to gradients in the $v_{||}$ distribution near the Alfven speed.

4 Summary

Measurements show classical behavior of both impurity ions and neutral beam-born fast bulk ions in MST. The combination of these two results cast a favorable light on the RFP configuration as a potential reactor. The hollow impurity profile is generally good for the removal of helium ash and other impurities from the plasma core. NBI-born fast ions in MST have a normalized Larmor radius comparable to that of fusion alphas in a reactor-sized machine. That the fast ions are well confined and thermalize before moving radially outward is a serendipitous result. Fast particles, and in particular a

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gradient in the fast ion density profile, at the resonant surface of a resistive tearing mode have a stabilizing influence on the mode and reduce the associated magnetic fluctuation considerably. To date, this has been observed only for the core-most mode in MST (due to the on-axis deposition of the high power beam) and has had no effect on background plasma confinement. However, should there be a way to flatten the fast ion density profile through the core and push the gradient to the mid-radius region, the opportunity to stabilize the modes responsible for overlapping magnetic islands may very well improve the thermal confinement. The other relevant observation is that a variety of energetic driven particle modes have been observed in NBI-heated discharges. These of course can have an important effect on burning plasmas as a mechanism for transporting the fusion products away before thermalization.

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