MAJORITY ION HEATING BY NEUTRAL BEAM INJECTION AND CONFINEMENT OF FAST IONS IN THE MADISON SYMMETRIC TORUS REVERSED FIELD PINCH

J. K. Anderson[1], A. F. Almagri[1], B. E. Chapman[1], V. I. Davydenko[2], P. Deichuli[2], D. J. Den Hartog[1], C. B. Forest[1], G. Fiksel[1,3], A. A. Ivanov[2], D. Liu[1], M. D. Nornberg[1], J. S. Sarff[1], N. Stupishin[2], J. Waksman[1]

[1] *University of Wisconsin, Madison WI 53706 USA; jkanders@wisc.edu*
[2] *Budker Institute of Nuclear Physics, Prospekt Lavrent'eva 11, Novosibirsk 630090, Russia*
[3] *Laboratory for Laser Energetics, University of Rochester, Rochester NY 14610, USA*

A new 1 MW neutral beam injector (START-20F) is in operation on the Madison Symmetric Torus (MST) reversed field pinch. The beam, consisting of two arc discharge plasma generators, an optimized ion optical system and an integrated neutralizer/ injector tank, operates at 25kV and up to 40A of neutrals for a 20 msec pulse (compared to a typical MST pulse length of 60 msec). The injected 1 MW of hydrogen neutrals (with approximately 85% in the full energy component) is significant compared to the 3-4 MW of ohmic input power in a typical target discharge. At this beam energy and a background electron density of about 1x10^{19} *m*$^{-3}$ *and temperature* $\leq$*1keV, roughly 90% of the injected power is deposited within the plasma. Initial experiments with the high power NBI show a large heating of the bulk ions: the fit of the width of energy spectrum as measured by Rutherford scattering (which is generally related to core ion temperature) quickly increases from 180eV to 230eV. This apparent significant and rapid heating of bulk ions is difficult to explain by classical collisions only, as modeling predicts 75% of the injected power is deposited on electrons and 15% on ions. The confinement of the fast ions (measured by the persistence in time of fusion neutrons due to a small fraction of deuterium in the beam fuel) is much greater than the canonical 1 msec confinement of particles and energy in the MST. The fast particle confinement is measured to increase with magnetic field strength. Further recent experiments document fast particle confinement time versus direction of injection (parallel or antiparallel to central magnetic field), beam energy, and background plasma properties.*

I. INTRODUCTION

Neutral beam injection into the reversed field pinch (RFP) plasma presents an opportunity to study several effects of fast ions and their interaction with the background plasma in a relatively weak but strongly sheared magnetic field. The magnetic field in the standard RFP configuration does not form nested toroidal surfaces as found in the tokamak, but rather a stochastic field exists due to overlapping islands of resonant magnetic perturbations. Thus a magnetized charged particle can, without collision, follow a field line from the hot plasma core to outside the region of confinement. This stochastic magnetic transport dominates the behavior of electrons in the standard RFP operating mode, and in MST their confinement is typically about 1 msec. Fast ions, sourced by neutral beam injection, exhibit a different behavior [1] as the guiding center of a 25keV hydrogen ion does not precisely follow the magnetic field lines. The fast ions are in fact well confined, with a characteristic confinement time that can be a factor of 20 or more higher than the background electrons [2]. This good confinement of fast ions leads to a time accumulating, peaked fast ion density profile which can have a significant effect on the background plasma through classical Coulomb collisions.

In this paper, we report initial results of high power neutral beam injection on MST made possible with the recent installation of a 1 MW START-20F injector on MST. While there is clearly an effect due to momentum injection (through an observed acceleration of impurity ions and resonant magnetic perturbations within the plasma), here we will report the results of initial experiments aimed at characterizing fast ion confinement and heating of background ions within the plasma. Many more intriguing experiments await in the near future with the measurement of electron temperature behavior and evolution of the fast ion energy distribution; these results may influence quantitative analyses presented herein although none of the conclusions will be affected.

II. FAST ION DENSITY AND BULK HEATING

With tangential injection, the NBI is an abundant source of fast ions in the plasma core. Beam neutrals are primarily ionized in the dense plasma core (typical central electron density is $1\mathrm{x}10^{19}$ m^{-3}) and well confined; with 20 msec of injection there is a period of ramp-up and a significant peaking of the fast ion profile. Figure 1 is a plot of the evolution of the fast ion density as predicted by the TRANSP tokamak transport code[3] using the magnetic and kinetic profiles and beam geometry of MST. In this simulation, 1 MW NBI is injected starting at t = 15 msec for a 20 msec duration and an assumed constant electron temperature profile with central value of 400 eV is used. Three features of the fast ion profile evolution are noteworthy. First, the central fast ion density increases on a roughly 10 msec timescale to a value between 15 and 20% of the background electron density. Second, the profile is strongly peaked. Finally, at beam turn-off the simulation (which considers classical processes) shows the fast ion density decaying on about a 10msec time scale.

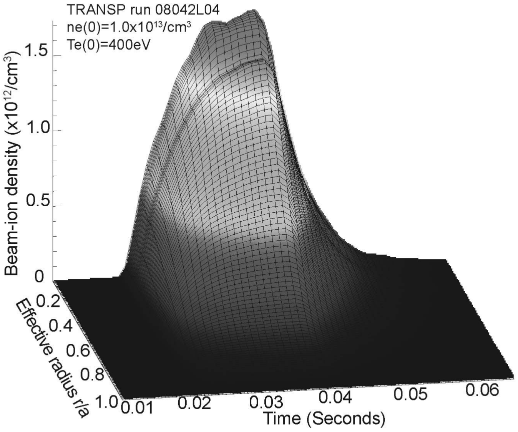

Figure 1: Modeled fast ion density profile versus time using the TRANSP tokamak code. The profile is strongly peaked, and increases with time for the duration of the injected pulse.

The fast ion density behavior with time is necessary to compute the heat deposition profiles on ions and electrons. At MST-like temperatures and a 25keV beam, most (about 75%) of the NBI energy is directed to the electron fluid; about 15% of the injected energy is directed into the bulk ions with the remainder shining through without ionization or being deposited into impurity ions.

The change in bulk ion temperature (preliminary measurement) near the plasma core has been measured throughout the time of high power NBI using a Rutherford scattering diagnostic [4] and is plotted in Figure 2. A 16kV, 3A helium neutral beam (with a 3 msec pulse) is directed vertically into the plasma and a neutral particle analyzer on an angle $9^{o)}$ from vertical measures the energy width of the scattered He atoms. The energy width can be deconvolved to determine the temperature of the background ions (deuterium is the main fuel in MST) from which the He atoms have scattered. The intersection of the two finite widths (He beam width and analyzer acceptance cone) yields a spatial average over the innermost 15% of the plasma minor radius. As the diagnostic beam is a short pulse compared to the NBI duration, several reproducible discharges are averaged together with the systematically shifted relative beam fire time to map out the time evolution of $T_i(0)$ throughout NBI injection.

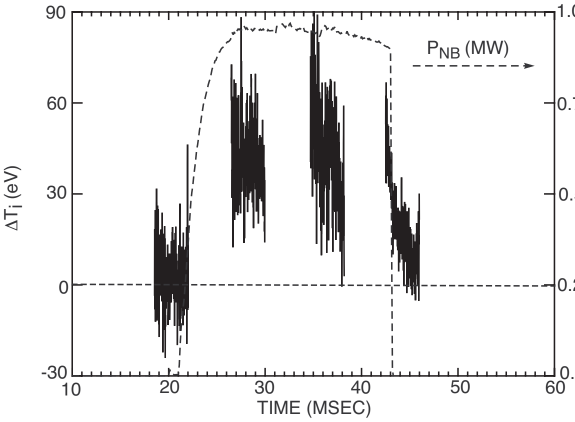

Figure 2: Difference in core bulk ion temperature between NBI and non-NBI discharges versus time. The ions are heated about 40eV in a short time.

The dotted line in Figure 2 is the representative NBI power, nearly 1MW for 20 msec, while the solid, noisy line is the computed difference in background ion temperature (for reference, the central ion temperature value is around 180 eV at t = 20 msec; the difference is plotted for convenience as the non NBI $T_i(0)$ evolves with time). It is important to note that the diagnostic is quite complex: the measured width of energy of passing neutral atoms is well over 1keV for a temperature fit of 250eV. Also, the consideration of 10-15% density of fast hydrogen compared to bulk deuterium may have an effect on the data fitting that is not yet considered. The preliminary data show a substantial and quickly responding change in measured signals; the interpretation is not yet complete. However, using the fit of width as a reasonable indication of temperature, there are some observations to make. The small difference measured before $t = 20$msec (NBI fire time) is an indication that the averaged discharges are similar before NBI and the comparison is valid. The core temperature increases quickly and a 40eV difference is established by t=25 msec; ΔT_i is no longer ramping up. The 40eV difference is sustained until beam turn-off, at which point the change in temperature decays to zero on a 1.5 msec timescale.

The relatively fast decay is indicative of a bulk ion energy confinement time of about 1-2 msec; however, the change in T_i of 40 eV is quite large compared to expectations: for strictly classical processes and a flat ion temperature profile, simple estimates predict about a 10eV change in ion temperature (and about 60eV change in electron temperature) for 1 MW absorbed power.

Repeating NBI experiments with a time resolved Thomson scattering measurement of electron temperature is a priority in understanding the ion heating. Detailed analysis of Rutherford scattering data is underway to consider the effect of 15-20% hydrogen from NBI mixed in with the background deuterium ions. Further consideration of the ion profile shape is necessary as well: a strongly peaked profile with a core temperature change of 40eV may be possible from classical collisional heating.

III. FAST ION CONFINEMENT

The confinement of fast ions within the plasma can be studied experimentally by doping the hydrogen NBI fuel with a small amount of deuterium. The fast deuterium ions can fuse with background deuterium ions and the resulting neutron flux

$$n_n = n_f n_i < \sigma v >_{d-d} \qquad (1)$$

is a measure of the product of fast deuterium ion density n_f, the bulk ion density n_i, and the fusion reaction rate $< \sigma v >$ which is a strong function of the fast ion energy. The slowing of the fast ions due to classical collisions can be well modeled and is a strong function of the electron temperature. The density of fast ions within the plasma is a balance between the source and loss rates; at beam turn-off this is described as a decaying exponential

$$n_f = n_{f0} e^{-t/\tau_{fi}} \qquad (2)$$

where n_{f0} is the fast ion density at beam turn-off. An experimental measurement of time resolved neutron flux can then be used to estimate the fast ion confinement time τ_{fi} as shown in Figure 3. In this example, the neutron flux decays on a 4 msec timescale (solid line fit to the neutron flux data, not easy to see in figure) but due to the classical slowing down of the fast ions, the inferred fast ion confinement time is around 10 msec. The short dashed (nearly coincident with the solid line) and large dashed lines are the expected neutron flux considering a fast ion confinement time of 10.5 msec and infinite confinement, respectively. This calculation is sensitive to the local electron temperature which has been estimated based on similar discharges with Thomson scattering diagnostic available.

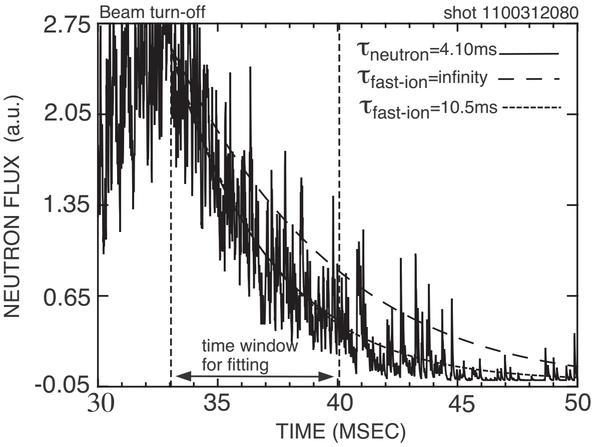

Figure 3: Neutron rate is used to estimate fast ion confinement time. The neutron flux decays on a 4 msec timescale but due to the classical slowing down of the fast ions, the inferred fast ion confinement time is around 10 msec in this example. For reference, the large dashed line is the expected neutron flux for perfect confinement of the fast ions and the decay of neutron signal is due solely to the classical slowing of the fast ions.

The fast ion confinement values are investigated in several different plasma conditions and summarized in Figure 4. The measured confinement time (with central electron temperature estimated from plasma current and electron density) is plotted versus central magnetic field strength. The toroidal confining field is generated by poloidal currents within the plasma in the RFP, and as such its strength is proportional to the plasma current; it is maximum at zero minor radius (where the fast ion density is also maximum) instead of the familiar 1/R field of a tokamak. Points in solid plot symbols are plotted for injection with ions parallel to the plasma current (co-injection) and points in dotted plot symbols are confinement times for ions injected anti-parallel to the plasma current. (In practice, this is achieved by reversing the direction of the plasma current without altering the injector geometry.) The different plot shapes indicate different electron density ranges.

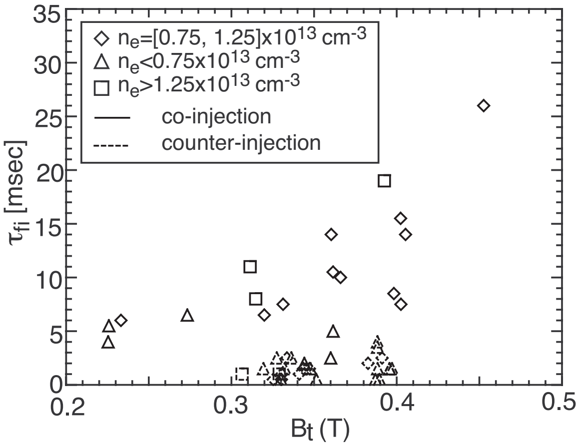

Figure 4: Fast ion confinement time increases with central magnetic field strength. The points in solid plot symbols are plotted for ions injected parallel to background current and show much higher confinement than points plotted in dashed plot symbols (ions injected anti-parallel to background plasma current). The different plot symbol shapes are used to indicated the varying background electron density for each measurement.

There are several clear conclusions from this scan. First, the confinement of co- injected ions is, as expected, much larger than that of the counter injected ions. For co-injected ions, the confinement time goes up strongly with magnetic field strength, perhaps scaling with $|B|^2$. The dependence on electron density is somewhat less obvious, although the data qualitatively support that charge exchange with background neutral particles is an important loss mechanism for the fast ions– higher electron density and hence a steeper edge gradient decreases the central background neutral density for a given amount of fueling. A detailed study of fast ion confinement with a measured electron temperature and neutral density profile will help complete several details of this analysis.

IV. SUMMARY

A new 1 MW neutral beam injector is installed on MST. Commissioning of the beam is complete and first experiments have been run, with measurements of core ion temperature change and confinement of fast ions (via neutron flux) presenting interesting initial results. There is a definite change to the ion distribution within the plasma, and perhaps the core bulk ion temperature is increased by about 40 eV (or about 20%) compared to non NBI-heated discharges. An upcoming measurement of the electron temperature profile evolution with NBI will help with comparison to classical heating predictions. Further upcoming measurements of carbon ion temperatures via charge exchange spectroscopy and a 50kV, 4.5A hydrogen diagnostic neutral beam will complement the difficult measurement of heating of bulk ions during NBI on MST. The fast ion confinement time (as measured by the persistence of neutron flux following beam turn-off) is well understood in terms of comparison to background electrons, direction of injection with respect to plasma current, and with the strength of the confining field in the plasma.

ACKNOWLEDGMENTS

The authors wish to acknowledge the ongoing collaboration with Budker Institute of Nuclear Physics and the large effort undertaken to install and maintain three separate neutral beams on MST. This work is supported by USDOE.

References

[1] S. V. PUTVINSKII, “Alpha particles in tokamaks,” in *Reviews of Plasma Physics*, edited by B. B. KADOMTSEV, Consultants Bureau, New York, **18**, 239 (1993).

[2] G. FIKSEL, B. F. HUDSON, D. J. DEN HARTOG, R. M. MAGEE, R. O’CONNELL, S. C. PRAGER, A. BEKLEMISHEV, V. I. DAVYDENKO, A. A. IVANOV and Y. A. TSIDULKO, ”Observation of Weak Impact of a Stochastic Magnetic Field on Fast-Ion Confinement,” *Physical Review Letters*, **95**, 125001 (2005).

[3] R. J. GOLDSTON, D. C. MCCUNE, H. H. TOWNER, S. L. DAVIS, R. J. HAWRYLUK and G. L. SCHMIDT, ”New techniques for calculating heat and particle source rates due to neutral beam injection in axisymmetric tokamaks,” *Journal of Computational Physics*, **43** 61 (1981).

[4] J. C. REARDON, G. FIKSEL, C. B. FOREST, A. ABDRASHITOV, V. I. DAVYDENKO, A. A. IVANOV, S. A. KOREPANOV, S. V. MURACHTIN and G. I. SHULZHENKO, ”Rutherford scattering diagnostic for the Madison Symmetric Torus reversed-field pinch,” *Review of Scientific Instrumentation*, **72**, 598 (2001).