I. New Neutral Beam Provides a Good Tool for Fast Ion Study

A new 1MW Neutral Beam Injector (NBI) has been installed on the MST and aims to achieve plasma heating, momentum injection and current drive.

- Fast ions are produced by NBI through collisions with the bulk plasma and they need to be confined long enough to transfer their energy and momentum to plasma ions and electrons.
- Fast ion confinement is extensively studied in tokamaks, but not in RFPs.
- Large Larmor radius due to low magnetic field, \( B_t \approx B_p \)
- Large magnetic fluctuations, stochastic magnetic field
- \( v_r \gg v_{\phi} \), fast ions may drive Alfven instabilities

Previous study with 1ms, 20kV deuterium short pulses suggests that fast ion confinement in the MST is much better than it could be expected from simple estimates based on magnetic field stochasticity and the difference is attributed to different resonance properties of magnetic field and fast ions due to ion drifts. [Ref. 1]

- More detailed experiments and modeling with the new 1MW NBI have been performed to study fast ion confinement in different plasma conditions. New fast ion diagnostics are under testing or design. [Ref. 1]

II. Neutron Flux can be Utilized to Monitor Fast Ion Population

- 3ms, 1MW (25kV,40A) short neutral beam pulses, doped with 3% deuterium, are injected into deuterium plasmas.
- The neutron flux is dominated by the D-D fusion reaction between the deuterium fast ions and background plasma ions because fusion reaction rate exponentially increase with relative energy.
- The neutron flux is measured by scintillator-based neutron detector and the decay process following beam turn-off can be used to infer fast ion confinement time.
- Shots with strong sawtooth crashes are avoided for fast ion confinement study.
- Sawtooth crashes can cause strong slowion heating and thus induced relatively large neutron flux fluctuations.
- Sawtooth crashes can change density and temperate profile rapidly and induce fast ion loss.

III. TRANSP Predicts Centrally Peaked Fast Ion Density Profile

- MST equilibrium and profile data in \( F=0 \) plasmas are adapted for TRANSP simulation, which includes a Monte-Carlo module for the neutral beam injection physics.
- Define the computational boundary at some point before the reversal surface.
- All equilibrium and plasma quantities are converted from poloidal flux coordinates to toroidal flux coordinates, which is required by TRANSP simulation.
- The TRANSP simulation predicts that the confined fast ions are mainly in the plasma core \( (r/a<0.2) \) with density up 15% of central electron density and most fast ions are passing particles with pitch \( (V_{||}/V) \) around 0.9 due to beam injection geometry.
- Modeling for standard plasmas and PPCD plasmas is more challenging and is under way because RFP equilibrium is notably different from tokamak. (The existence of reversal surface makes the toroidal flux non-monotonic.)

IV. Fast Ion Loss Time is Determined from Neutron Decay Process after Beam Turn-off

- Neutron flux:
  \[
  \int \frac{dE}{E} \dfrac{Z_f \nu_f \nu_i}{m_n e Z_i} \left( \dfrac{4 \pi}{m_e e^2} \right)^{1/2} \sum_i m_i \varepsilon_i \varepsilon_i^{1/2} \wedge n_i \wedge \varepsilon_i
  \]
- \( T_e \), measured with Thomson scattering
- Plasma density \( n_p = n_i \) measured with FIR interferometer
- Central plasma density and temperature are essential since both fast ion density and plasma density are peaked around the magnetic in the MST.

If fast ions are perfectly confined, the neutron decay time is

\[
\tau_{\text{neutron}} = \frac{1}{\gamma} \frac{dE}{dE} \frac{dE}{E^2} \tau_{\text{conf}} \frac{E_2}{E_0} \frac{E_0}{E_1} \sum_i m_i \varepsilon_i^{1/2} \wedge n_i \wedge \varepsilon_i
\]

- With some fast ion loss mechanism (prompt loss, charge exchange loss with background neutrals, stochastic diffusion...), the neutron decay time is approximated
  \[
  \frac{1}{\tau_{\text{neutron}}} = \frac{1}{\tau_{\text{conf}} + 1/\Gamma_{\text{classical}}}
  \]

V. Good Fast Ion Confinement with Co-current NBI

- Fast ion confinement time is larger than the thermal confinement times of particles and energy

- \( F=0 \) plasma \( \tau_{\text{cond}}(5\mu s) > \tau_{\text{conf}}(\mu s) \)
- Standard stochastic plasmas \( (F=0.2) \) \( \tau_{\text{cond}}(10\mu s) > \tau_{\text{conf}}(1~\mu s) \)
- Improved confinement (PPCD) \( \tau_{\text{cond}}(20\mu s) > \tau_{\text{conf}}(10\mu s) \)
- But it is only 1/3 to 1/2 of fast-ion slowing down time.

- Fast ion confinement time slightly increases with magnetic field strength in standard stochastic plasmas.

VI. Poor Fast Ion Confinement with Counter-current NBI

- NBI can be counter-injected into MST by reversing the plasma current direction. Both neutron flux magnitude and decay time are much smaller in the case of counter-current NBI than with co-current NBI, which indicates large orbit loss and poor fast ion confinement.

VII. Some Puzzling Observations from NBI Experiments

- In high current \((550kA)\) PPCD plasmas, the increase of neutron flux due to NBI is much smaller than expected although the neutron decay process in low current \((200kA)\) PPCD plasmas suggests fast ions are well confined.
- Neutral beam deposition profile in high current PPCD plasmas is quite different from that in low current plasmas or hollow plasma density profile in high current PPCD profile? [Ref. 1]

VIII. New Diagnostics will Measure Fast Ion Distribution

- Fast ion \( H_+ (\text{FIHA}) \) diagnostic is under design and will be used to measure Doppler-shifted charge-exchange recombinaction light from neutralized fast neutral particles.
- \( \psi \rightarrow \psi_{\text{FIHA}} \rightarrow \psi_{\text{NN}} \) by similar to fast ion \( D_0 \) diagnostic in tokamak devices. [Ref. 5]
- An advanced neutral particle analyzer (ANPA) is under testing and will be used to measure charge exchange neutral particles in a broad energy range, from hundreds of eV to study the bulk ion dynamics to tens of keV to study the confinement of fast ions, formation of high energy ion tails, etc.
- \( \geq 20 \) energy channels
- \( \geq 30-300kV \) deuterium/hydrogen ions
- \( \geq 1ms \) time resolution

IX. Conclusions and Future Plan

1) Analysis of neutron decay process indicates fast ions are relatively well confined in standard and PPCD plasmas in co-NBI heating scenario.
2) The fast ion confinement is poor in counter-NBI scenario, about 1 ms, comparable to stochastic diffusion time or thermal particle confinement time.
3) Some puzzling observation from NBI experiments in high current PPCD plasmas.

- New fast ion diagnostics are under development to measure fast ion distribution and will help study fast ion slowing down process and fast ion dynamics during magnetic reconnection events.

References