# Neutral Beam Injection Experiments in the MST Reversed Field Pinch

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THE UNIVERSITY of WISCONSIN MADISON

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# Fast Ions are Barely Studied in RFP Concept

- **Fast ion confinement and transport in Reversed Field Pinch (RFP) devices could be quite different from in Tokamaks.**
  - $B_t \sim B_p$, $\rho_{fi}/a$: 0.1~0.25 → large prompt loss
  - Large magnetic fluctuations, stochastic magnetic field → could lead to rapid diffusion of charge particles
  - $V_{fast\text{-}ion} > V_{Alfvén}$ → fast ions could drive Alfvén instabilities

- **The newly installed 1 MW neutral beam injector on MST provides a good test-bed for fast ion study in RFPs.**
  - Interplay between magnetic fluctuations and fast ion confinement
  - Fast ion driven instabilities
  - Control of MHD dynamo and tearing modes?
  - Plasma beta limit?

# Outline

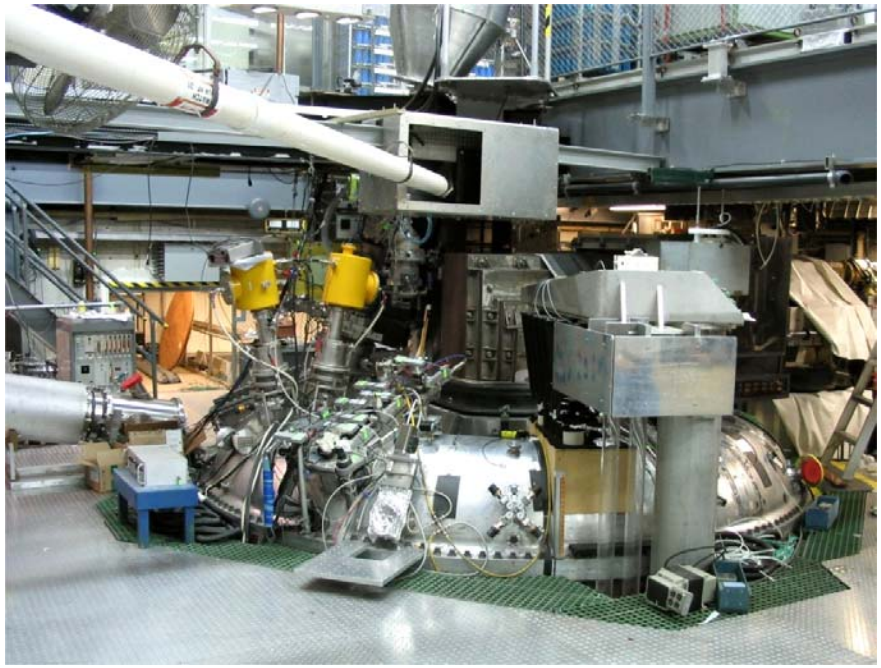
- **Hardware: MST, heating neutral beam and major diagnostics**

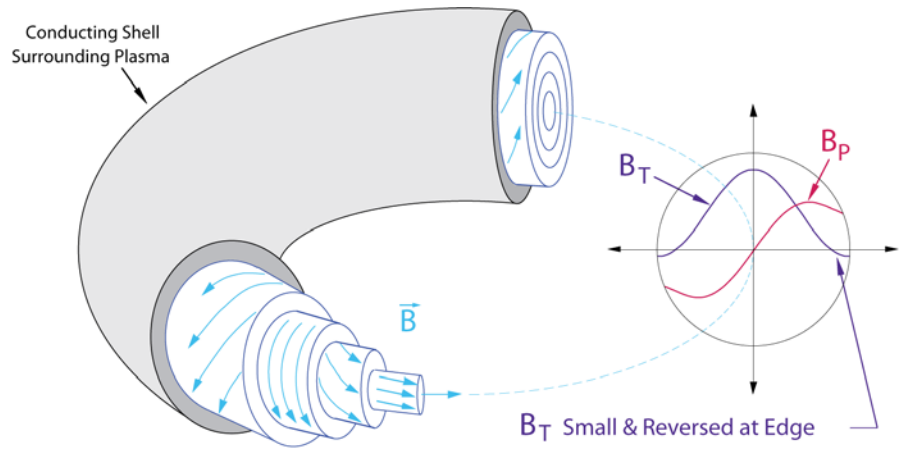
- **Experiments of fast ion confinement**
  - Comparison with classical theory and TRANSP modeling

- **Effects of neutral beam injection on thermal plasmas**
  - Reduction of core mode amplitude and increase of mode rotation
  - Fast ion induced bursting modes
  - Electron heating in improved confinement regime

- **Conclusions**

# Madison Symmetric Torus Reversed Field Pinch (MST RFP)






- R = 1.5 m; a = 0.52 m
- $I_p$: 200-600kA
- Density $n \sim 10^{13}$ cm$^{-3}$
- Temperature $T_e$ up to 1.5 keV
- $B_T$, $B_P$ are comparable (<0.5T)

➢**Standard RFP plasmas**

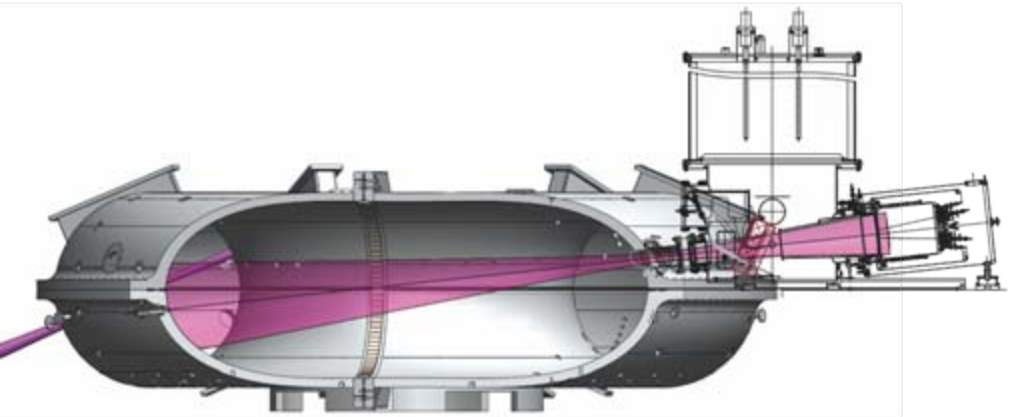
•Non-reversal plasmas $F=B_\varphi(a)/\langle B_\varphi\rangle=0$ ($q(a)=0$)

•Standard reversal plasmas, $F<0$ ($q(a)<0$) characterized by magnetic reconnection bursts

➢**Improved confinement (PPCD)**

- $\tilde{b}/b$ reduced by a factor of ~5

# Significant Population of Fast Ions are Generated by Neutral Beam Injection



| NBI Parameter | Specification |
|---|---|
| Beam energy | 25 keV |
| Beam power | 1 MW |
| Pulse length | 20 ms |
| Composition | 95-97% H, 3-5% D |
| Energy fraction (E:E/2E/3:E/18) | 86%:10%:2%:2% |

- Tangential injection to maximize beam deposition
- Co-current or counter-current injection by reversing $I_p$
- Fast ion diagnostics:
  - ❑ Scintillator-based neutron detector
    - Neutron emission is dominated by beam-target reactions for certain plasma density range
  - ❑ Advanced neutral particle analyzer (ANPA)
    - Simultaneously measure charge exchange H and D neutrals
    - 10 channels per mass species
    - E: 1-30 keV, ΔE:2-3 keV, Δt: ~0.1 ms

# Fast Ion Confinement Time is Inferred from Neutron Flux Decay Process After Short Pulse Neutral Beam Injection

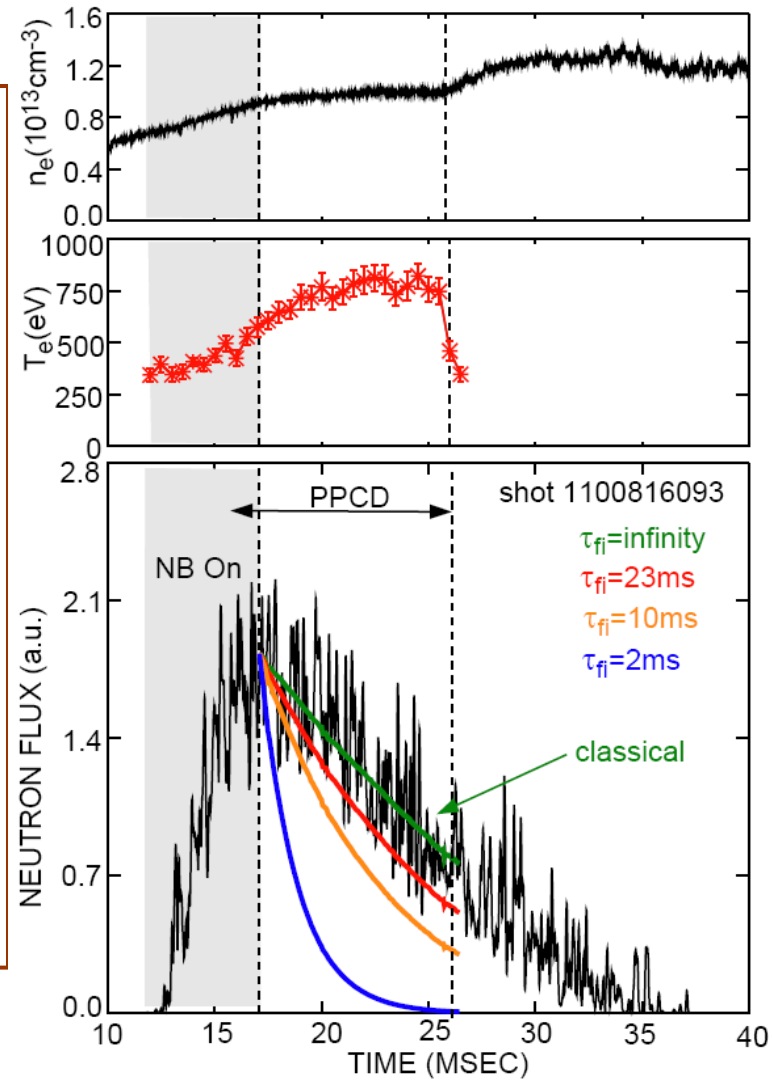
- Neutron: $\Gamma_n(t) \propto \int_V n_{fi}(t) n_i(t) < \sigma_{dd}(E_{fi}(t)) v_{fi}(t) > dV$
- Neutron decay process is the combination of fast ion loss and fast ion slowing down. If these two terms are decoupled,

$$1/\tau_{n-\exp} \approx 1/\tau_{fi} + 1/\tau_{n-classical}$$

- Assuming no fast ion loss, $\tau_{n-classical}$ can be calculated from classical slowing down theory

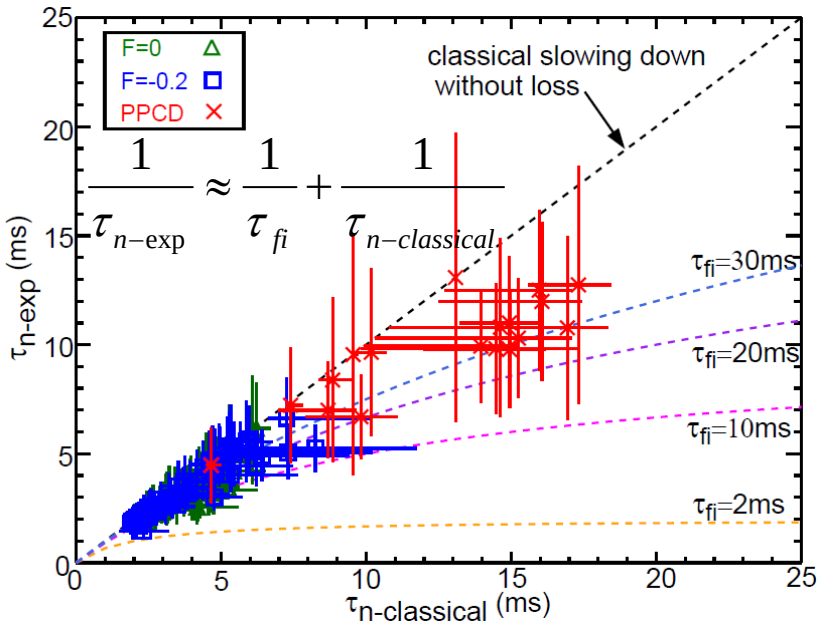
$$\tau_{n-classical} = -\int_{E_n}^{E_b} \frac{dE_{fi}}{\{dE_{fi}/dt\}_{classical}} \cong \frac{\tau_{se}}{3} \ln \frac{E_b^{3/2} + E_c^{3/2}}{E_n^{3/2} + E_c^{3/2}} \quad *$$

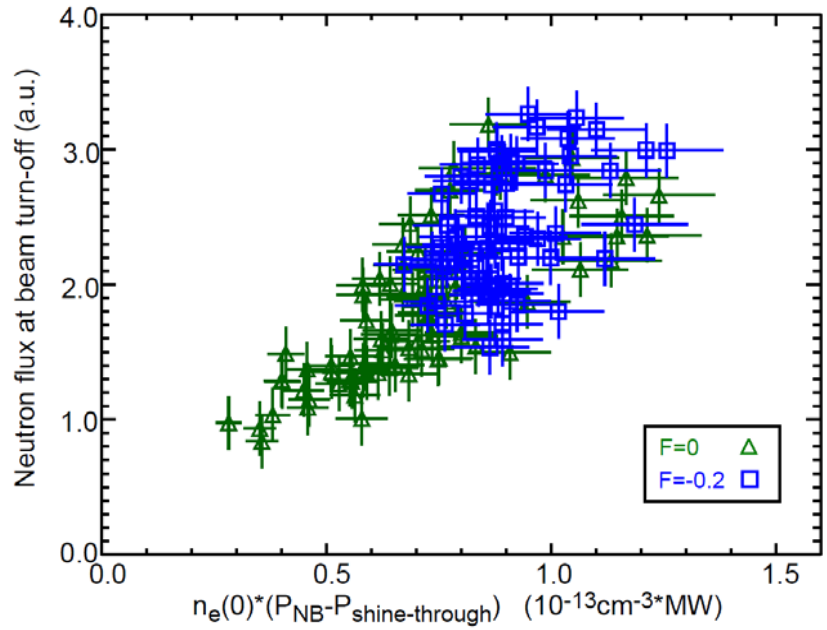
- Strong magnetic reconnection events are excluded for this analysis




* J. D. Strachan *et al*. Nucl. Fusion, 21 (1981)

# Fast Ion Behavior is Roughly Consistent with Classical Theory in Spite of Stochastic Magnetic Field

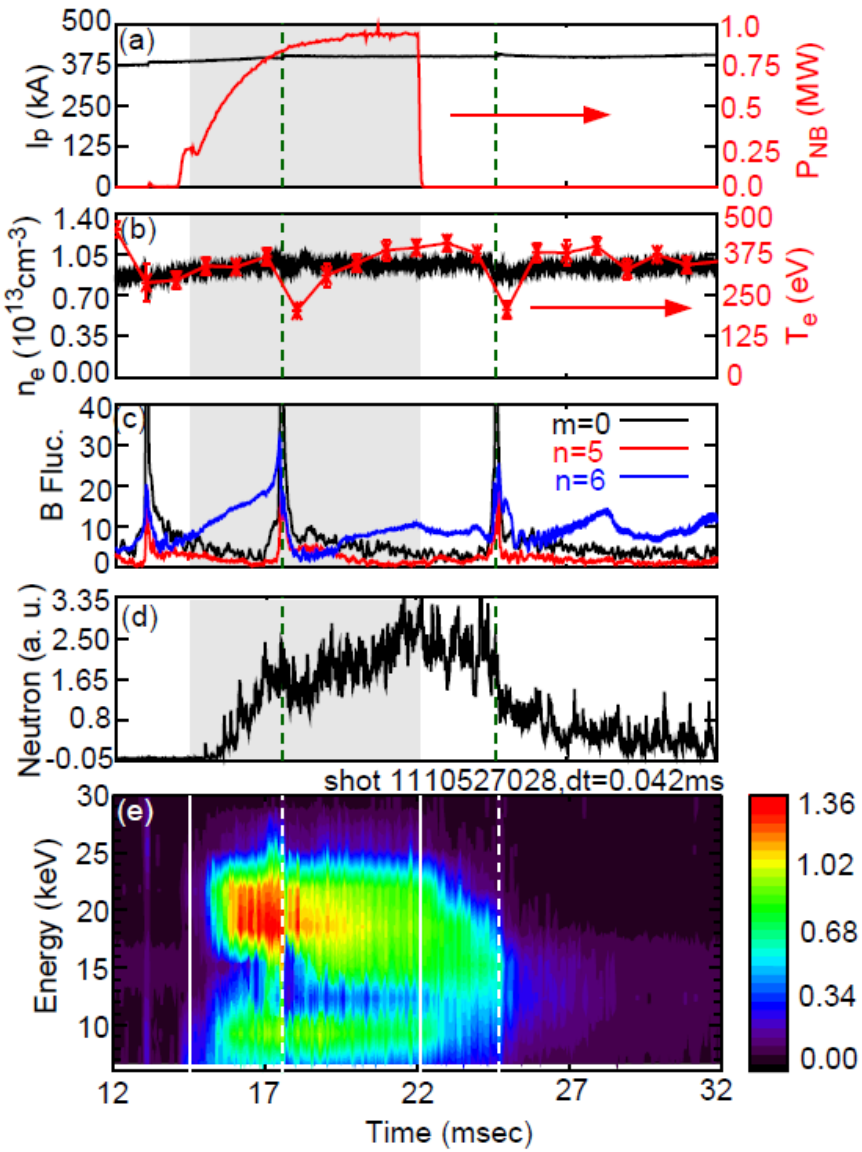


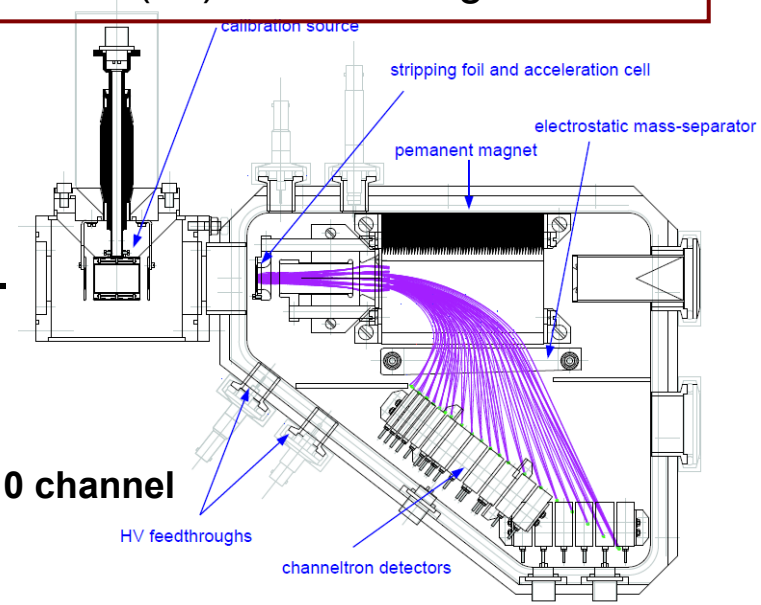

- $\tau_{n-\exp} \sim \tau_{n-classical}$ → Fast ions behave roughly classically
- $\tau_{fi}$ is much larger than thermal particle and energy confinement time
  - Standard F=0 and F=-0.2 RFP plasmas $\tau_{fi}(10ms) > \tau_{i,thermal}(1 \sim 2ms)$
  - Improved confinement regime (PPCD) $\tau_{fi}(25ms) > \tau_{i,thermal}(10ms)$

  But $\tau_{fi} \sim$ 1/2 of $\tau_{slowing-down}$ → may affect NB heating efficiency
- Peak value of neutron flux increases with plasma density, as expected

# Slowing Down of Hydrogen Fast Ions is Observed on Advanced Neutral Particle Analyzer (ANPA)

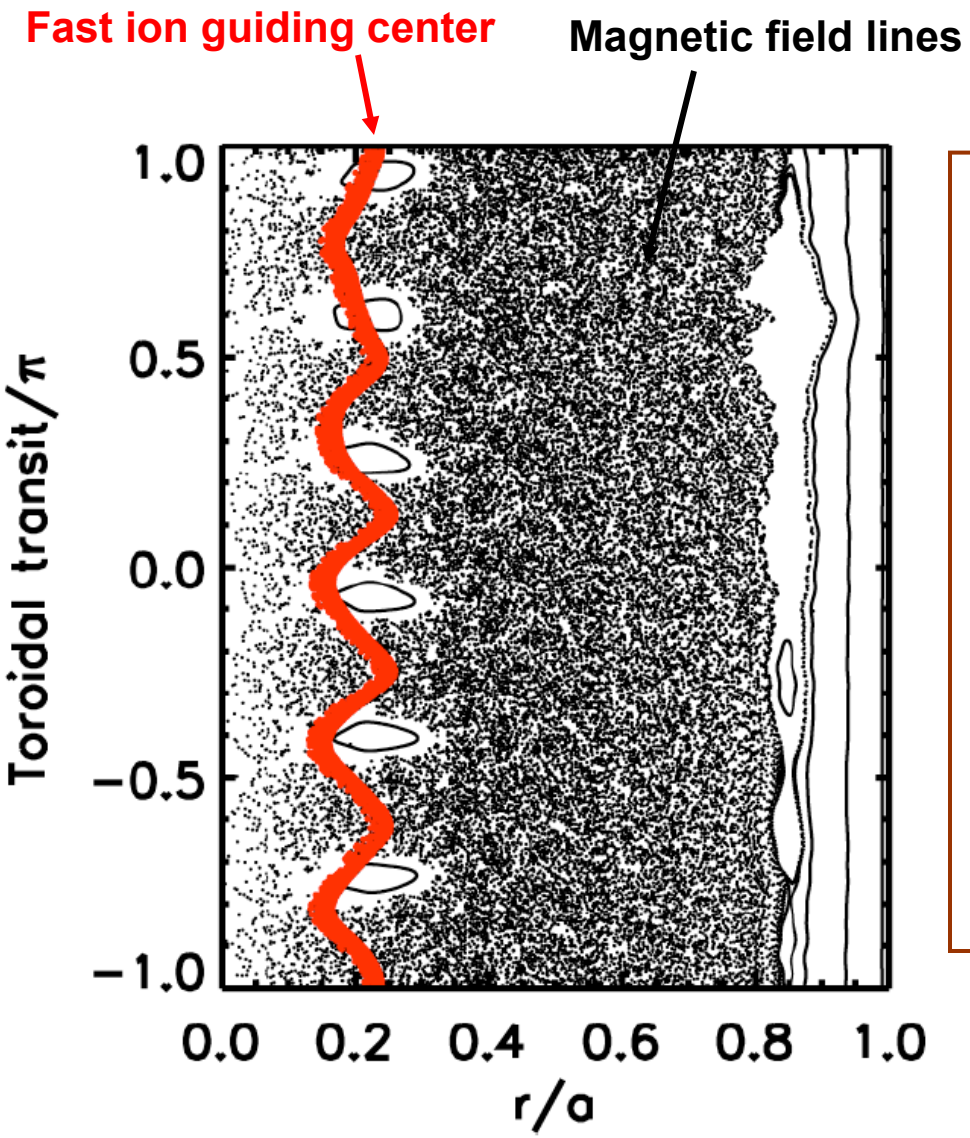



- Charge exchange H signals persist a few ms after NB turn-off until a sawtooth occurs → Good fast ion confinement
- Neutron detector and advanced NPA look at different portions of fast ion distribution
  - Neutron: volume-averaged, mainly from passing fast ions ($D^+$) in the core
  - Advanced NPA: passive CX, mainly from trapped fast ions ($H^+$) near the edge




**E: 1-30 keV**
**ΔE:2-3 keV**
**Δt: ~0.1 ms**
**Hydrogen: 10 channel**

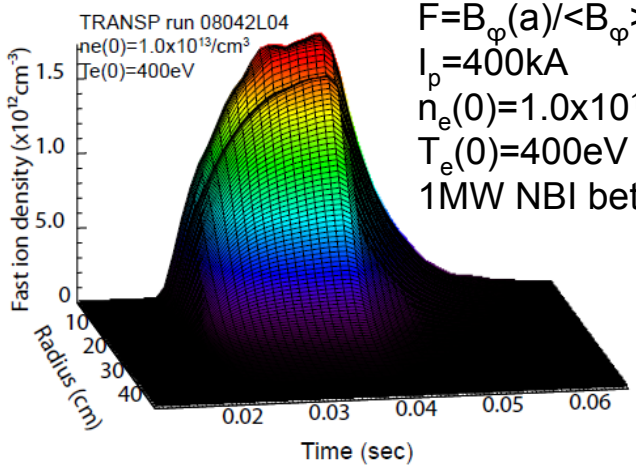
# The Good Confinement of Fast Ions to in Stochastic Magnetic Field is Attributed to the Grad B and Curvature Drift



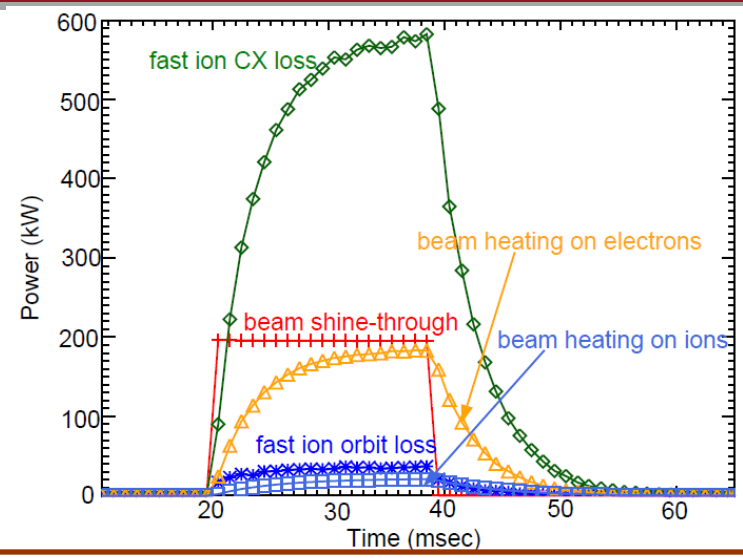

- Overlapping of magnetic islands can cause magnetic stochasticity and result in rapid transport of charged particles. E.g. electrons in standard RFP plasmas, $\tau_e = 1 \sim 2ms$
- Particle orbit of fast ions may not be affected since the guiding center drift (grad B and curvature drifts) make fast ions out of resonance with background magnetic fluctuations. → good confinement of fast ions

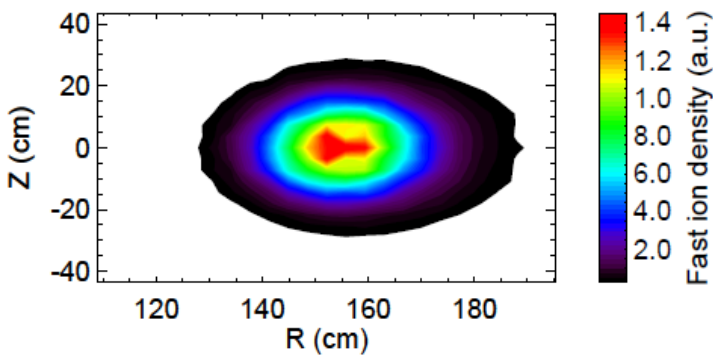
*G. Fiksel *et al. PRL* 95 (2005)
B. Hudson PhD Thesis 2006

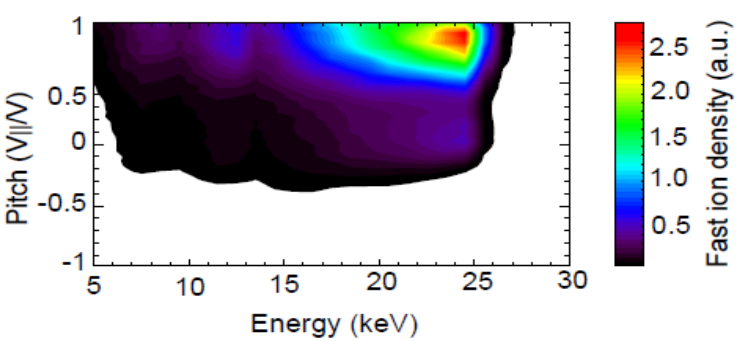
# TRANSP/NUBEAM Modeling Predicts Centrally Peaked Fast Ion Density




$F=B_\varphi(a)/\langle B_\varphi\rangle = 0$ or $q(a)=0$
$I_p$=400kA
$n_e(0)=1.0\times10^{13}cm^{-3}$
$T_e(0)=400eV$
1MW NBI between [20,40] ms




**TRANSP/NUBEAM Modeling of NBI into a Standard F=0 Plasma shows that:**

- Local $n_{fi}$ could be as high as 15% of $n_e$
- Fast ions are confined in the plasma core (r/a<0.2)
- Mainly passing particle with pitch $v_{||}/v$=0.9
- 20% shine-through loss, similar to measurements
- 55% power loss due to charge exchange
- Neutron decay time similar to the measurements
- $\beta_{fi}$~3% vs $\beta_{thermal}$ ~ 8%

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  - Electron heating in improved confinement regime
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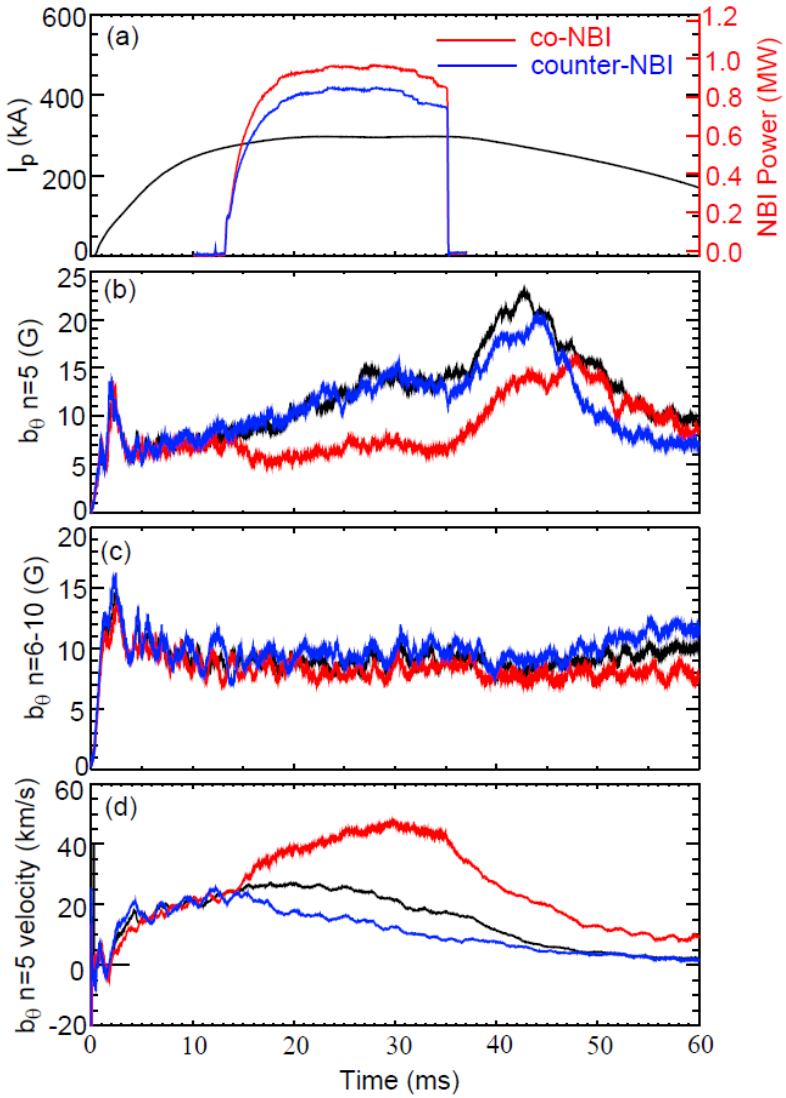
# NBI Reduces Core-most Tearing Mode Amplitude and Increases Plasma Rotation and Shear

$F=B_\varphi(a)/\langle B_\varphi\rangle = 0$, $I_p=300$kA

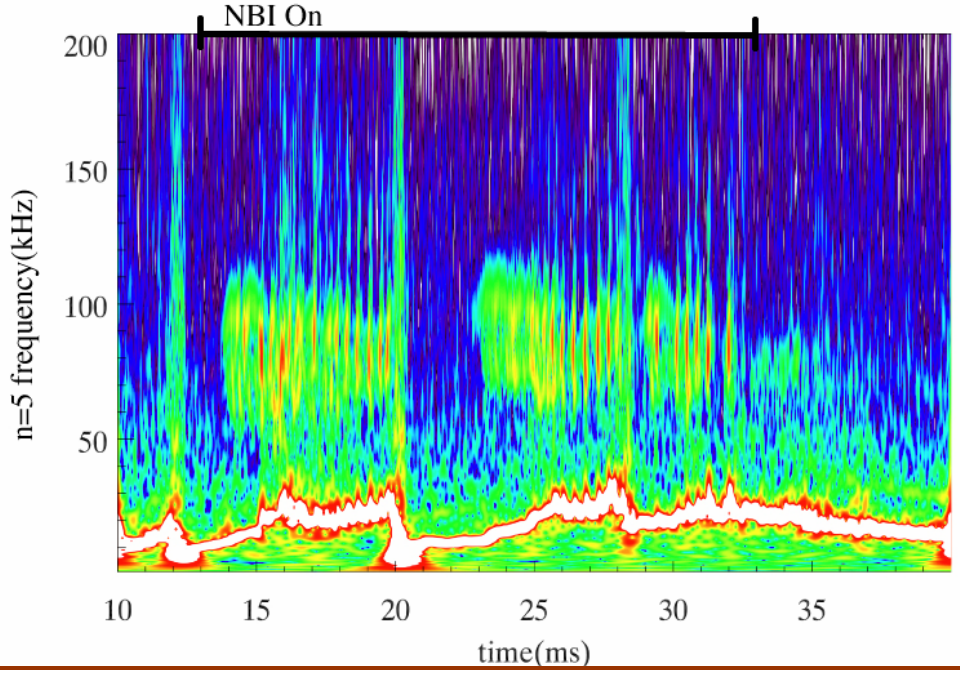



- ➢ Strong stabilizing effect on the core-most n=5 tearing mode with co-injection, not obvious in counter-injection
- ➢ All the other tearing modes (n=6-10) are unaffected in co- or counter-injection
- ➢ Toroidal rotation and shear increase in co-injection

→ NBI applies a significant torque to plasmas

- ➢ Mechanism of mode stabilization not yet identified
- Altered $J_{||}$ profile affects tearing mode stability
- Altered $J_{||}$ profile removes core mode resonance condition
- Stabilization due to fast ions at tearing mode layer by finite Larmor radius effect

# NBI Induces Bursting Modes

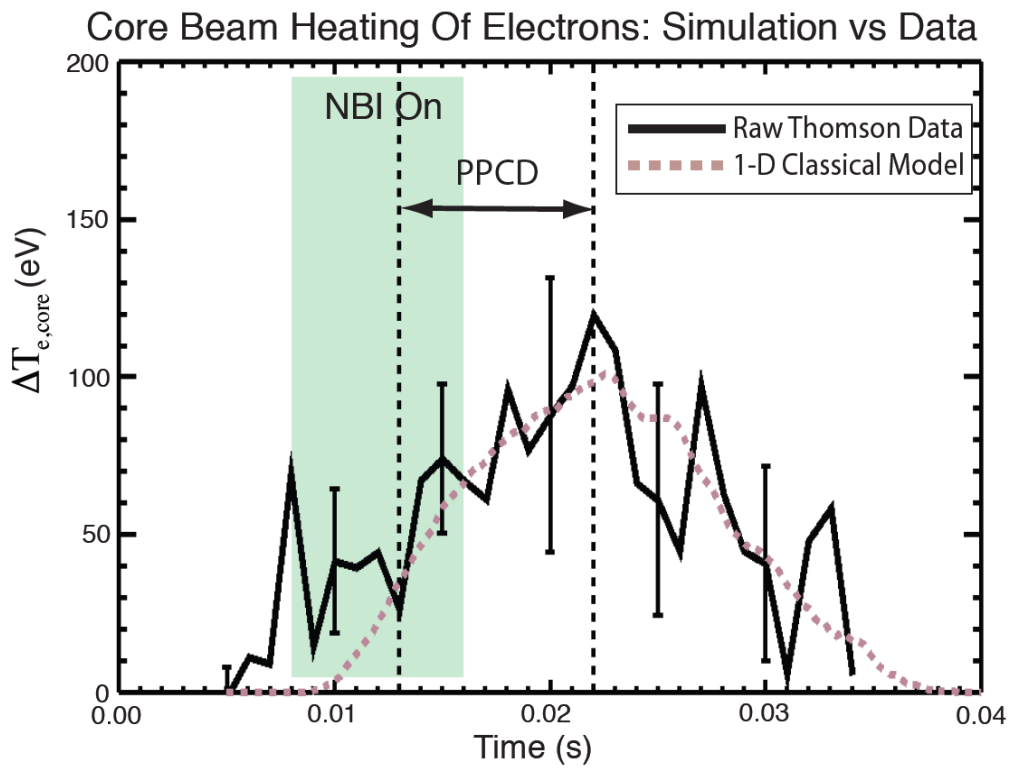



$F=B_\varphi(a)/\langle B_\varphi\rangle = 0$ (or $q(a)=0$ )
$I_p$=300kA
$n_e=0.7\times10^{13}cm^{-3}$

- NBI induced bursting magnetic fluctuations have been detected on magnetic coils in F= 0 (or q(a)=0 ) plasmas with co-NBI, not in any F<0 plasmas.
- Frequencies are in the range of 60~150kHZ with n=4 or n=5, m=1, much less than the predicted TAE frequency (~300kHz)
- The strongest coherence activity scales inversely with density, but does not scale with magnetic field strength.
- The mode is not identified yet, could be EPM….

# NBI Induced Electron Heating is Consistent with Classical Theory

$\Delta T_e(0)$




- ~100 eV electron heating is observed during NBI into 200kA PPCD plasmas
- Heating continues at a steady pace during the enhanced confinement (PPCD) period, even after the NBI is turned off.
- Agrees with a 1-D classical heating model
- No obvious electron or ion heating observed in standard RFP plasmas

# Summary

- Fast ions in MST behave roughly classically in spite of stochastic magnetic field. The confinement time is much better larger than thermal particle and energy confinement time.
- TRANSP modeling is largely in agreement with observations. TRANSP suggests that charge exchange with background neutrals is the dominant fast ion loss mechanism and fast-ion beta could be as large as 3%.

**Effects of NBI on MST Plasmas**

- NBI reduces core mode amplitude and increases plasma rotation and shear.
- NBI induces bursting modes at frequencies of 60-150kHz that scales with density, not magnetic field.
- Over 100 eV electron heating is observed in PPCD plasmas with NBI. It can be explained by a 1-D classical heating model. No obvious electron or ion heating observed in standard RFP plasmas.