# Confinement of Fast Ions in the Stochastic Field of a Reversed Field Pinch

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# Abstract

The confinement of fast ions in the plasma is of interest to determine the efficiency of neutral beam heating and the energy dependence of transport. While the confinement of the bulk plasma in the RFP configurations is governed by the stochasticity of the magnetic field, the effect of the stochasticity on the fast ion confinement is unknown.

We have initiated numerical and experimental study of this phenomenon in the MST RFP. A 3D test particle motion code has been developed. A full magnetic (equilibrium and perturbation) field is given by the resistive non-linear MHD DEBS code and the magnitude of the perturbation magnetic field is varied to change the stochasticity. A background plasma can be added which results in the energy and momentum losses of the fast ions. Realistic neutral beam injection can be modeled with the fast neutral atoms originating at the plasma boundary and then being ionized and trapped inside the plasma, thus the heating efficiency can be calculated.

Experimentally the fast ion confinement is studied by injection of a 10 keV hydrogen diagnostic neutral beam into the plasma. The fast ions losses are measured by neutral particle analyzers.

# Motivation

- Confinement of fast ions is critical in NBI applications - heating, current drive.
- Confinement of bulk plasma in RFP depends on fluctuation of the magnetic field.
  - Magnetic fluctuations can be strong enough so the magnetic field becomes stochastic due to island overlapping.
  - Thermal particles stream along the stochastic magnetic field lines and quickly diffuse outward.
- If the ion gyroradius is large enough, would confinement be determined by the parallel streaming?
- Or the gyration will “average” somehow the overlapping magnetic islands?

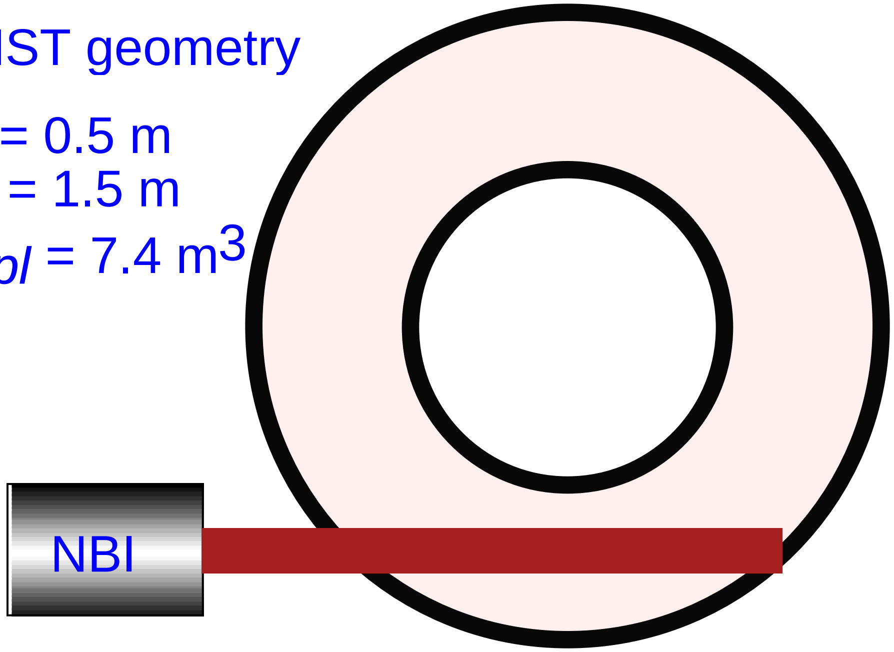
# Outline

- Simple model of NBI heating.
- Simulation results - code RIO.
  - Magnetic field stochasticity.
  - Field line diffusion and ion motion.
- Experimental results - fast ion confinement.
- Summary and future work.

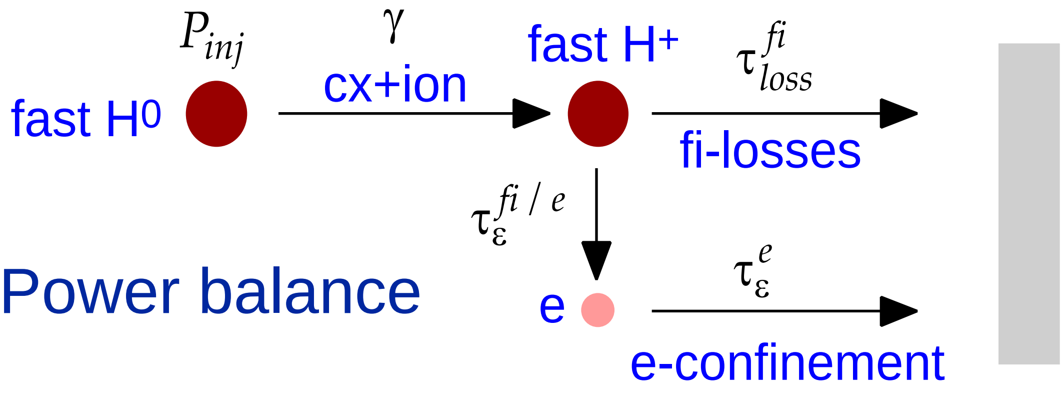
# NBI Power Balance

MST geometry

a = 0.5 m
R = 1.5 m
$V_{pl} = 7.4\ m^3$

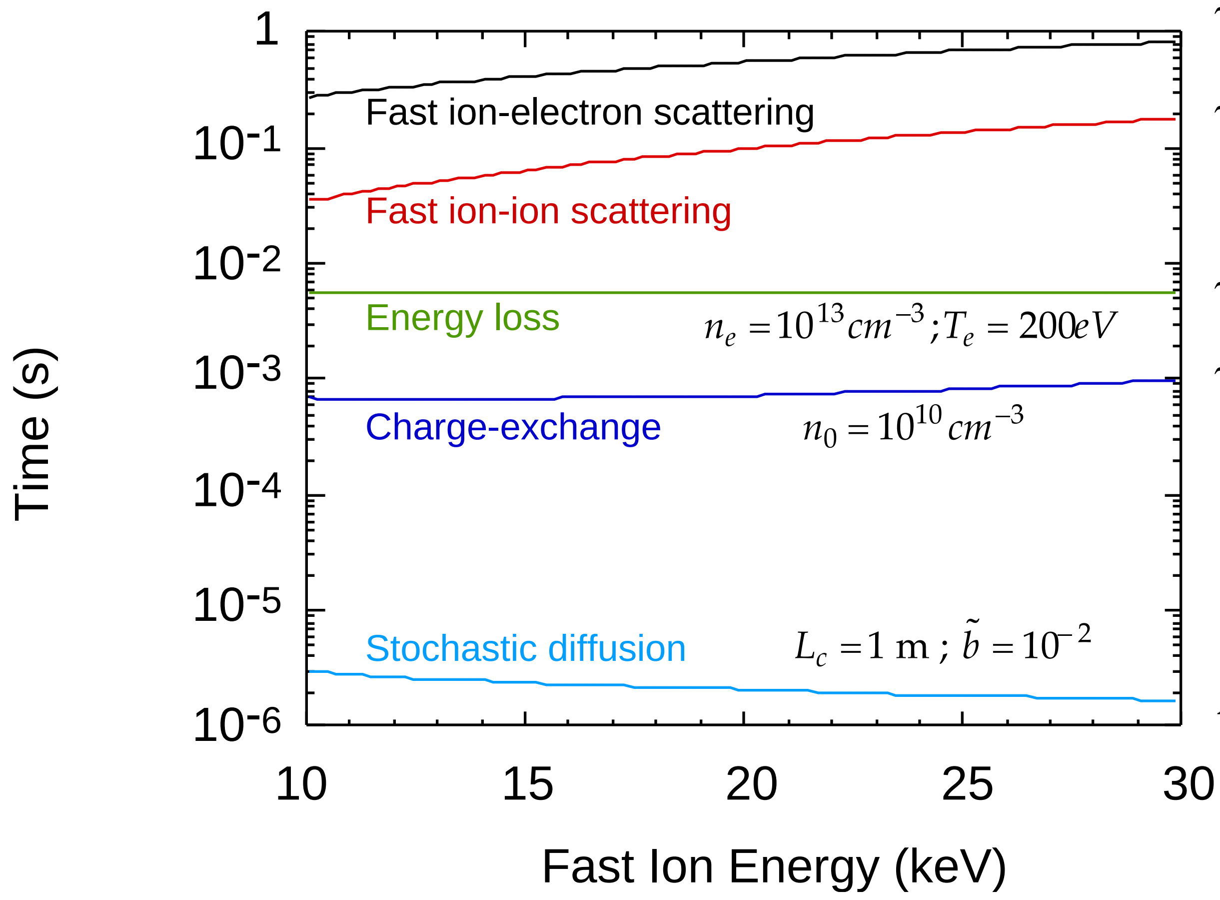


| | |
|---|---|
| $P_{inj}$ | NBI power |
| $\gamma$ | neutral trapping |
| $\tau_\varepsilon^{fi/e}$ | energy loss to electrons |
| $\tau_{loss}^{fi}$ | fast ion losses |
| $\tau_\varepsilon^{e}$ | electron energy confienement |



Power balance

# Fast ion confinement - range of characteristic times is very broad



$$\tau_{\perp}^{fi/e} = 3.1\times10^{8} E_{fi} T_e^{1/2} / n_e \lambda$$

$$\tau_{\perp}^{fi/i} = 5.5\times10^{6} E_{fi}^{3/2} / n_e \lambda$$

$$\tau_{\varepsilon}^{fi/e} = 3.1\times10^{8} T_e^{3/2} / n_e \lambda$$

$$\tau_{cx} = (n_0 v_{fi} \sigma_{cx})^{-1}$$

$$D_{st} = v_{fi} L_c \tilde{b}^2;\ \tau_{st} = a^2 / 6 D_{st}$$

# Good fast ion confinement is critical

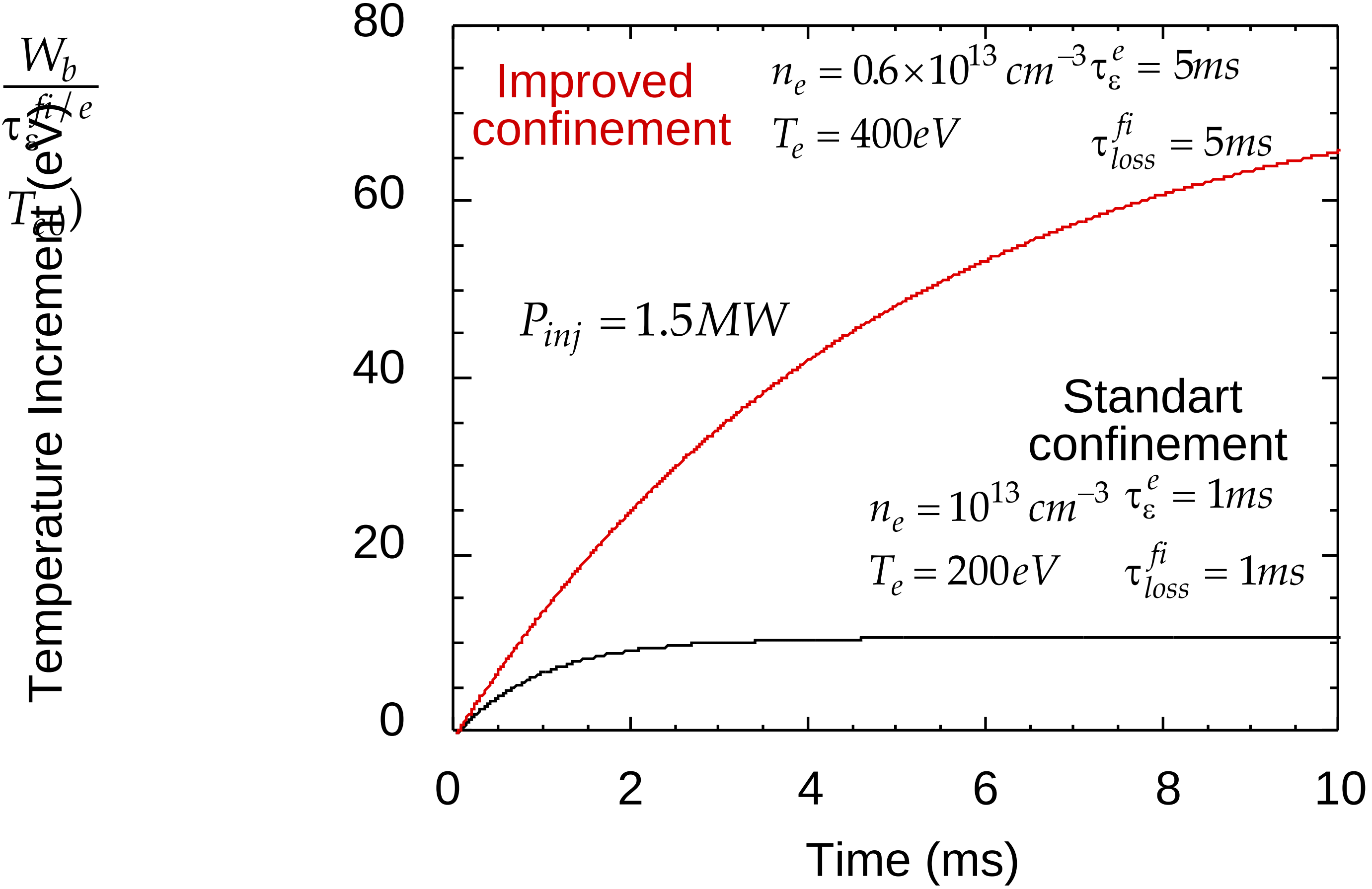
## 0-D electron heating model

$$\frac{dW_b}{dt} = -\frac{W_b}{\tau_\varepsilon^{fi/e}} - \frac{W_b}{\tau_{loss}^{fi}} + \frac{\gamma P_{inj}}{V_{pl}}$$

$$\frac{dW_e}{dt} = -\frac{W_e}{\tau_\varepsilon^{e}} + \frac{W_b}{\tau_\varepsilon^{fi/e}}$$

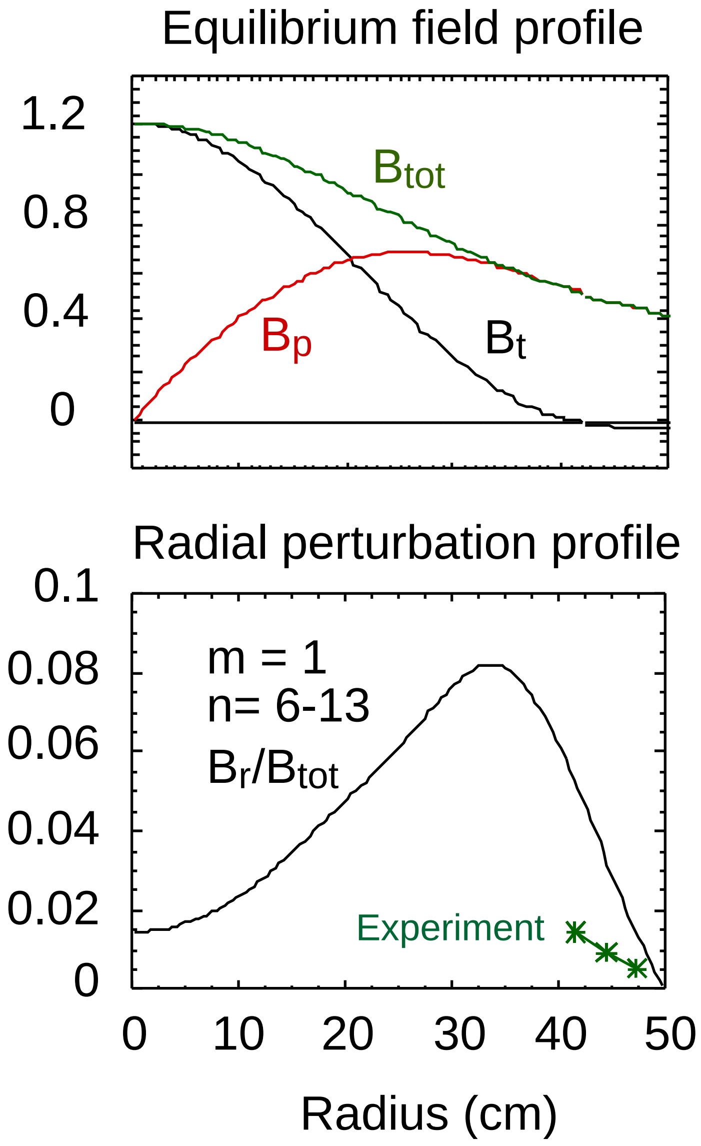
$$W_e = \tfrac{3}{2} n_e (T_e - T_{e0})$$

$$W_e = \frac{\gamma P_{inj}}{V_{pl}} \frac{\tau_{eff}^{fi}}{\tau_\varepsilon^{fi/e}} [\tau_\varepsilon^{e}(1 - e^{-t/\tau_\varepsilon^{e}}) + \tau_{eff}^{fi}(e^{-t/\tau_{eff}^{fi}} - e^{-t/\tau_\varepsilon^{e}})]$$



# Obtain equilibrium and perturbation field profiles with DEBS

- Magnetic fluctuations in RFP - large amplitude global tearing modes m=1, n=6, 7, 8, ...
- DEBS code - nonlinear resistive MHD code.
- Use DEBS to get equilibrium and perturbation field.
- Cylindrical geometry:
  a=0.5 m, L=2$\pi$Aa
  (A = 3 aspect ratio)
- $B_{r\ exp} = 0.3\ B_{r\ DEBS}$



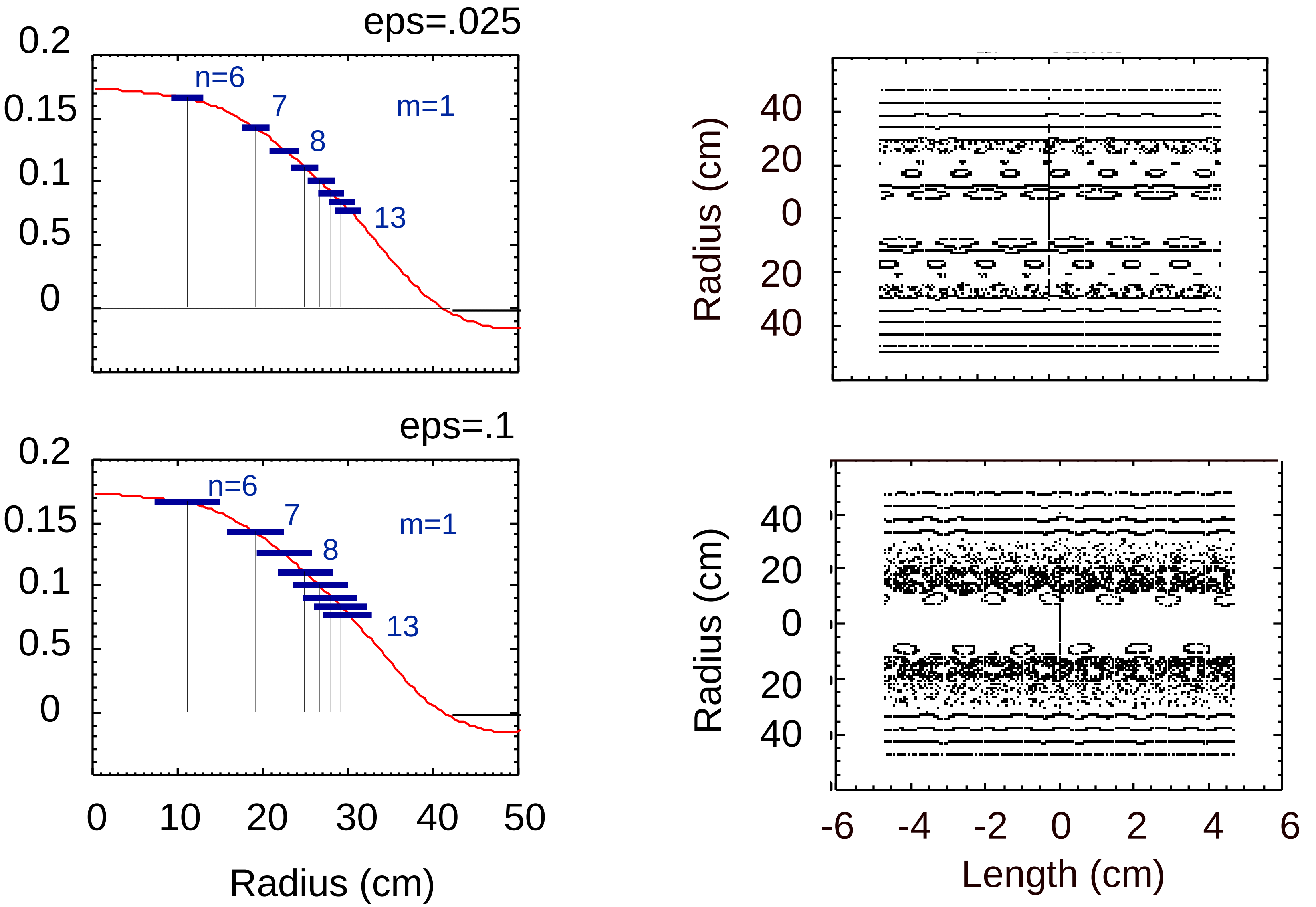
# Field line tracing

- Take perturbation fields from DEBS.
- Extract 8 largest modes m=1, n=6, 7, 8,…13
  $B_r$, $B_\theta$, $B_\varphi \propto \exp(m\theta - n\varphi + \mu_{mn})$
- Multiply mode amplitudes by a scaling factor $\varepsilon$
- Use code RIO for line tracing and puncture plot

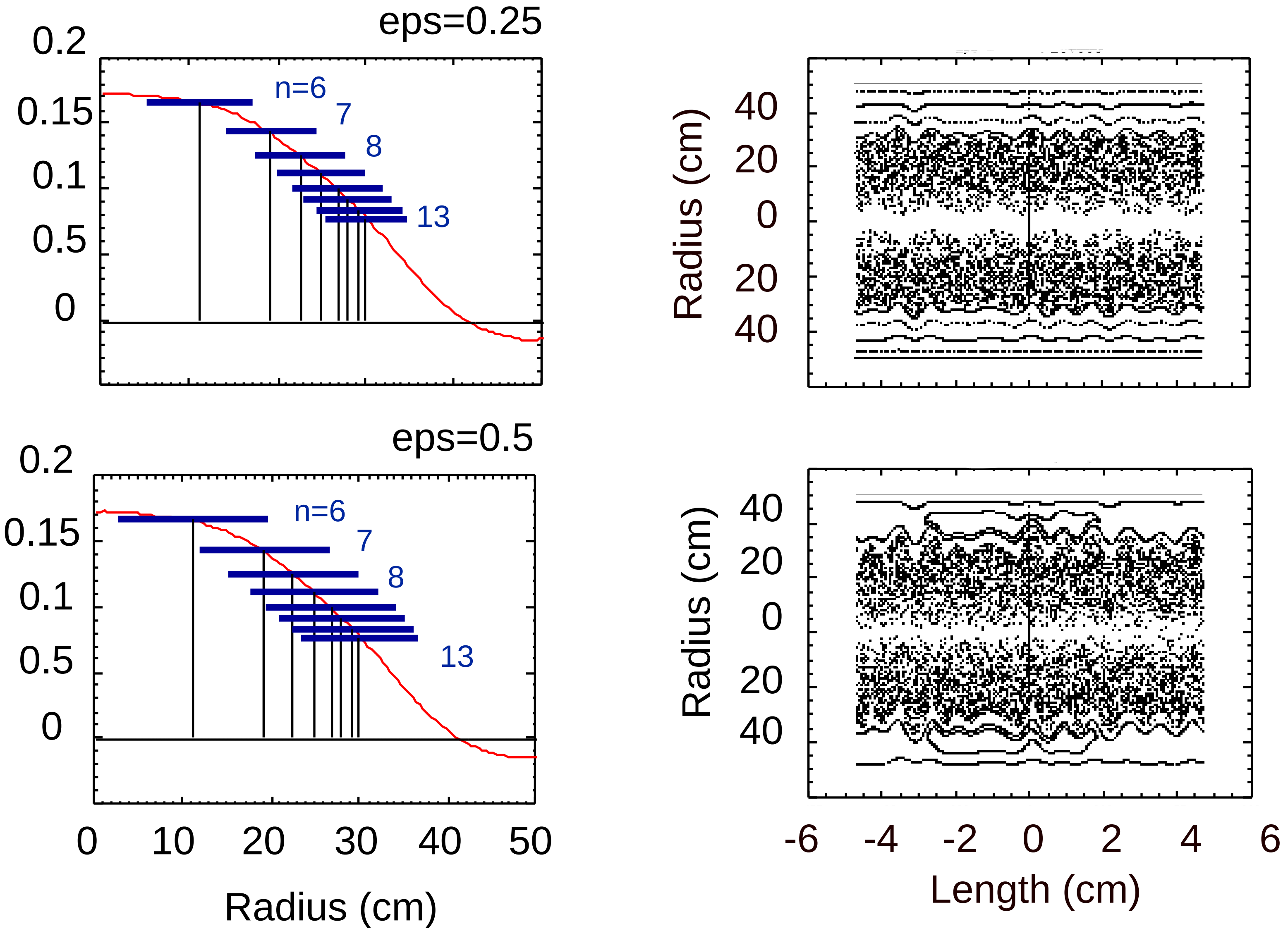
# Code RIO

- 3D, cylindrical or toroidal
- Field line tracing
- Fast ion motion in magnetic field
  - plasma background $n_e(r)$, $n_i(r)$, $T_e(r)$
  - drag on background electrons included
- NBI modeling

# Small ε – isolated islands



# Large ε – islands overlap and stochasticity



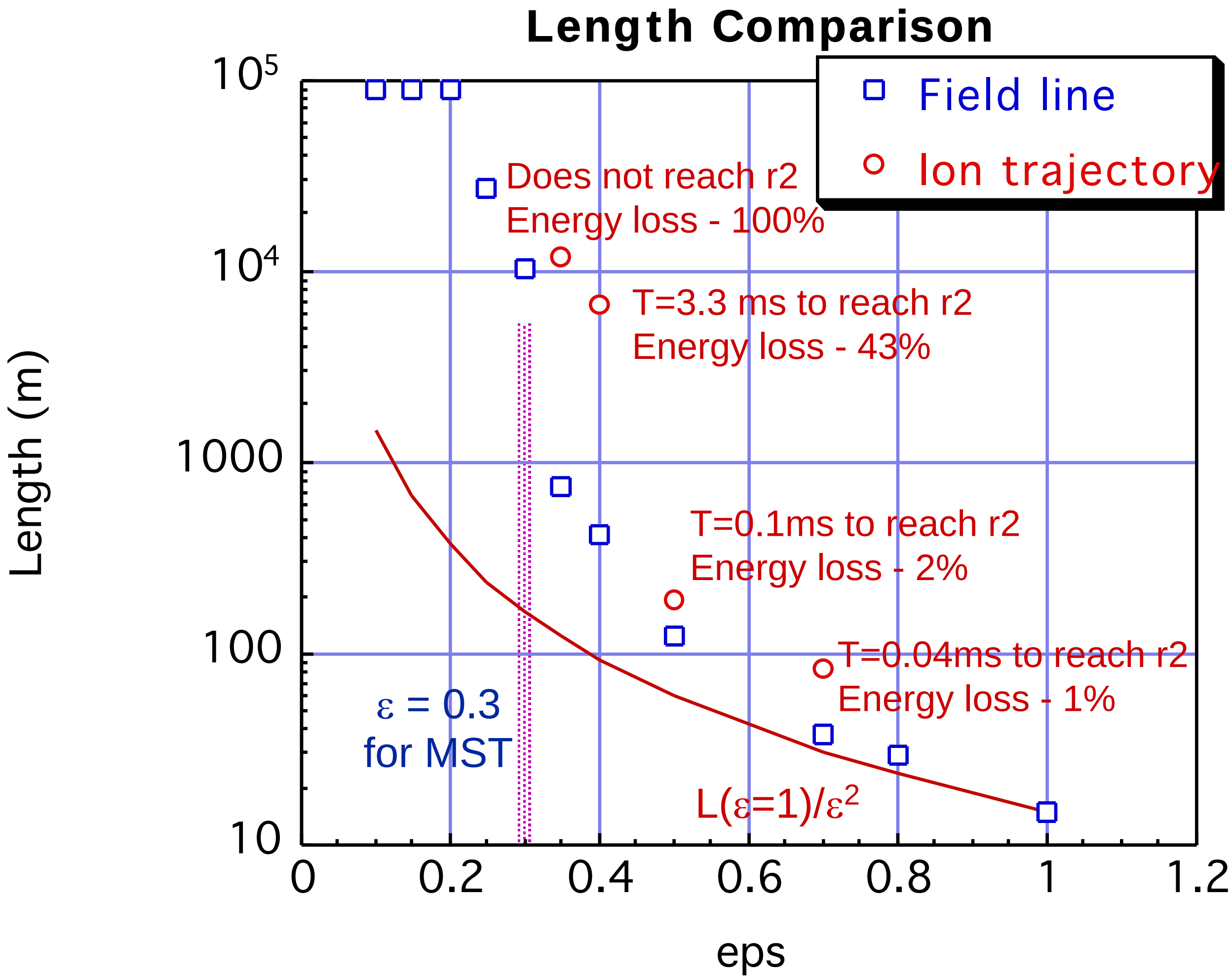
As ε increases, the islands start to overlap, beginning with the edge.

MST standard plasma corresponds to ε = .3

At high ε entire resonance region between
10 cm (n=6) and 30 cm (n=13) becomes stochastic.

Notice a non-linear island
developing at the reversal surface at high ε.

# Field lines and fast ion diffusion



- Pick a line starting at $r_1$
- See how long it takes to reach $r_2$
- The same with ions

$n_e$ [cm$^{-3}$] = $10^{13}$ $(1-r^4/a^4)$
$T_e$ [eV] = 200 $(1-r^4/a^4)$

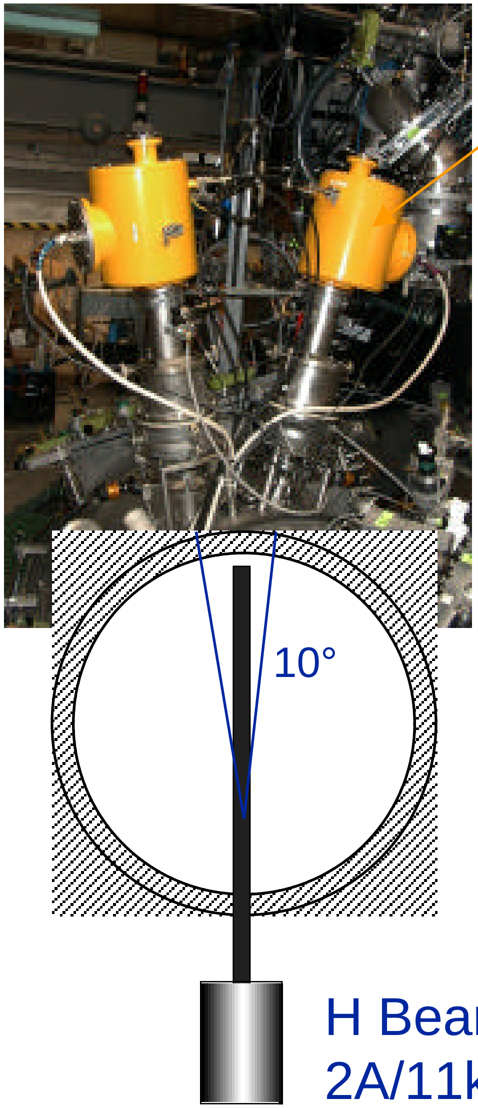
$E_0 = 20$ keV
$B_{wall} = 0.15$ T
$r_{ci}(0) = 6$ cm

$r_1 = 10$ cm, $r_2 = 30$ cm

# Simulation Results

- Field line and ion diffusion increases with ε
- At small ε line diffusion is lower than Q-L Rechester-Rosenbluth estimate $\varepsilon^{-2}$
- At small ε ions diffuse much slower than field lines. At ε = 0.3-0.4 (typical for MST) the fast ion confinement time is several ms which is comparable to plasma confinement time. Large fraction of energy is deposited.
- At larger ε ion confinement is poor and only a small fraction of energy is deposited.

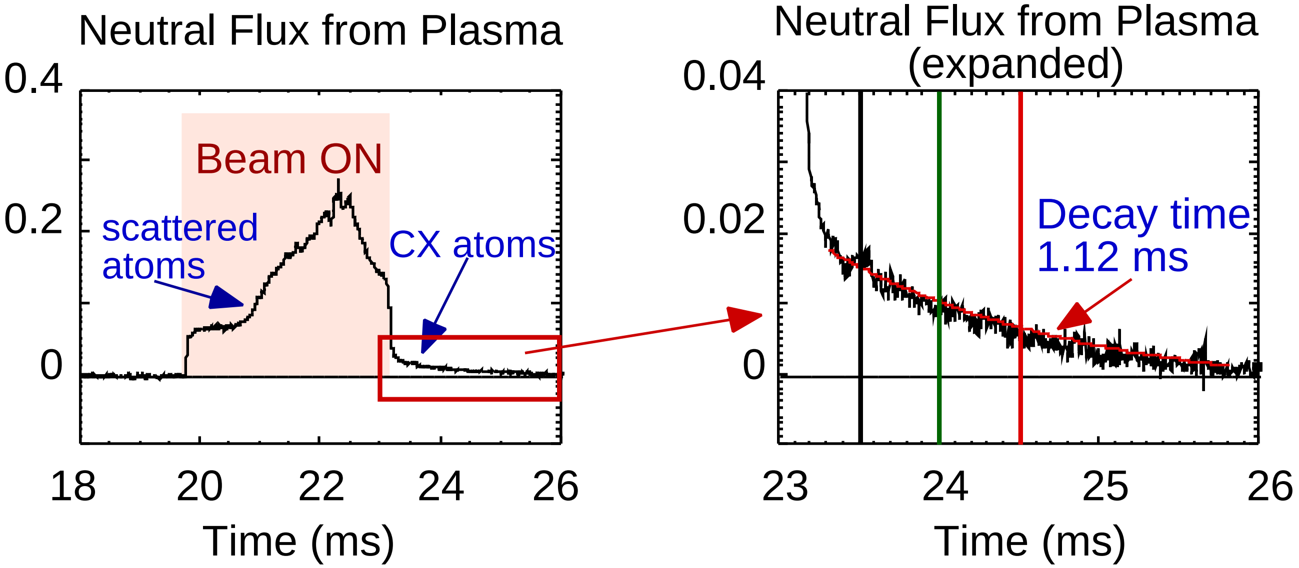
# Experimental Arrangement



Neutral Particle Analyzer (NPA)

- Fast H neutrals (11 keV) injected into plasma.
- The flux and the energy spectra of CX neutrals from the plasma are measured with an NPA.
- We use the same beam-NPA arrangement as for the Rutherford scattering diagnostic - notice small angle between the beam and NPA. Therefore, a large contribution to the neutral flux during the beam injection comes from the scattering of the beam, not from the CX atoms.
- Nevertheless, we observe a decaying flux of energetic CX atoms after them beam is turned off. They come from the trapped fast ions.

# Fast ion confinement time measured


Neutral Flux from Plasma

Neutral Flux from Plasma (expanded)

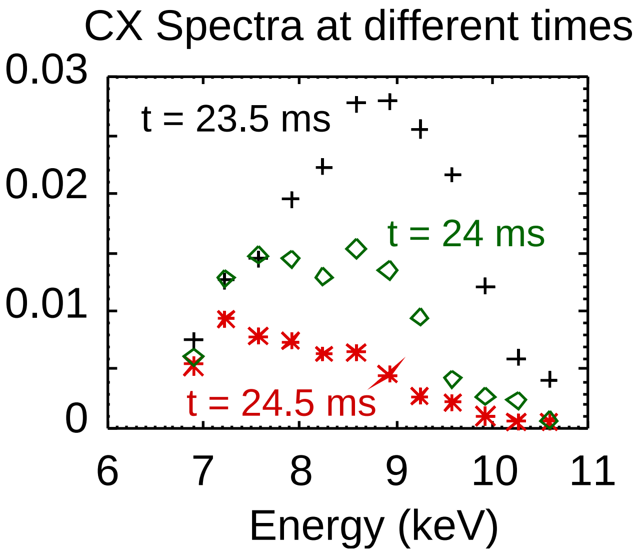
$n_e = 10^{13}\ \text{cm}^{-3}$

$T_e = 200$ eV

$\tau_{\text{fi loss}} = 1.1$ ms - comparable to plasma confinement time

Fast ion slowdown time $E(dE/dt)^{-1} = 5$ ms

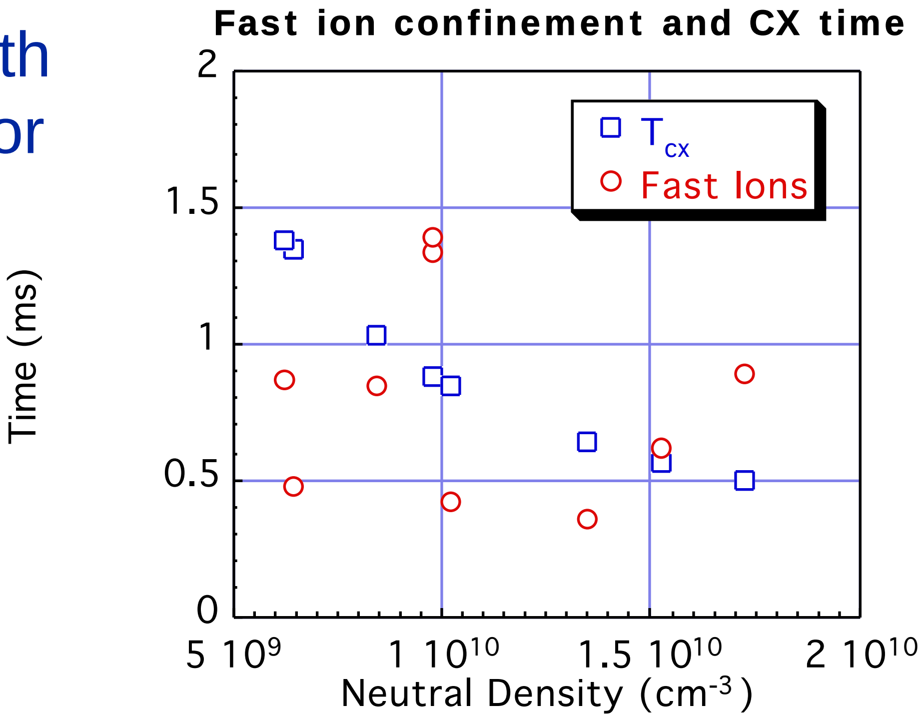
comparable to electron drag time $\tau_{\varepsilon\ \text{fi/e}} = 6$ ms

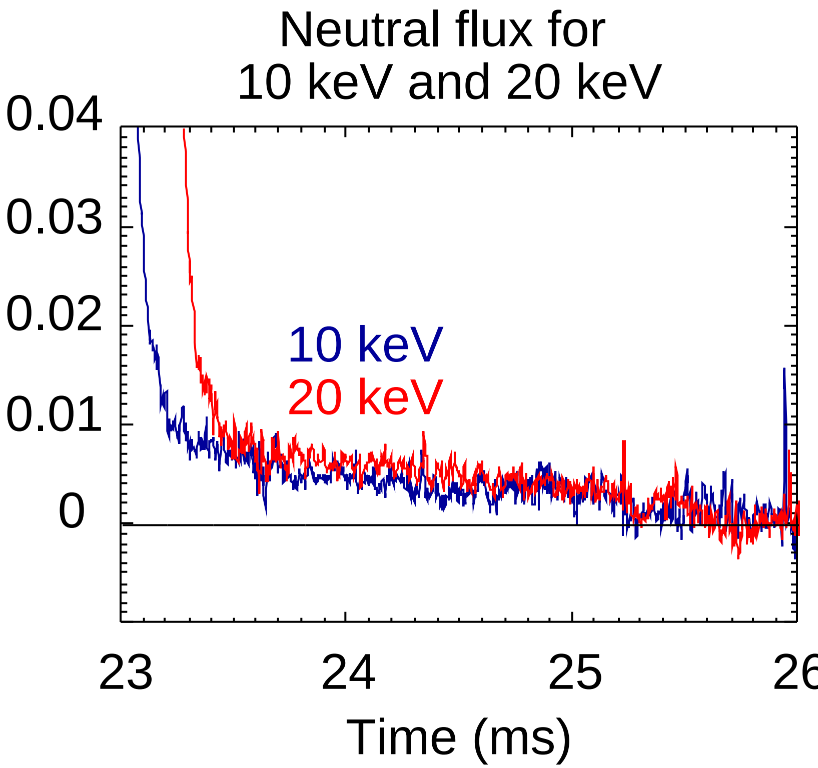

CX Spectra at different times

# Are fast ion losses due to CX?

$n_0$ was measured with calibrated $H_\alpha$ detector

$\tau_{cx} = (n_0 \, v_i \sigma_{cx})^{-1}$

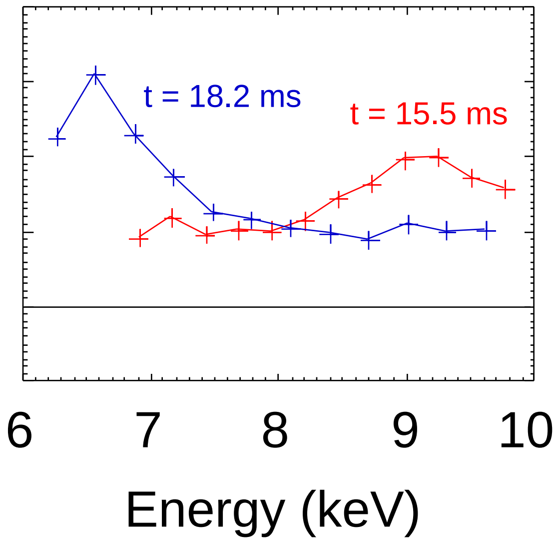




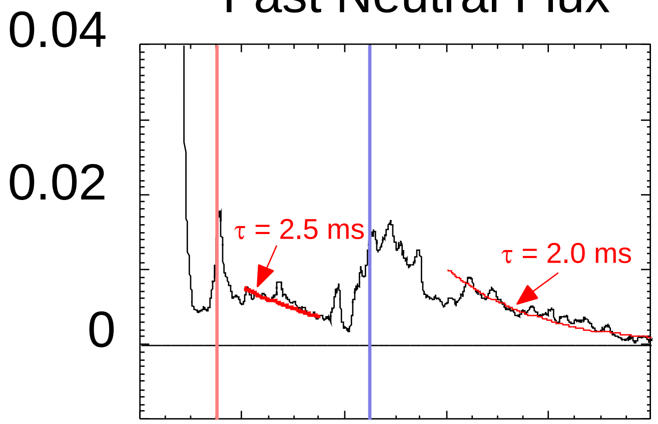
- Confinement comparable with CX times
- Confinement does not depend on energy

# Improved confinement regime

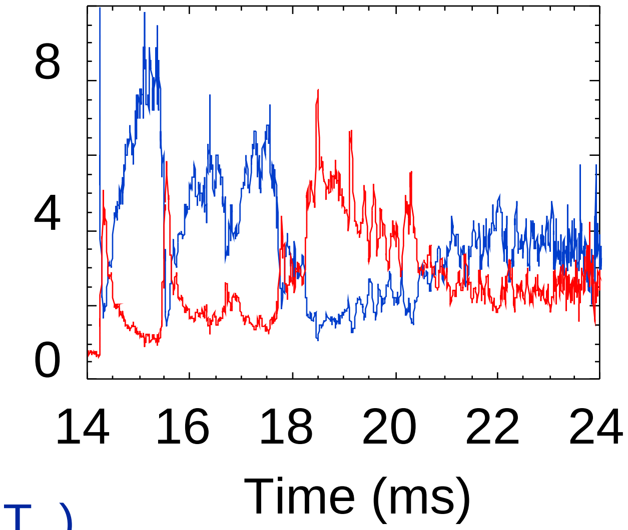
Energy Spectra
at different times



Fast Neutral Flux



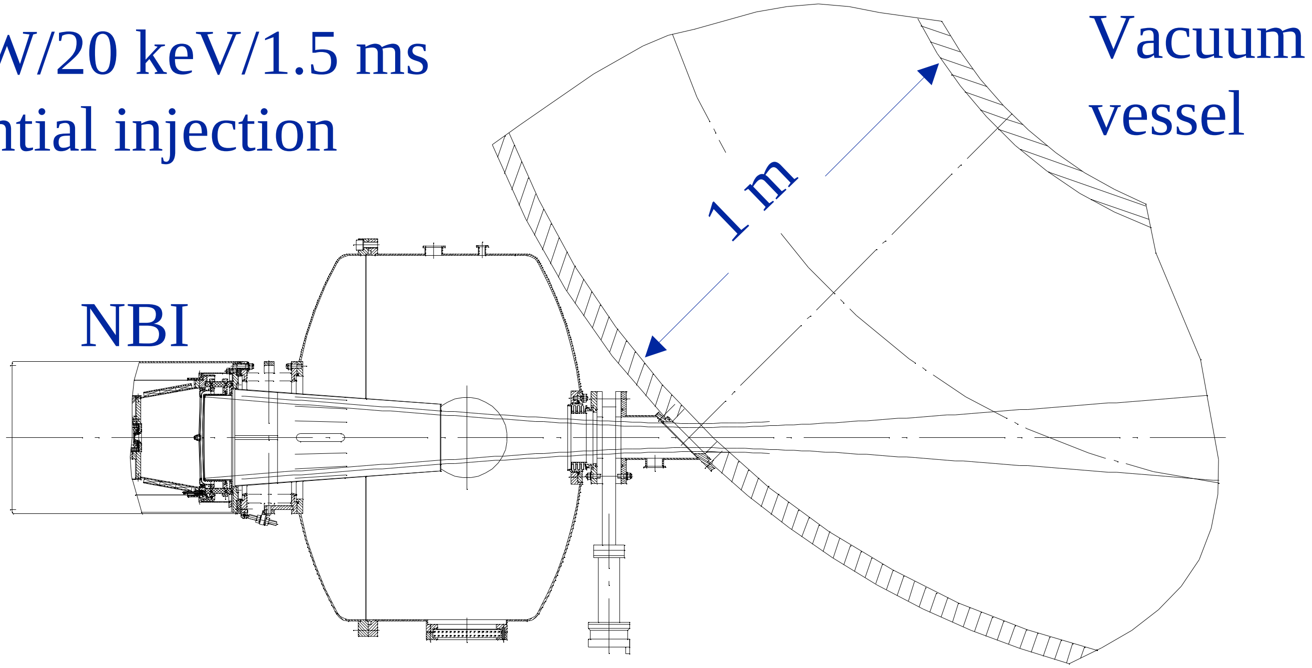
$\tau_{CX}$ (ms), $n_0$ ($10^9$ cm$^{-3}$)



- When MST operates in improved confinement regime the background neutral density drops (CX time is longer) and has a bursty behavior.
- Fast ion losses decrease and their flux correlates very well with the neutral density and anti-correlate with CX time.
- Fast ion slowdown time $E(dE/dt)^{-1}$ = 8 ms - higher than in standard plasma (lower $n_e$, higher $T_e$ )

# 1.5 MW NBI experiment planned on MST

1.5 MW/20 keV/1.5 ms
Tangential injection



- Improved measurement of fast ion confinement
- Direct measurement of plasma heating
- Plasma confinement and transport

# Summary

- Auxiliary plasma heating with neutral beams requires good confinement of fast ions.
- Numerical and experimental studies have been initiated to study fast ion confinement in a stochastic magnetic field of RFP.
- Preliminary results indicate that the fast ion confinement is better than predicted by quasi-linear estimate.
- The confinement seems to be limited by the charge-exchange with background neutrals. The fast ion slow-down time is determined by collisions with plasma electrons.
- Further studies are needed:
    - Simulations in toroidal geometry
    - Injection of a high power beam