Modeling of Low-frequency MHD-induced Beam-ion Transport In NSTX

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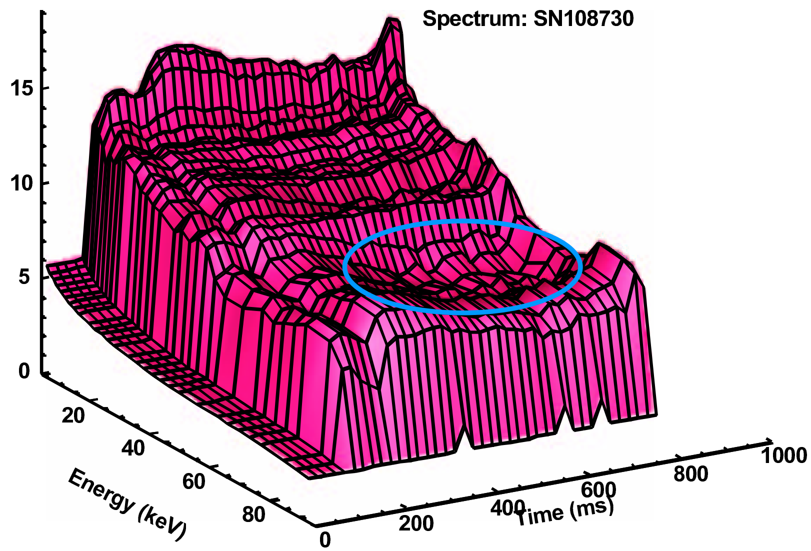
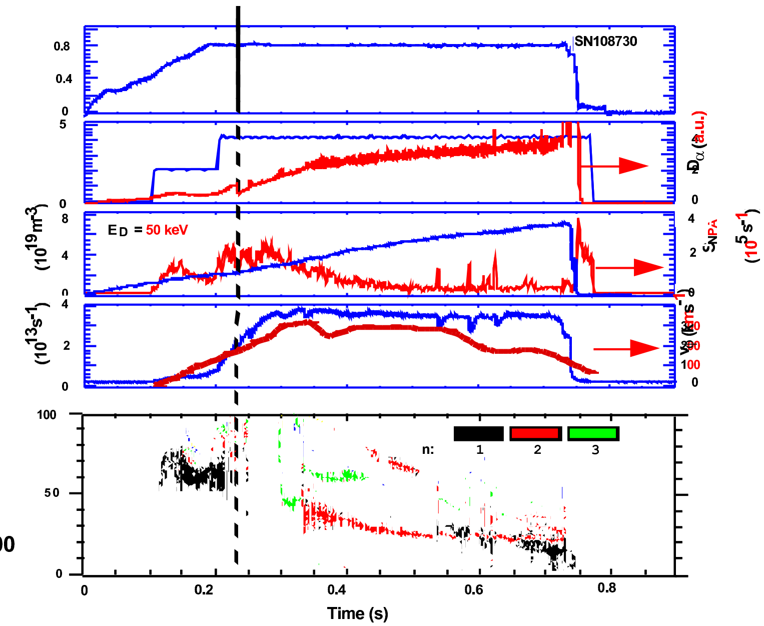
PRINCETON PLASMA PHYSICS LABORATORY

NPA measures beam ion signal depletion at $40 - 80 keV$





S.S.Medley et.al. NF'04 submitted

After H-mode transition $m = 4/n = 2$ mode is observed

Why NPA signal is depleted at those energies?

Motivation

NBI ion possible loss/redistribution raise question on

- first wall heat flux,
- heating efficiency.
- What about current drive?
  - ASDEX shows that at high P_{NBI} off-axis injected beam ions are flattened with the diffusivity of thermal plasma (Günter, EPS2004)

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- first wall heat flux,
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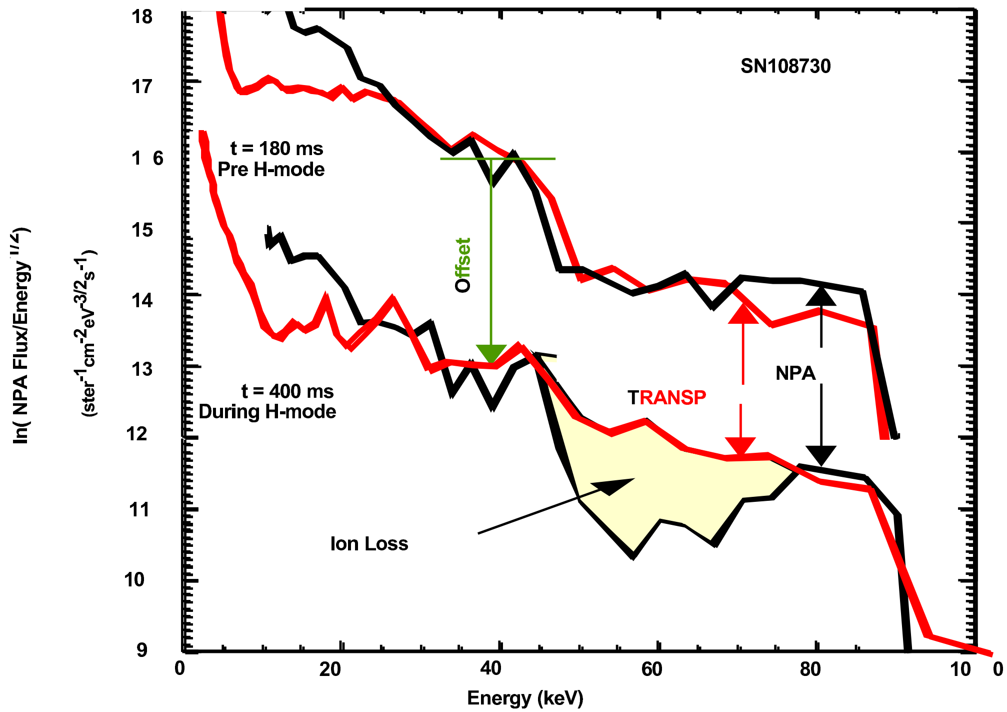
  - ASDEX shows that at high P_{NBI} off-axis injected beam ions are flattened with the diffusivity of thermal plasma (Günter, EPS2004)
  - Can ITER have steady state current drive? What can affect it?

TRANSP slowing down beam ion distribution vs NPA signal



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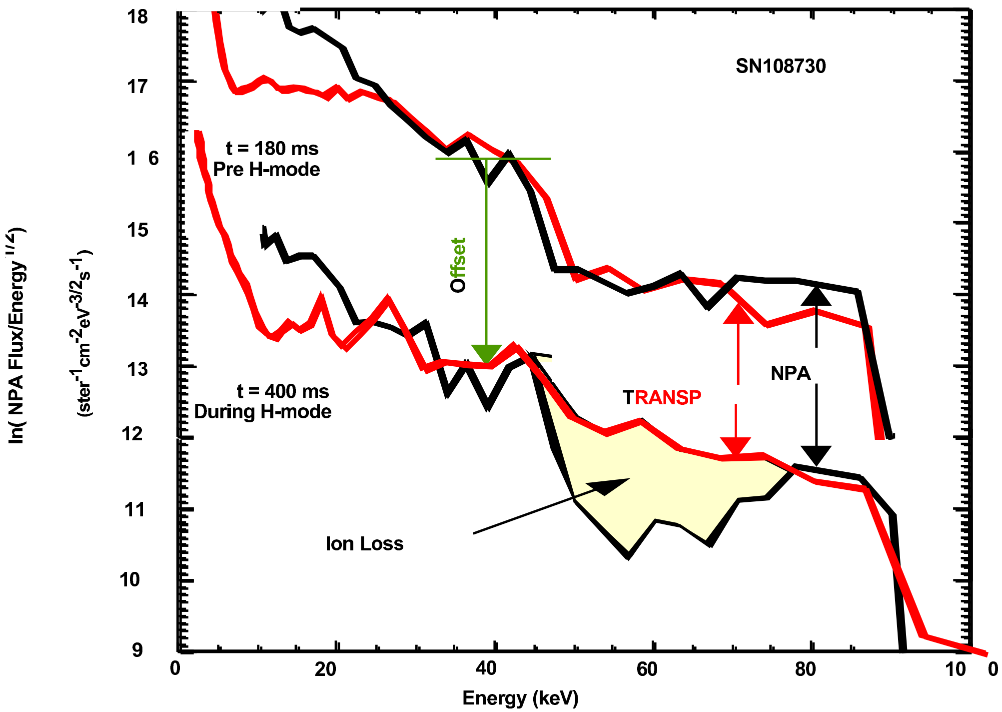


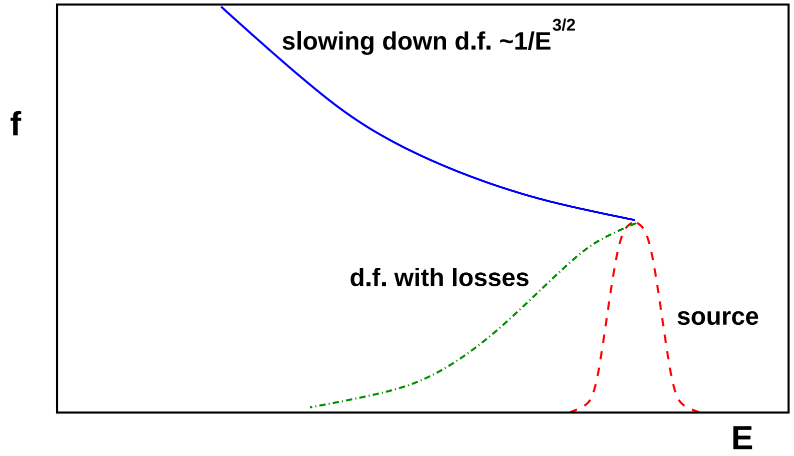
Why beam ions do not fill the gap and where do they go?

In this talk:

(1) what is the confinement time of beam ions

(2) can $m = 4/n = 2$ perturbation explain fast ion losses?

(I) Losses effect fast ion distribution function



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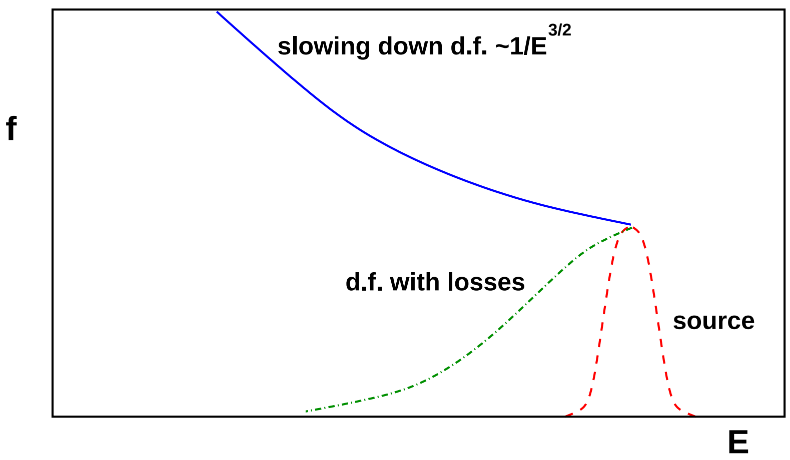

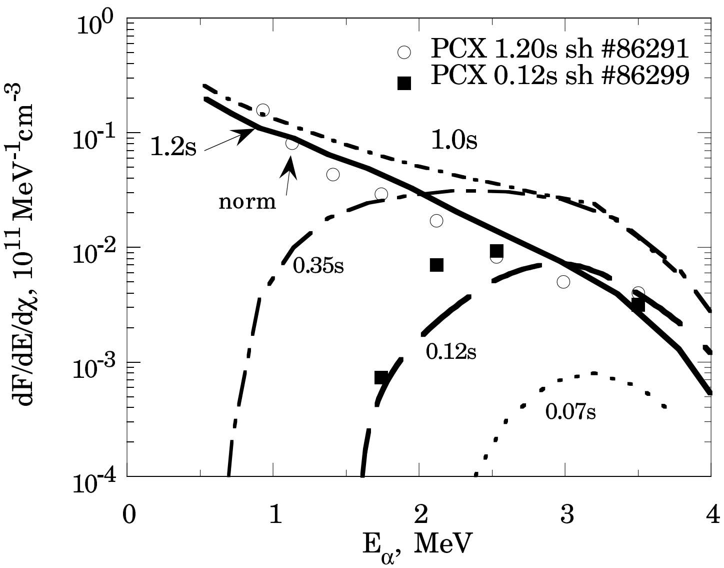

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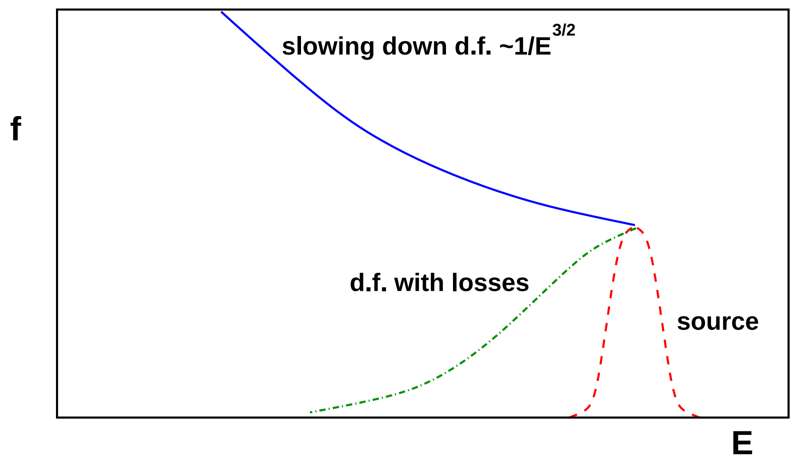

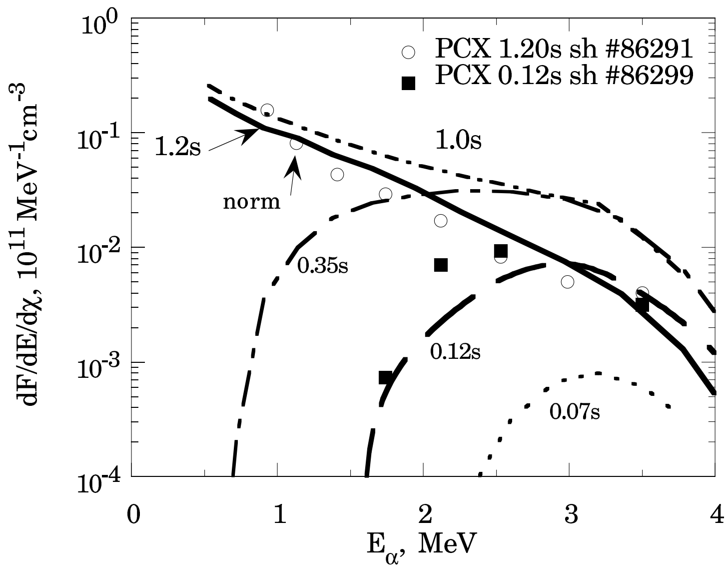

Kinetic equation in steady state (Cordey, Goldston, Mikkelsen, '81):

$$\frac{1}{\tau_{se} v^2} \frac{\partial}{\partial v} \left(v^3 + v_*^3\right) f - \frac{f}{\tau_{loss}} + S\delta\left(v - v_0\right) = 0 \tag{1}$$

Solution depends on the loss to drag time ratio

At finite τ_{loss} we obtain

$$f = \frac{Cn_b}{v^3 + v_*^3} \left(\frac{v^3 + v_*^3}{v_{b0}^3 + v_*^3} \right)^{\tau_{se}/3\tau_{loss}} \qquad (2)$$

and $f \sim 1/\left(v^3 + v_*^3\right)$ if $\tau_{loss} \to \infty$.

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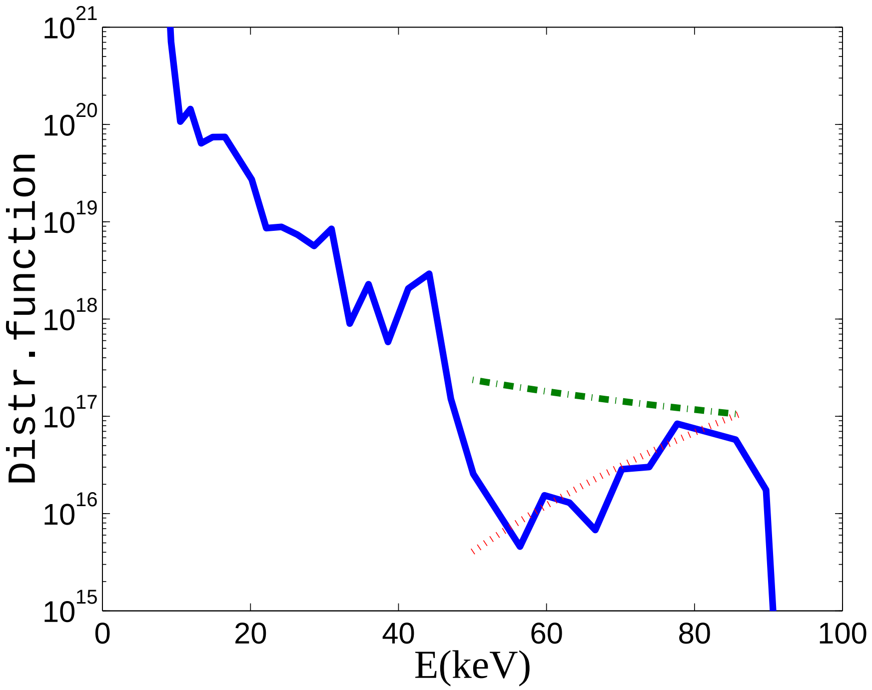

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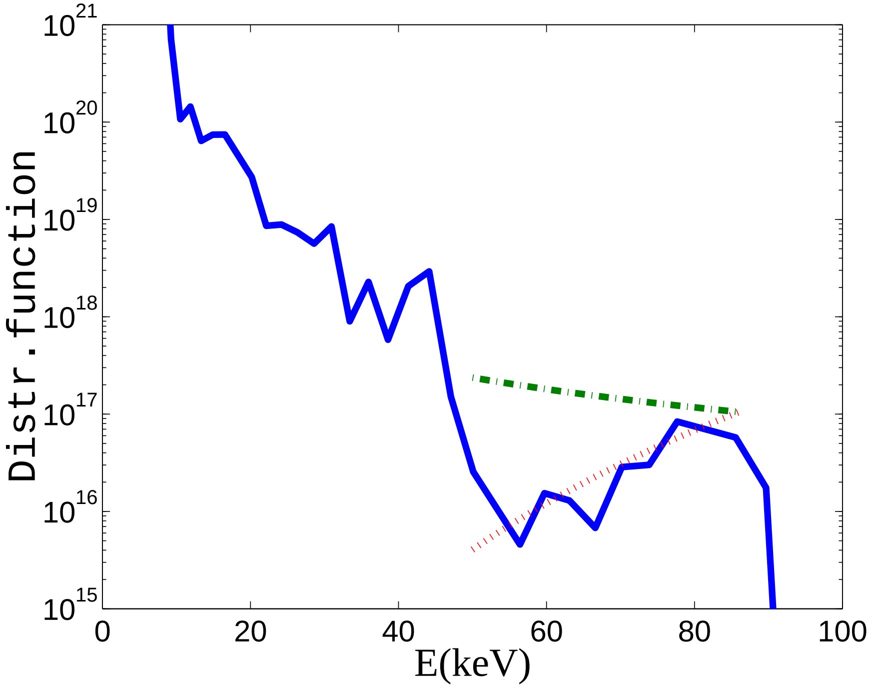

Implies that $\tau_{loss} = \tau_{se}/15$, i.e. $\tau_{loss} = 4msec$.

(II) What is the mechanism for “losses”/redistribution

Numerical study includes

1. plasma zero frequency $m = 4/n = 2$ perturbation,
2. amplitude on the order of $\delta B/B \sim 10^{-4}$,
3. strong toroidal sheared rotation,
4. pitch angle for NPA sight line $\chi \equiv v_{||}/v = 1.5125 - 0.629 R_{cx}[m]$,
   $\chi = 0.9 \Rightarrow R_{cx} = 0.97m$,
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5. realistic equilibrium and ORBIT code

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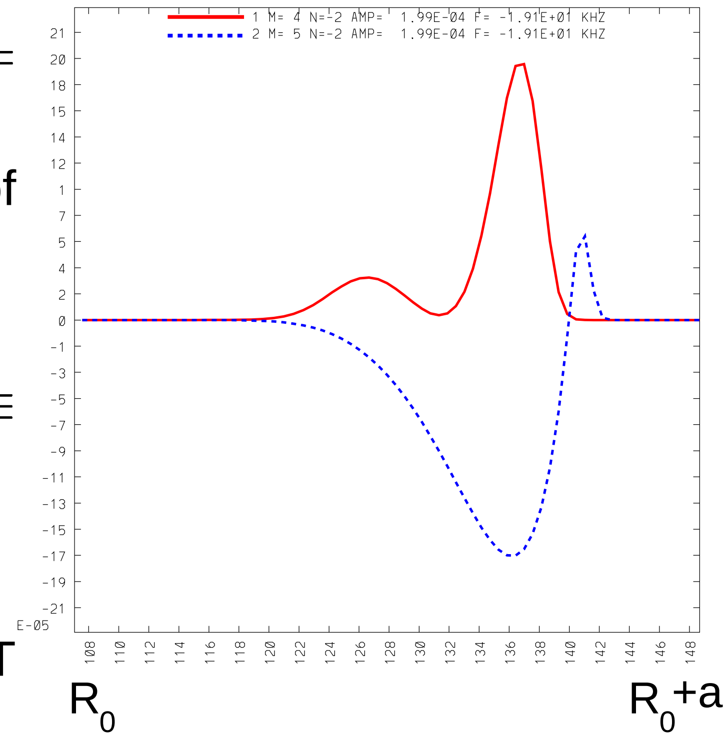


mode structure consistent with ideal MHD $\delta \mathbf{B} = \nabla \times \alpha \mathbf{B}$

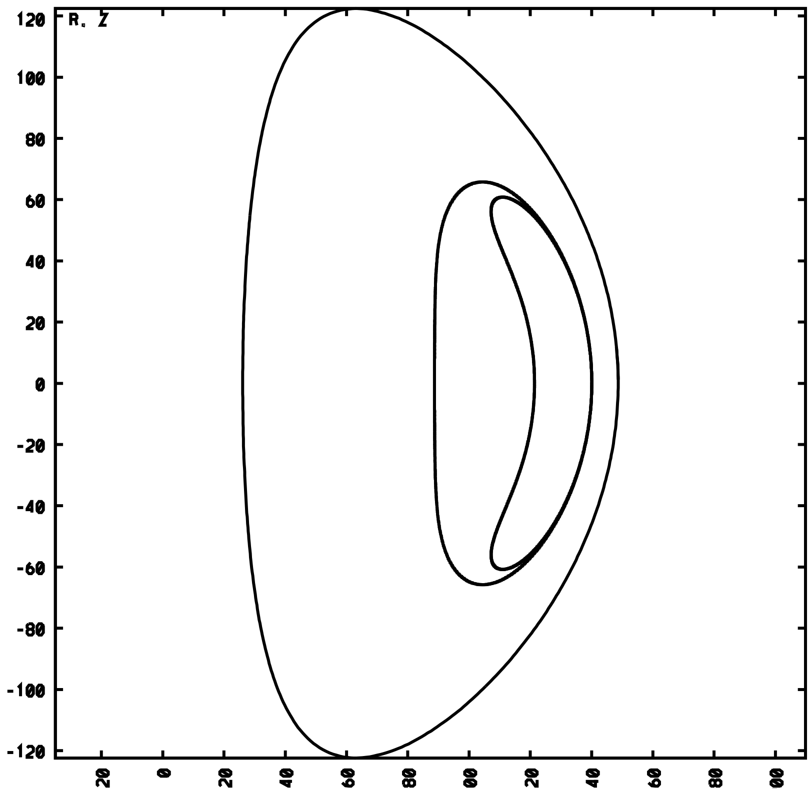
$$\alpha \sim (1 - nq/m)(r/r_s)^m \sin(n\varphi - m\theta), \text{ if } r < r_s$$

Beam ion orbits without perturbations

Example trapped ion orbit at $E = 70keV$ and $\chi = 0.55$.

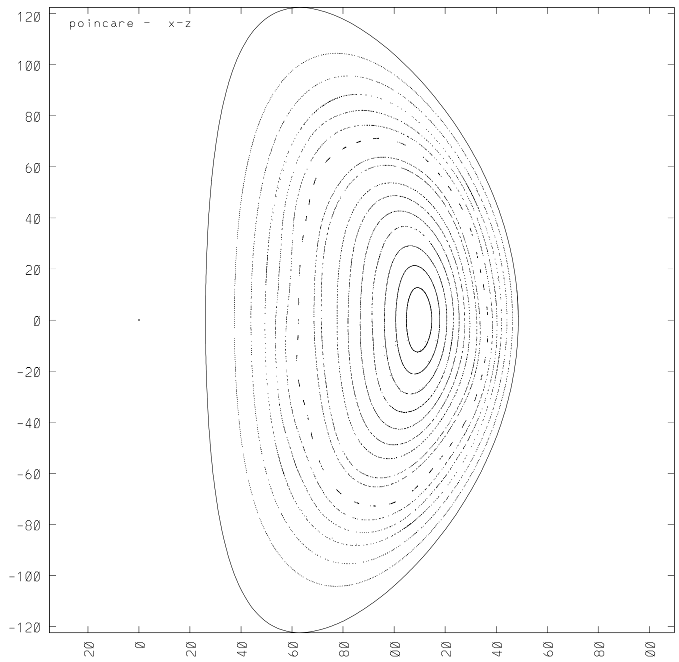
Electric field in NSTX - central potential $3.8keV$, central rotation $\dot{\varphi} = 8 \cdot 10^5 sec^{-1}$ -

1. changes particle orbits
2. effects precession frequency
3. shifts mode frequency



Islands in the real space (R-Z) with perturbations

w/out electric field



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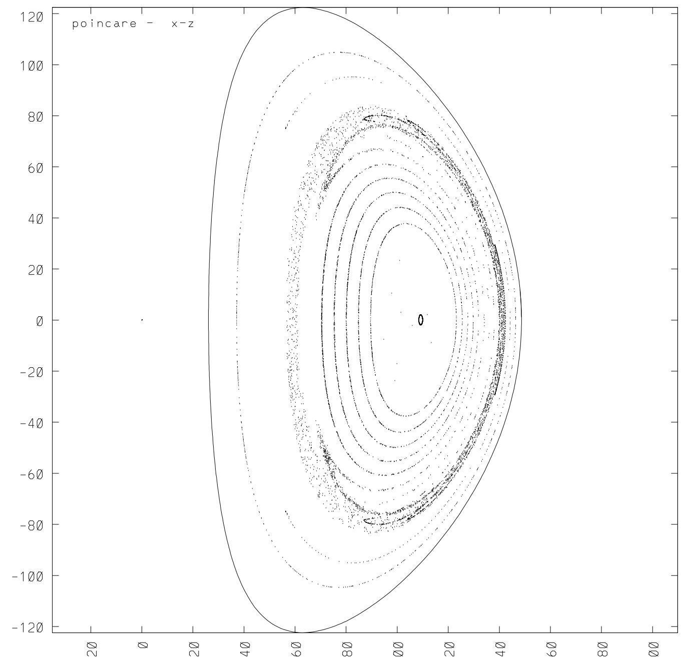
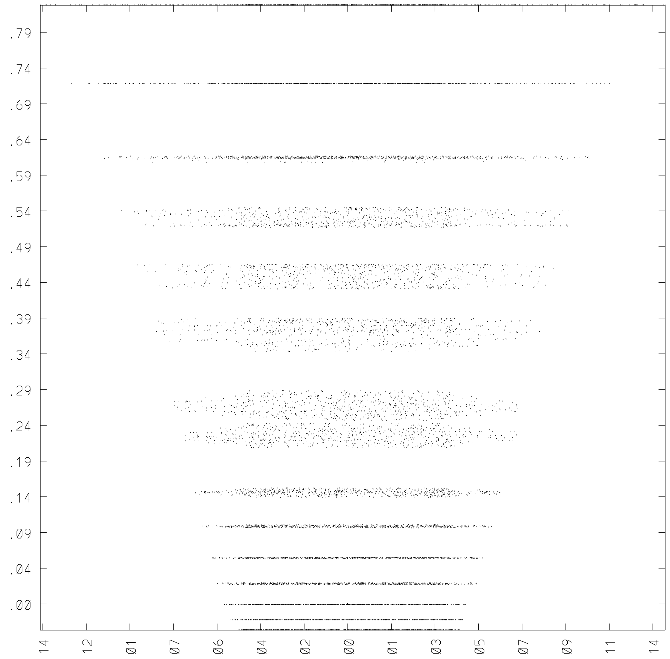


$E = 0.1keV$ and $\chi = 1$

Islands in $P_\varphi - (\omega - \varphi t)\ \left(\sim (r/a)^2 - (\omega - \varphi t)\right)$ *space*

w/out electric field



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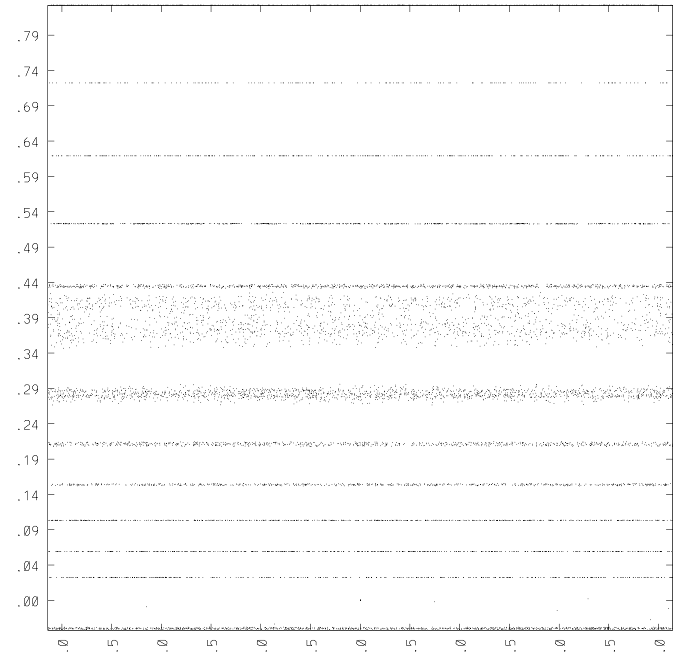

Wave-particle approximate resonance condition

$$\omega - \omega_{E\times B} - \left(k_{\|} + l/qR\right) v_{\|} = 0,\ l = \pm 1, 2, ... \qquad (3)$$

Frequency effect

- If $\omega = 0$ and there is no electric field, resonance is $k_{\|} + l/qR = 0$ - in real space
- If $\omega \neq 0$ and/or $\omega_{E\times B} \neq 0$ resonance involves phase space.

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Orbit width effect

1. In zero orbit width case, $l = \pm 1$ due to toroidal drift velocity $\cos\theta$-like modulation.
2. At large orbit width, only parts of particle orbit interact with the mode, $\Rightarrow |l| > 1$ appear.

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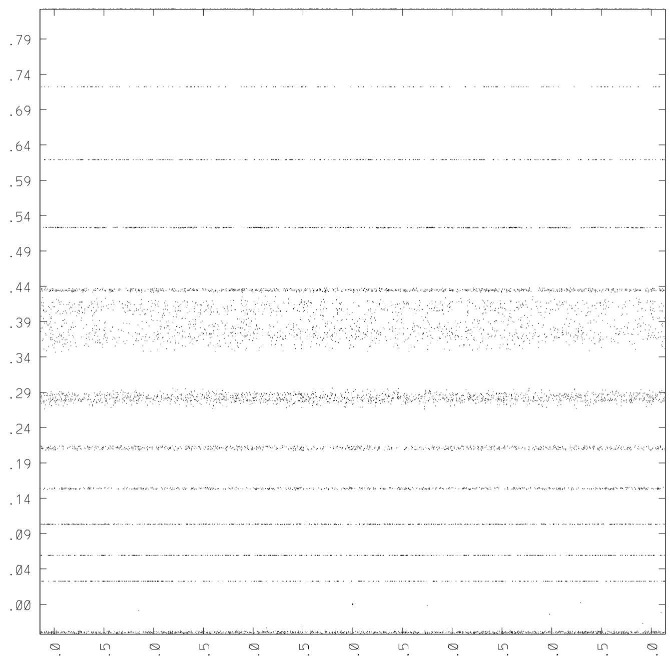
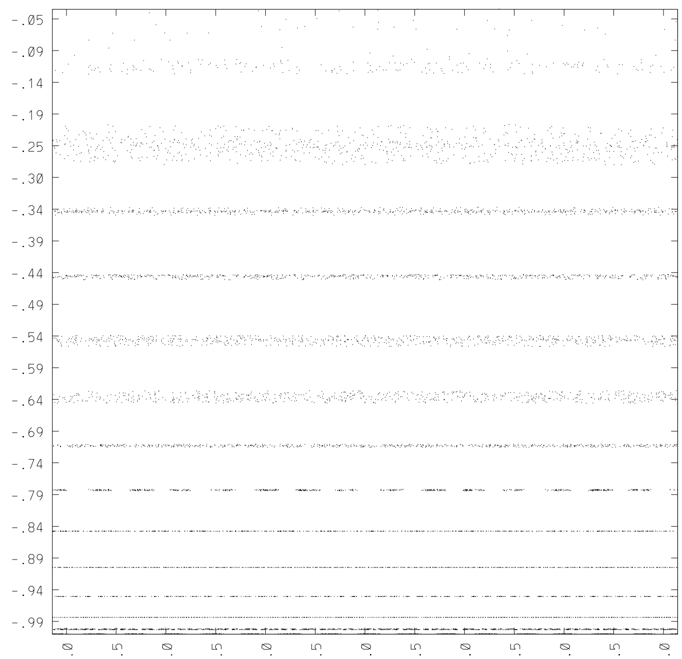
Since $|\omega - \omega_{E\times B}| \ll \left|v_{\parallel}\right| / qR$ the resonance is possible if $\left| k_{\parallel} qR + l \right| \ll 1$ at given magnetic surface.
Thus the resonance is selective (narrow in l) for low energies and broad for high energies.

Islands in $P_{\varphi} - (\omega - \varphi t)$ *for different energies*

$E = 0.1 keV$



$E = 70 keV$

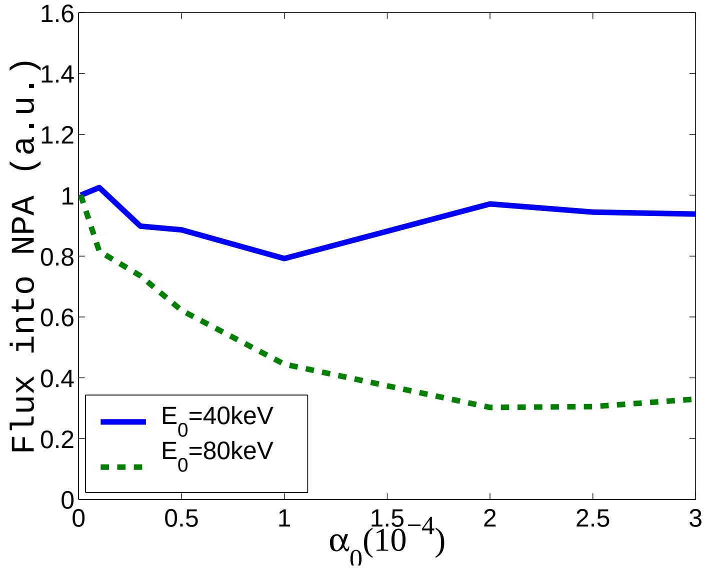


and $\chi = 1$, $\alpha_0 = 2 \times 10^{-4}$

Wide range of P_{φ} or r/a is affected.

Numerical results for injected ions at $E_0 = 40$ and $80 kev$

Allow for ion thermalization until $E = E_0/2$:



Fluxes vs.

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Particles are effected above $40 keV$.

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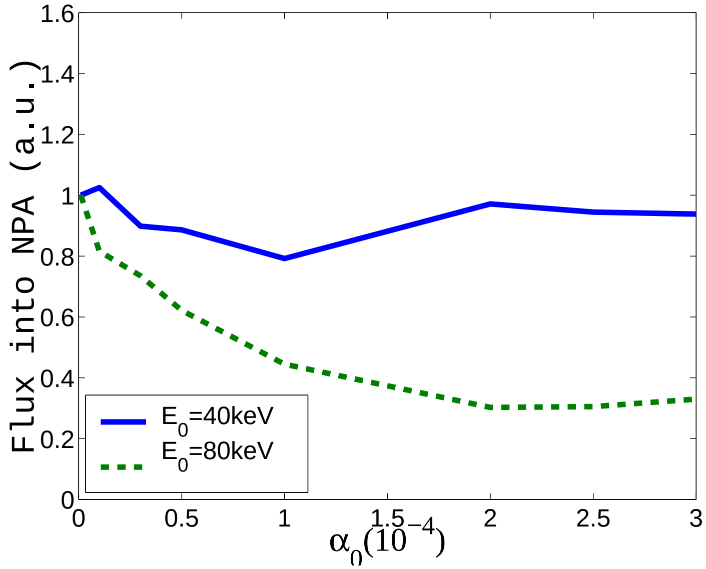
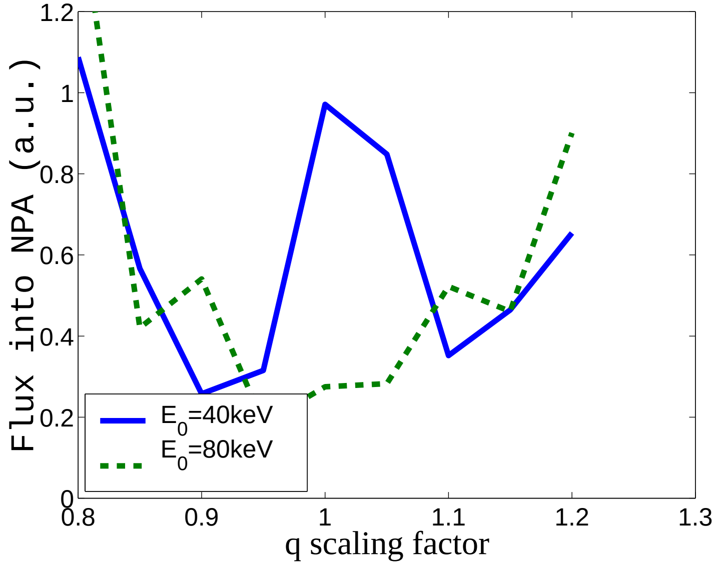




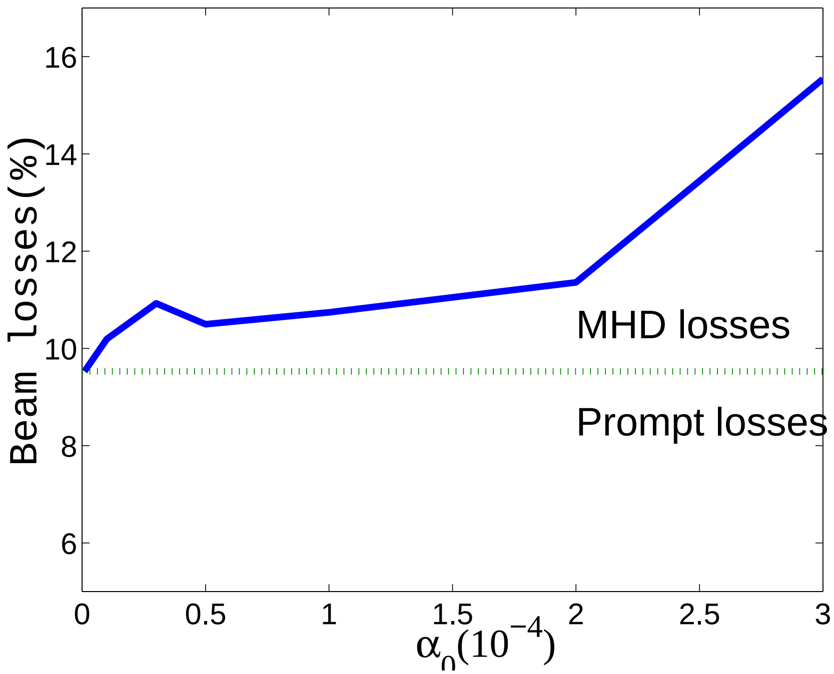
Fluxes vs. perturbation amplitude

Fluxes vs. q-factor $(q_{new} = q * (q - factor))$

Particles are effected above $40 keV$.

Shows sensitivity to resonant $k_{\parallel}$

Are there any losses due to MHD



At expected amplitudes $\alpha_0 = 2 - 3 \times 10^{-4}$ $(\delta B/B) \sim 10^{-3}$, $m = 4/n = 2$ mode can induce losses comparable to prompt losses.

Summary and conclusions

MHD activity observed in NSTX H-mode plasma is shown to be responsible for the NPA signal loss.

- Beam ion redistribution is energy selective affecting ions at $E = 50 - 80 keV$.
- Characteristic loss/redistribution time is $\tau_{loss} \simeq 4 msec$.