Neutral-Beam-Driven Instabilities and Their Impact on Beam Ions in a Reversed Field Pinch

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in collaboration with

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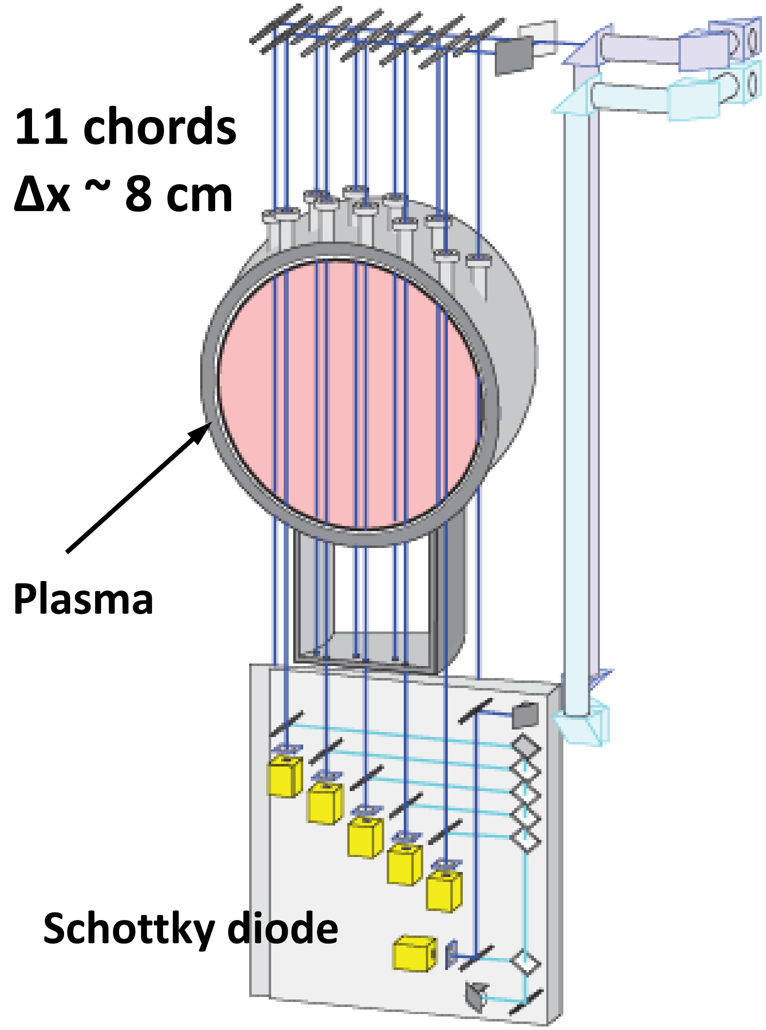
Outline

- NBI-driven modes in the reversed–field pinch:
  - spatial structure
  - fast ion-β dependence
  - three-wave coupling

- NBI reduction of innermost-resonant tearing mode

- Evidence for fast ion loss induced by NBI-driven modes

Multiple interferometry techniques diagnose equilbrium and fluctuation quantities.



phase noise ~ 0.01°

time response ~ 1 MHz

Standard interferometry:

$$\Phi_{\text{int}} \propto \int n_e dz \Rightarrow n_0, \tilde{n}$$

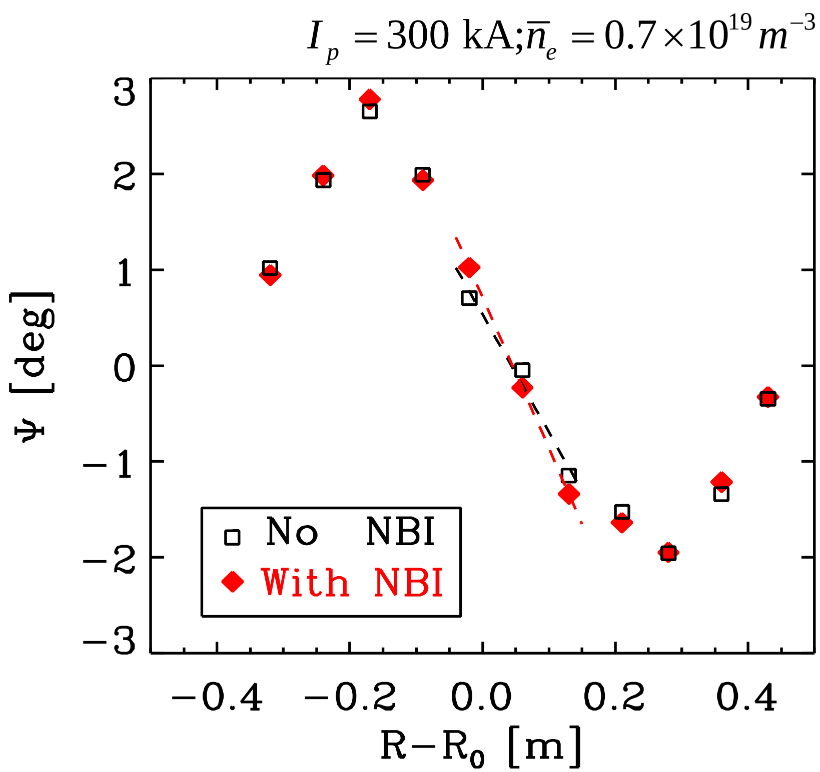
Polarimetry (Faraday Rotation):

$$\Psi_{\text{pol}} \propto \int n_e B_z dz \Rightarrow J_\phi, B_\theta, \tilde{b}_r, \tilde{b}_\theta, \tilde{j}_\phi$$

External magnetic coils:

$$\tilde{b}_\phi, \tilde{b}_\theta$$

Faraday rotation slope change suggests NBI current drive.



$$\Psi_{\mathrm{pol}} = c_F \int n_e B_z dz$$

$$\Rightarrow J_0 = \frac{2}{\mu_0 c_F} \left.\frac{\partial \Psi}{\partial x}\right|_{x\to 0} \frac{1}{\int n_e f(r,\alpha) dz}$$

where $x = R - R_0$ and $f(r,\alpha)$ is shaping factor for current density profile.

$$J_0 \propto \left.\frac{\partial \Psi}{\partial x}\right|_{x\to 0}$$

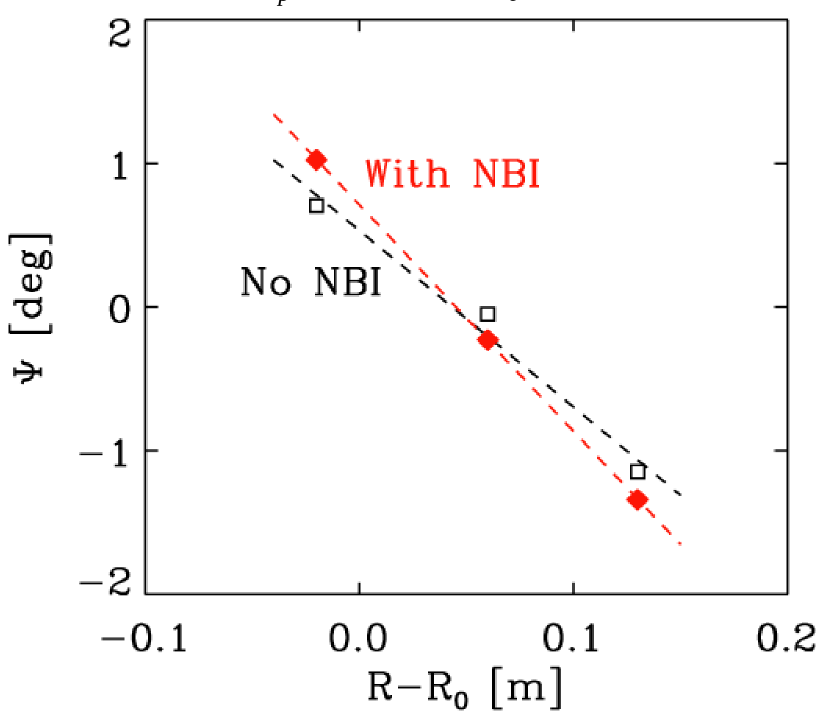
No NBI: $\left|\frac{\partial \Psi}{\partial x}\right| = 12 \pm 1 \quad \mathrm{deg/m}$

With NBI: $\left|\frac{\partial \Psi}{\partial x}\right| = 15 \pm 1 \quad \mathrm{deg/m}$

- **Faraday rotation measurement suggests that NBI increases central plasma current density by (25±10)%.**
- **TRANSP shows that central fast ion density is 25% of electron density.**

Faraday rotation slope change suggests NBI current drive.

$I_p = 300$ kA; $\bar{n}_e = 0.7\times10^{19}\, m^{-3}$



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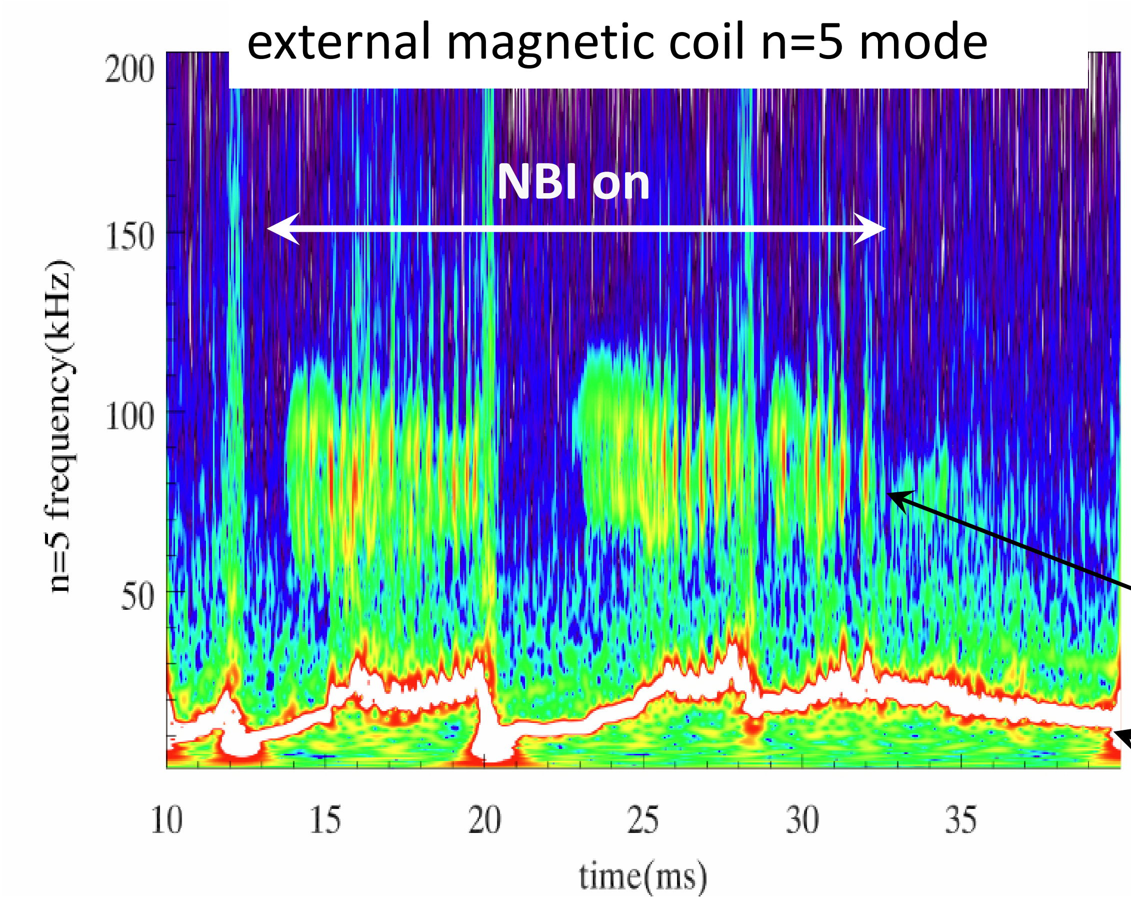
- **TRANSP shows that central fast ion density is 25% of electron density.**

Bursty modes are observed with NBI.



Ip = 300 kA

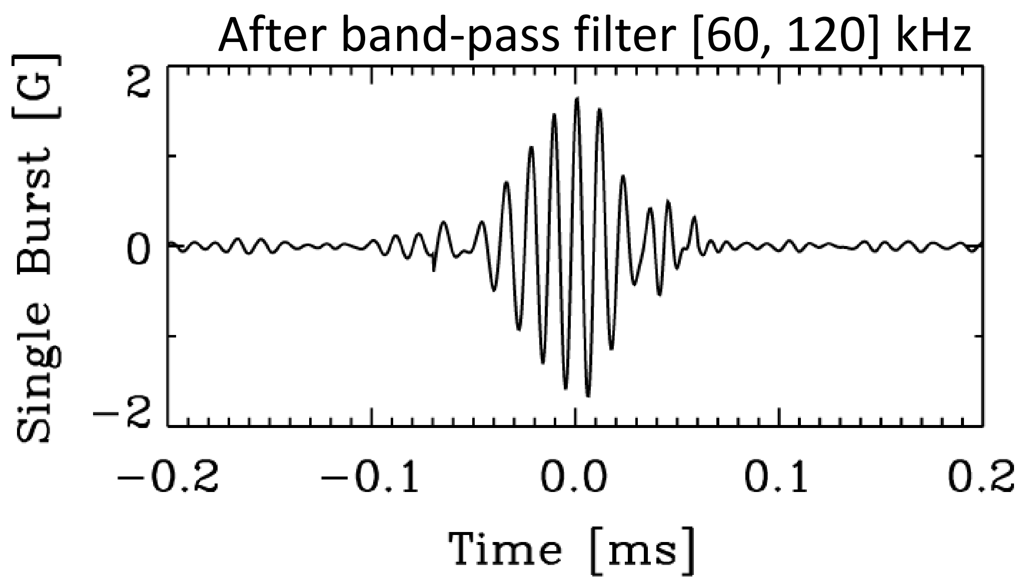
ne = $0.7 \times 10^{19} m^{-3}$

NBI induced mode

Global Tearing mode

- n=5 bursty NBI-driven modes
  - frequency scales inversely with density but weak dependence on |B|.
  - identity remains unresolved.

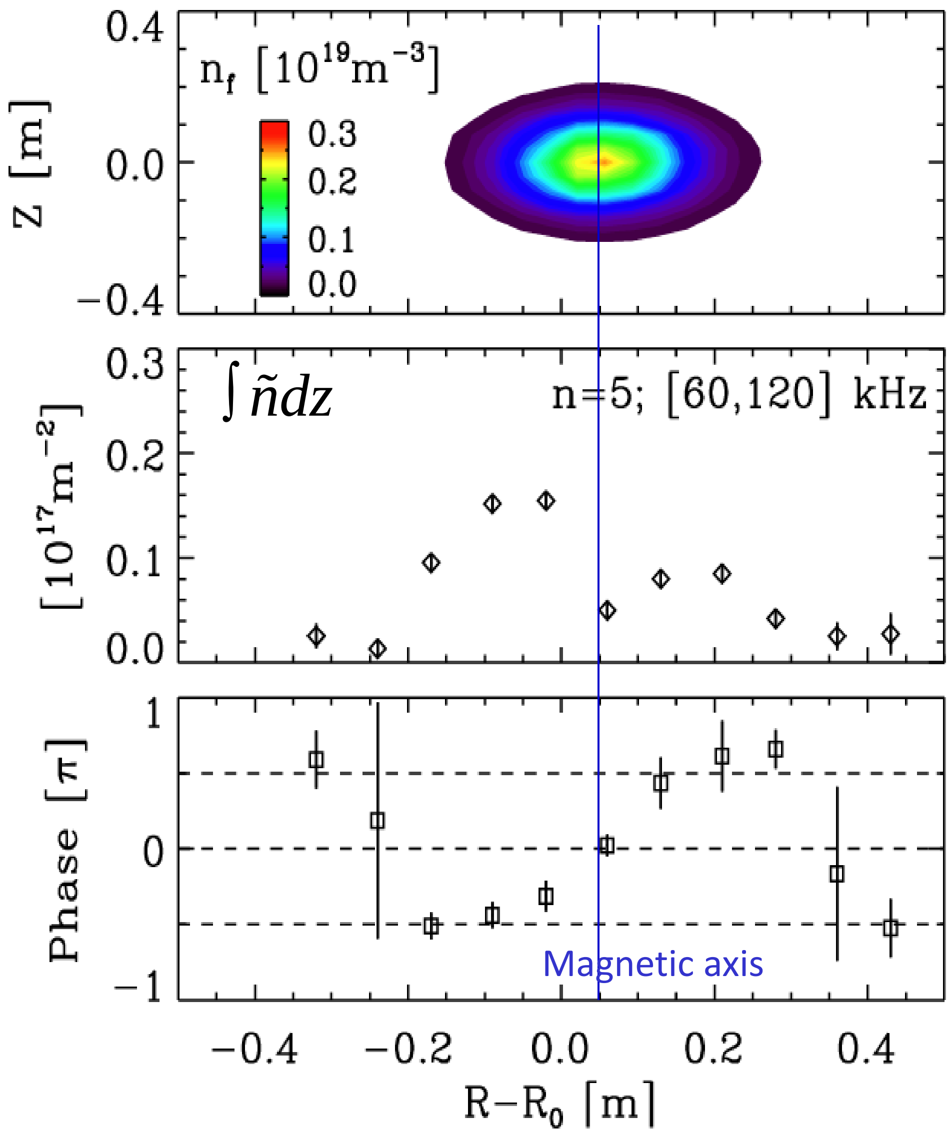
Single burst of NBI-driven mode



- Each burst has a duration ~0.06 ms (~160 Alfvèn times a/υ_A) and a fish-bone like structure.

- Ensemble analysis is performed over many bursts.

Density fluctuations associated with NBI-driven modes peak in the core where fast ions reside.



- TRANSP modeled fast ion density peaks in the core,

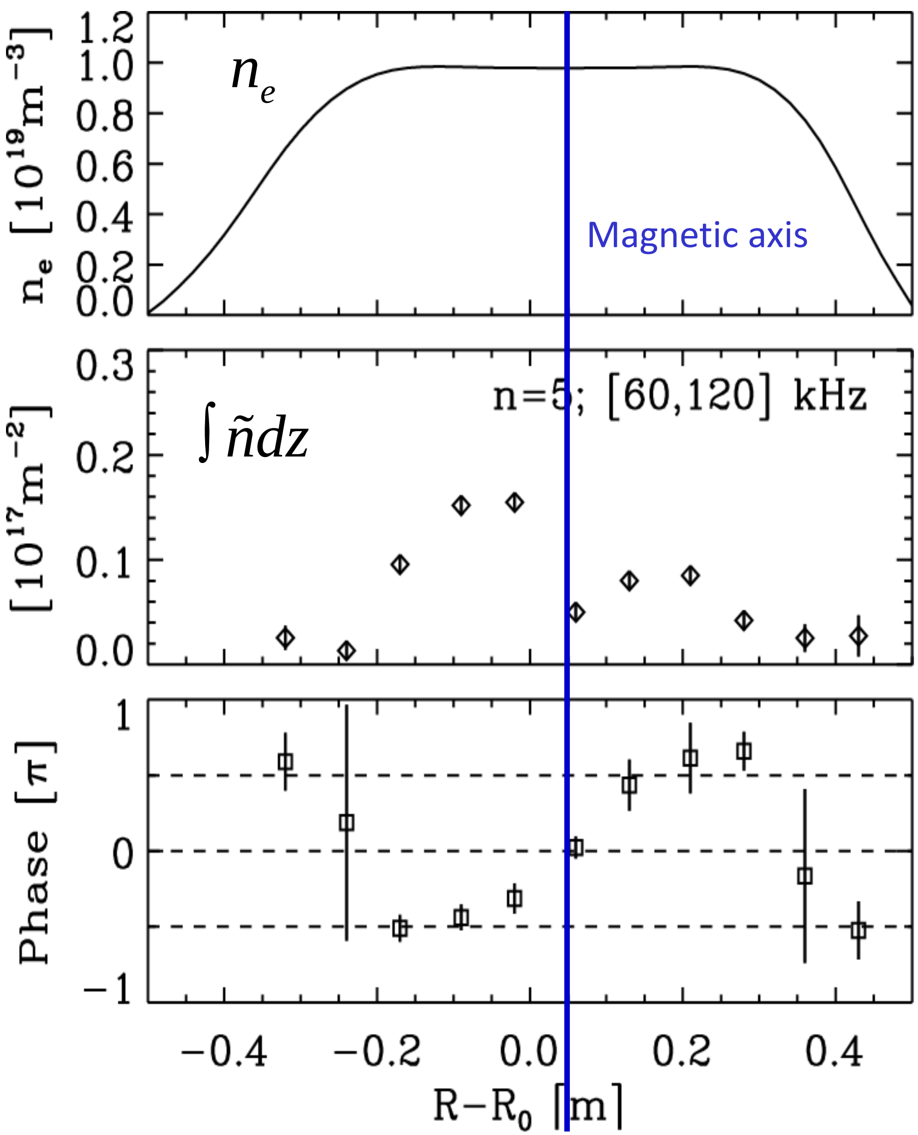
$$\frac{n_{f0}}{n_{e0}} \sim 25\%$$

- $\int \tilde{n} dz$ peaks for central chords with an inboard and outboard asymmetry

$$\frac{|\int \tilde{n} dz|_{peak}}{\int n dz} \sim 0.2\%$$

- π phase shift across the magnetic axis indicates an m=1 feature.

Density fluctuation peaks near the core where equilibrium density gradient is small.



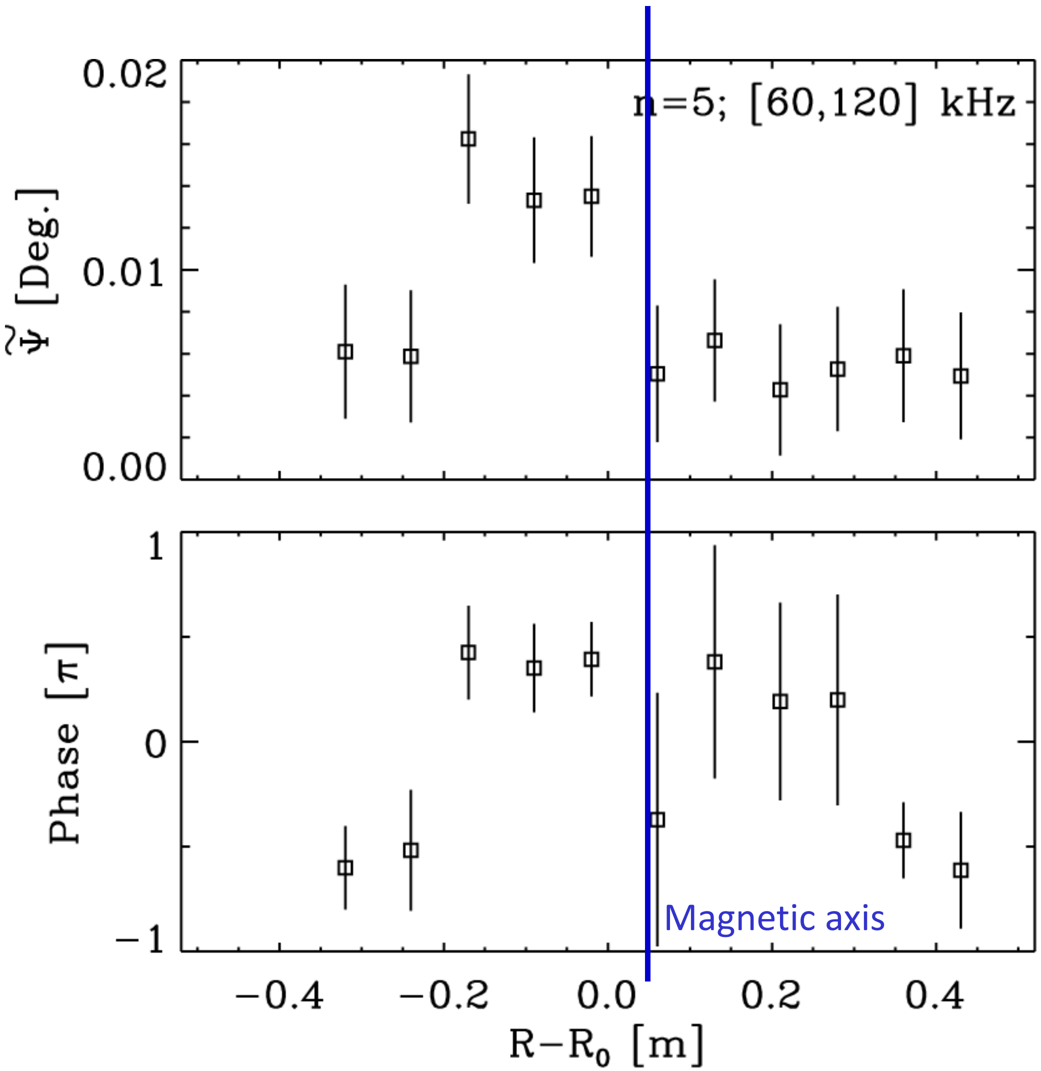
- From linear MHD, density fluctuation arises from density gradient (advection) or compression

$$\tilde{n}_e = -\left(\vec{\xi}\cdot\nabla\right)n_e - n_e\left(\nabla\cdot\vec{\xi}\right)$$

- $\int \tilde{n} dz$ peaks where ∇n_e is small,
  - compressional effect?
  - others?

- Phase shift across |R-R_0|~0.3 m, where ∇n_e is large.

Faraday-polarimetry fluctuations are measured and contain information on internal magnetic fluctuations.

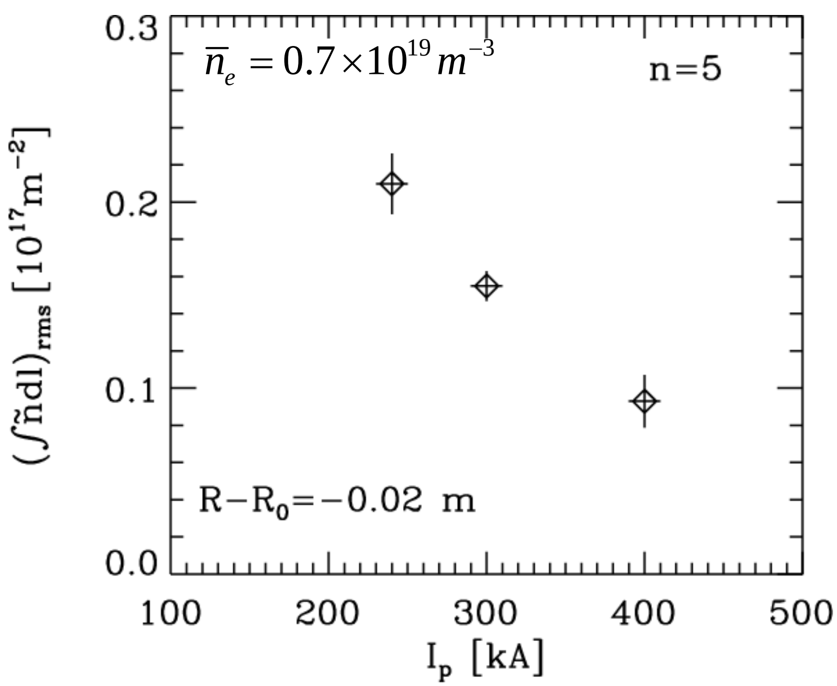


$$\tilde{\Psi}_{pol} = \int \tilde{n} B_z dz + \int n \tilde{b}_z dz$$

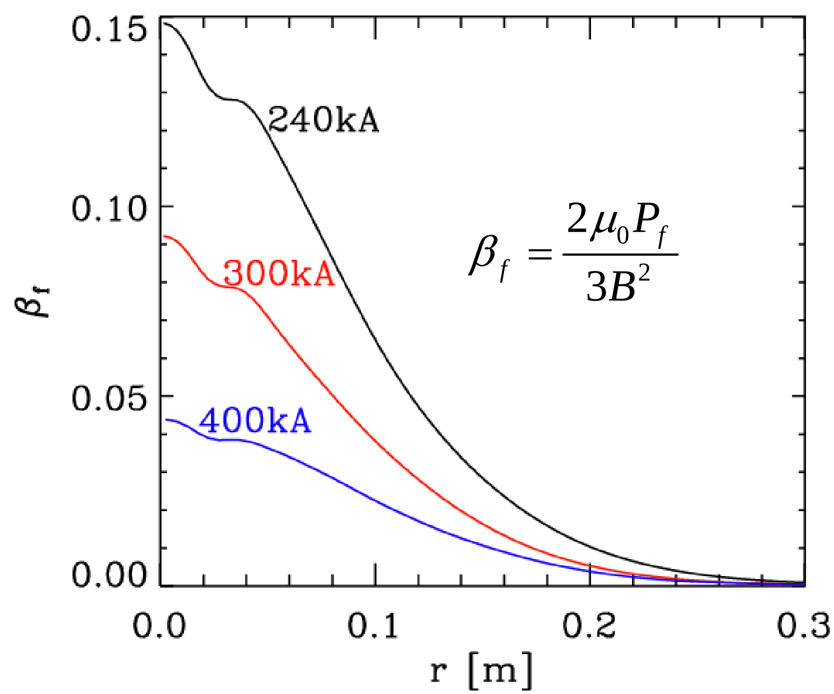
- Faraday fluctuations also peaks in the core with inboard/outboard asymmetry, similar to density fluctuations.

NBI mode decreases as plasma current increases, suggesting a β_f dependence.

density fluctuations



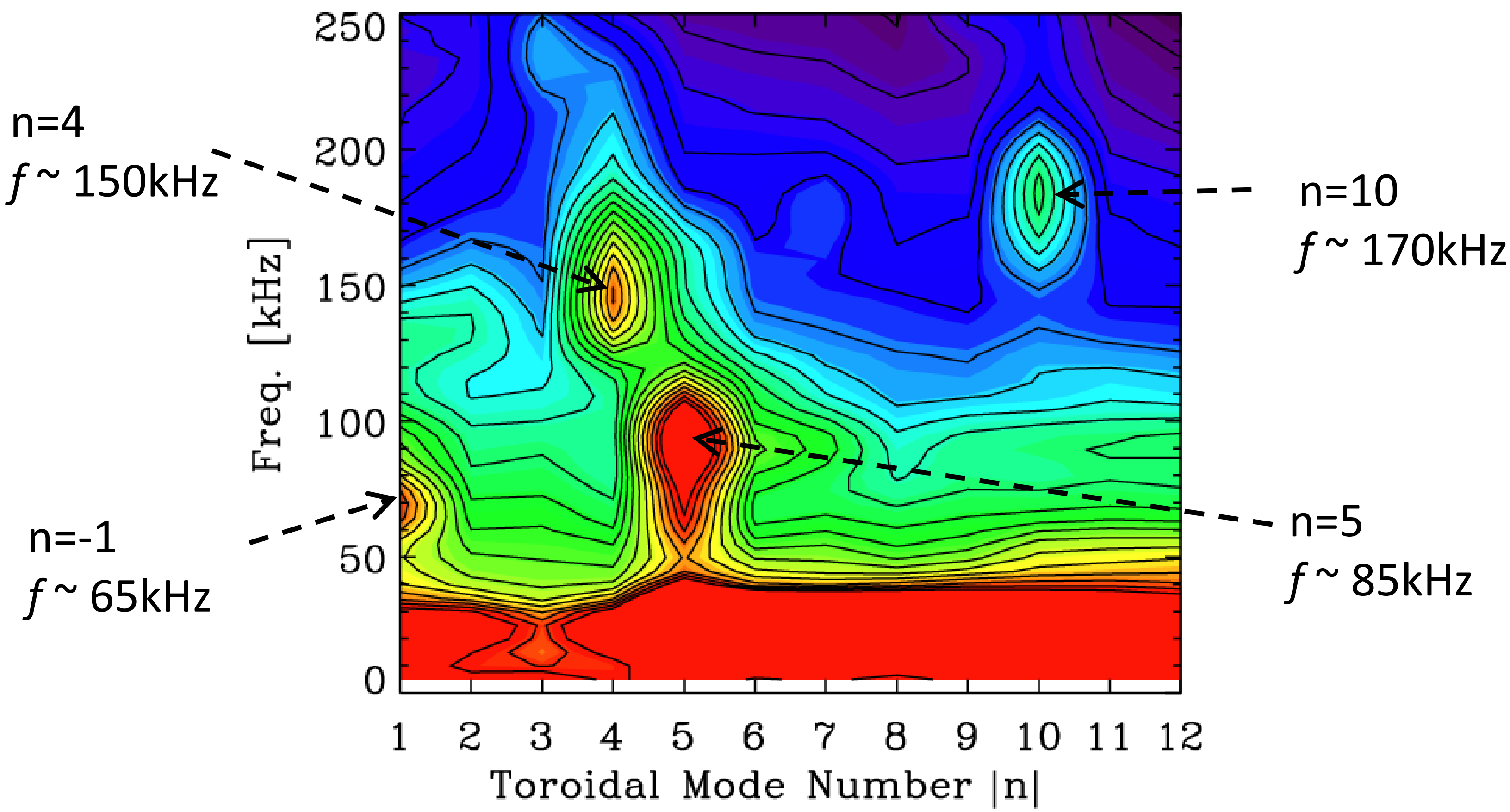
Fast-ion β profiles from TRANSP



Decrease of β_f is largely due to increase of B

- As plasma current increases, density fluctuations associated with NBI-driven modes decrease.
- **Increase of current leads to a reduction of β_f, thereby reducing free energy for driving instabilities.**

Multiple coherent NBI-driven modes are detected.

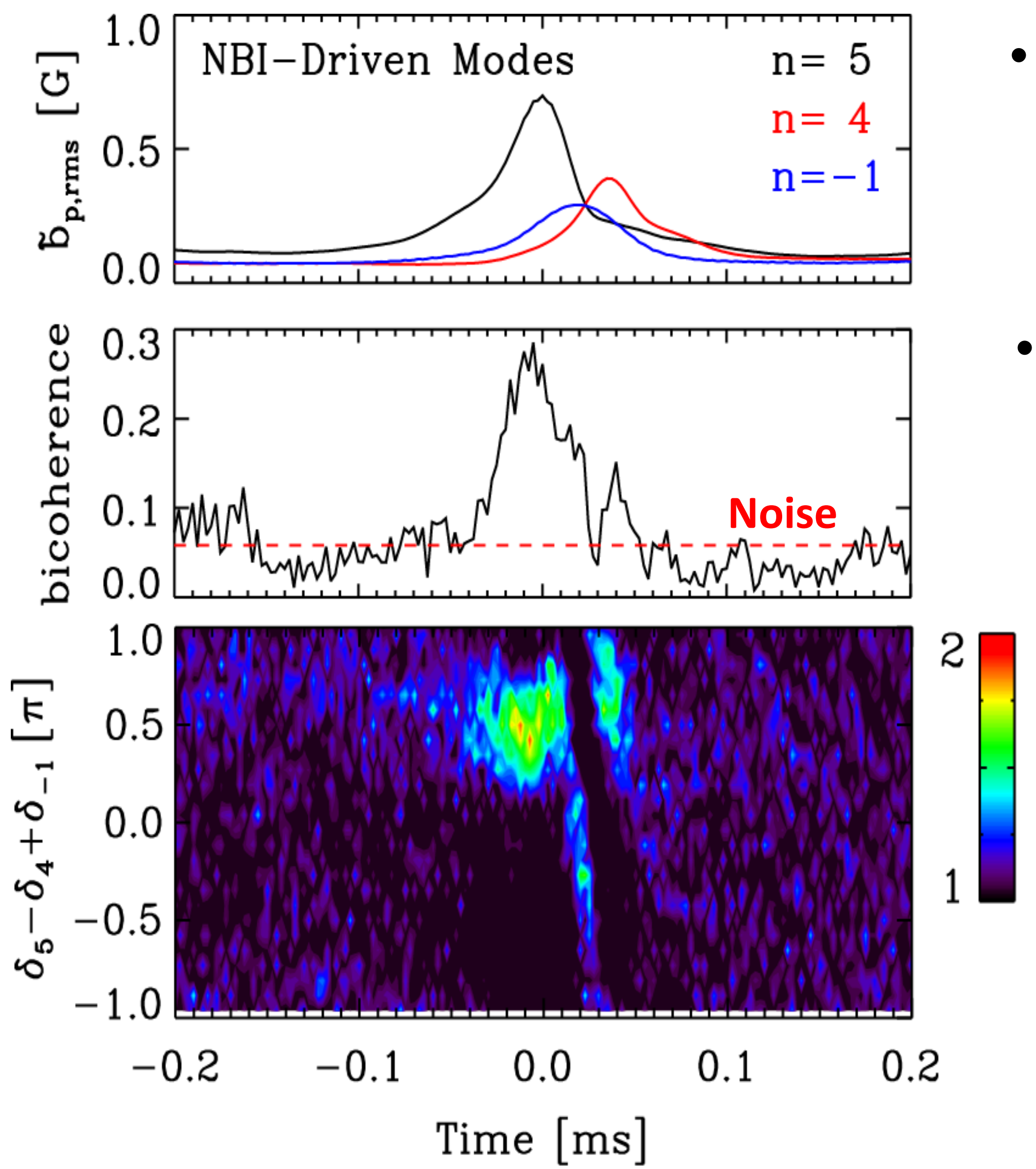


- **Toroidal mode numbers and frequencies satisfy three-wave matching condition:**

$$f_{n=5}(85\text{ kHz}) = f_{n=4}(150\text{ kHz}) - f_{n=-1}(65\text{ kHz})$$

$$f_{n=10}(170\text{ kHz}) = 2\times f_{n=5}(85\text{ kHz})$$

Three-wave coupling among multiple NBI-driven modes is observed.



- Stronger n=5 mode occurs prior to weaker n=4 and n=-1 modes.

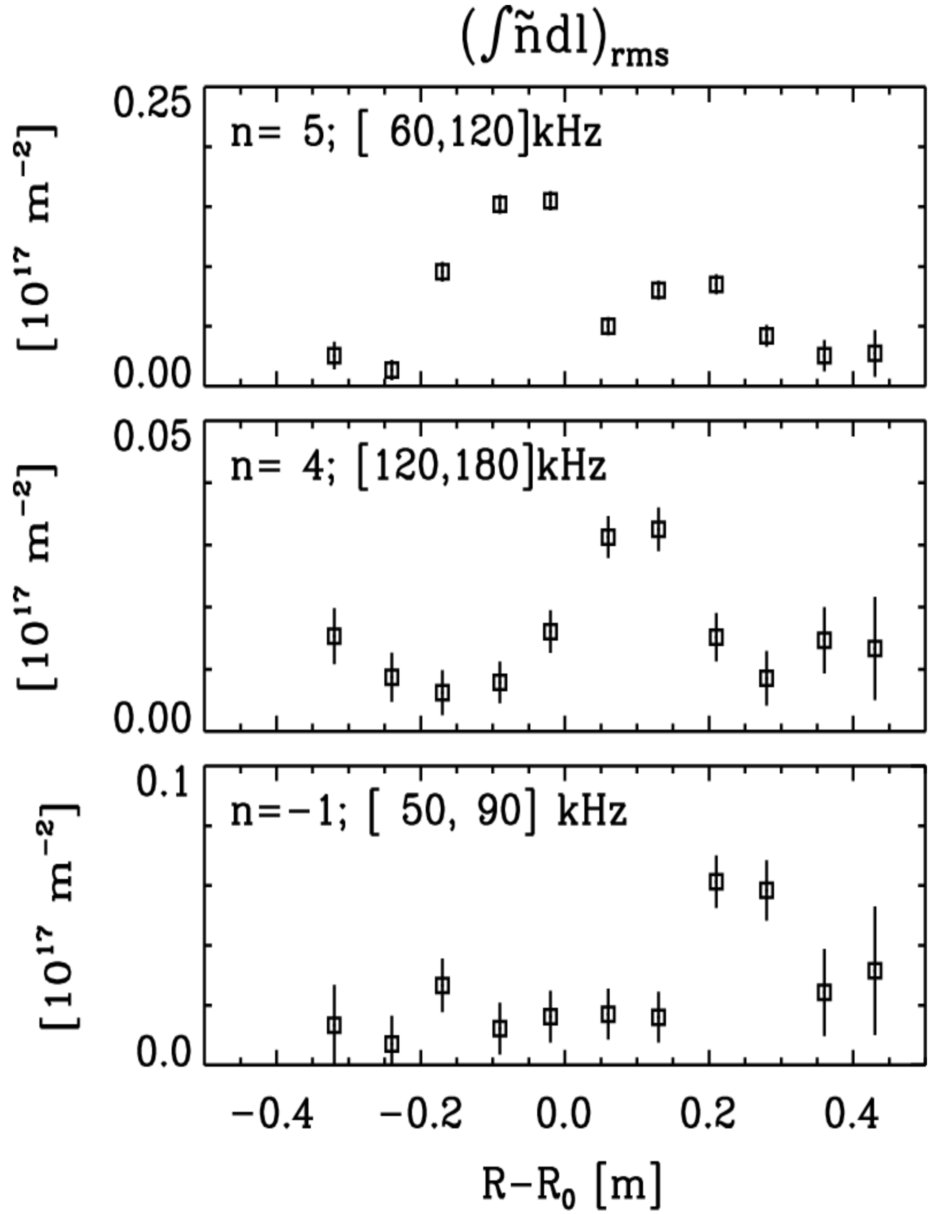
- Significant bicoherence:

$$\beta_{-1,4,5} = \sqrt{\frac{\left|\left\langle \tilde{b}_{n=-1}\tilde{b}_{n=4}\tilde{b}_{n=5}\right\rangle\right|^2}{\left\langle\left|\tilde{b}_{n=-1}\tilde{b}_{n=4}\right|^2\right\rangle\left\langle\left|\tilde{b}_{n=5}\right|^2\right\rangle}}$$

- Phase locking:

$$\delta_{n=5} - \delta_{n=4} + \delta_{n=-1}$$

Density fluctuation spatial structure changes with mode number.



- n=5 has largest density fluctuations while n=4 is weakest.

$$|\int \tilde{n} dz|_{peak} \,/\, \int n dz$$

n= 5	0.21%
n= 4	0.05%
n=-1	0.09%

- Both n=4 and n=5 modes are core-localized but with different structure.

- Both n=5 and n=-1 density fluctuations have large inboard and outboard asymmetry:
  - inboard dominates for n=5
  - outboard dominates for n=-1

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  - fast ion-β dependence
  - three-wave coupling
- **NBI reduction of innermost-resonant tearing mode**
- Evidence for fast ion loss induced by NBI-driven modes

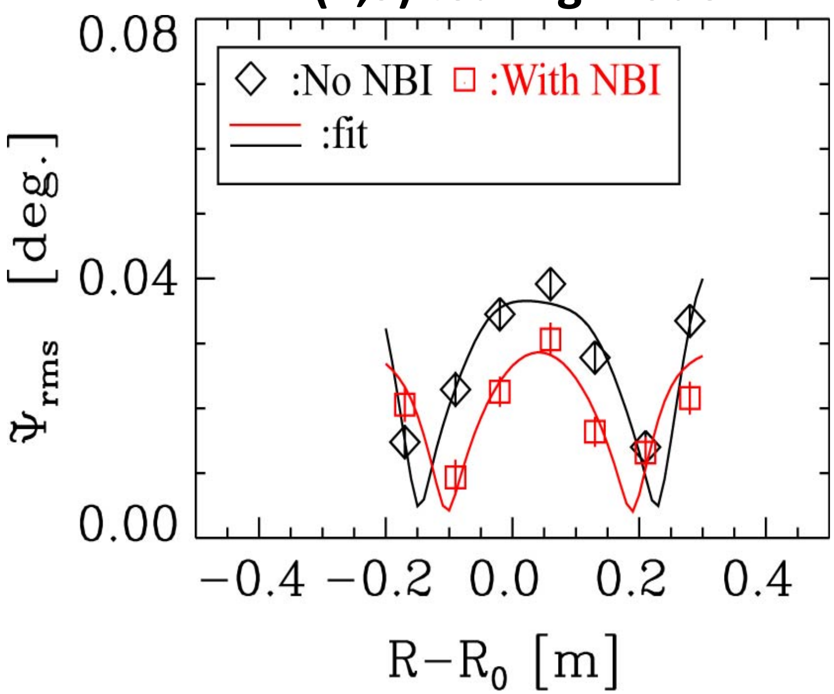
Local magnetic and current fluctuations can be obtained from polarimetry fluctuations.

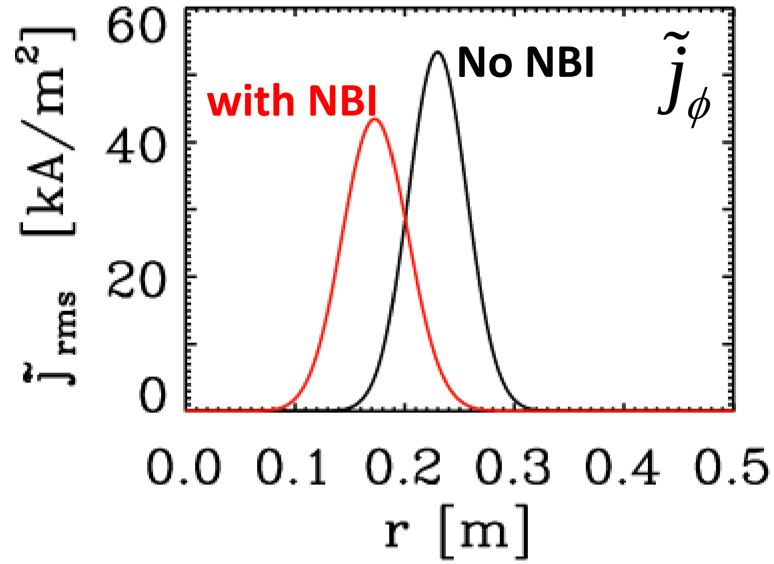
Polarimetry fluctuations

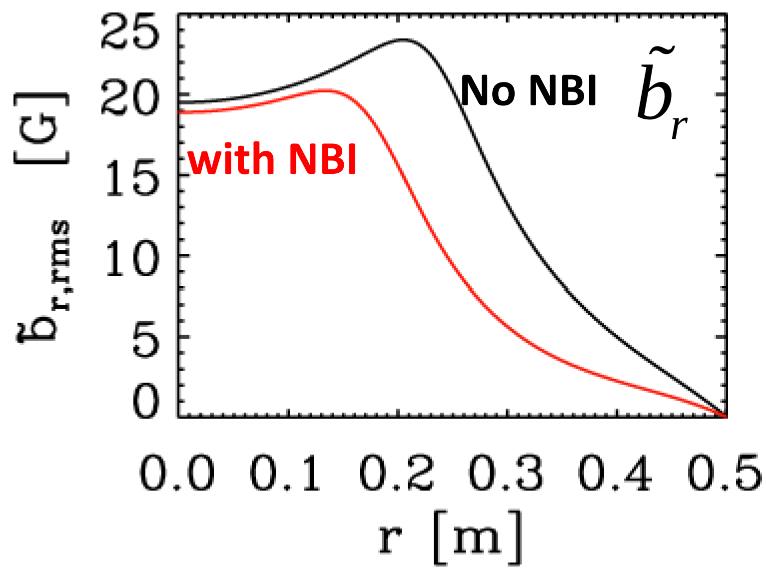
$$\tilde{\Psi}_{pol} = \int \tilde{n} B_z dz + \int n \tilde{b}_z dz$$

Parameterized fit ⇨

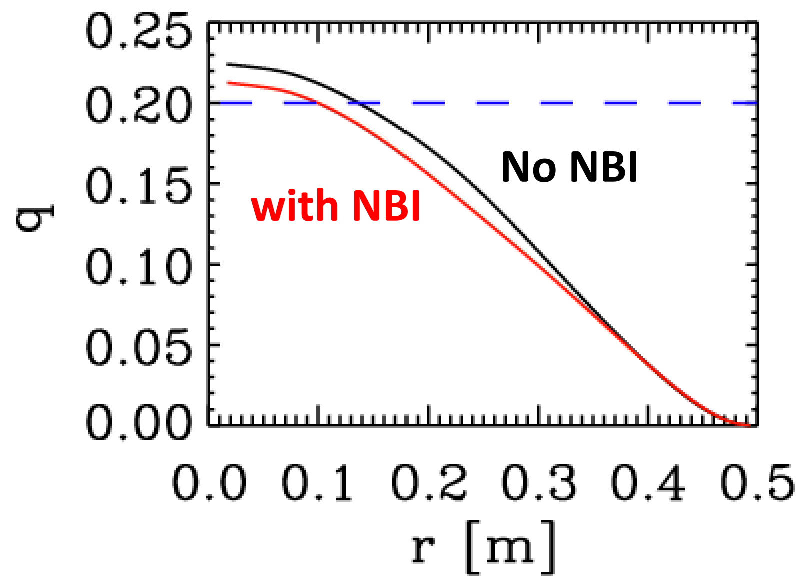
innermost core-resonant (1,5) tearing mode

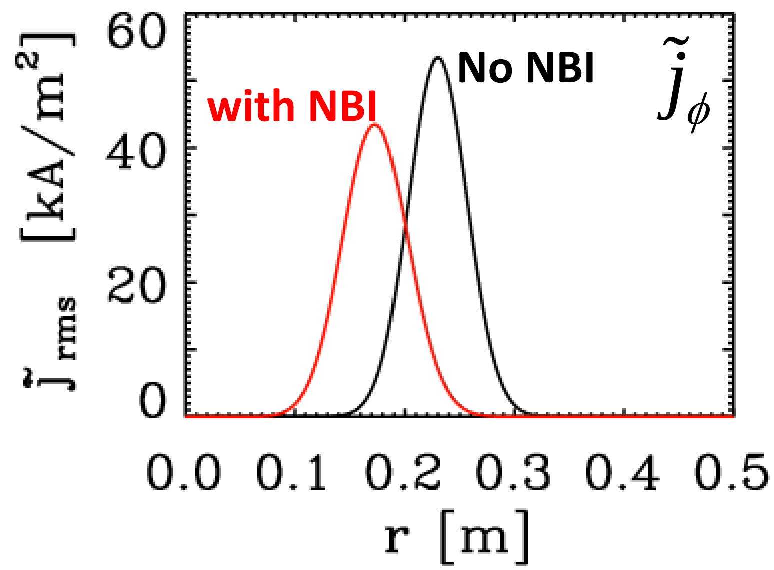


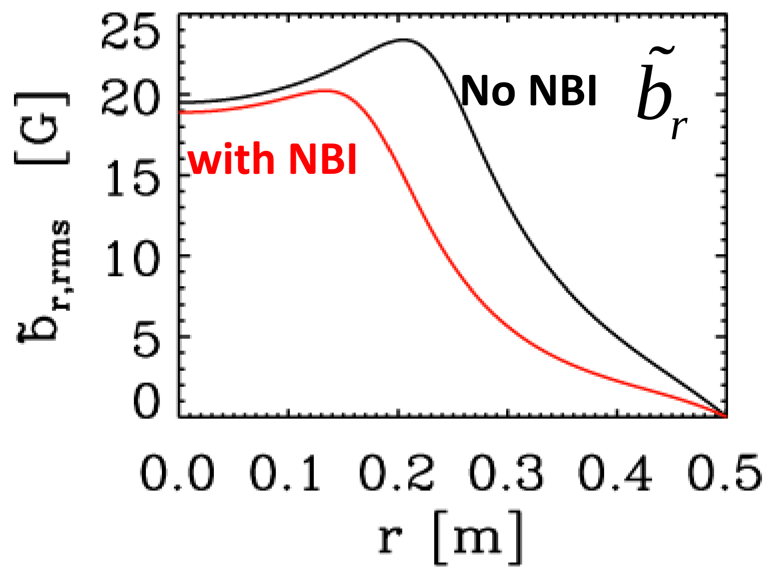




NBI leads to global reduction of innermost core-resonant (1,5) tearing mode.







- **NBI inwardly moves current sheet, consistent with q profile change.**

Outline

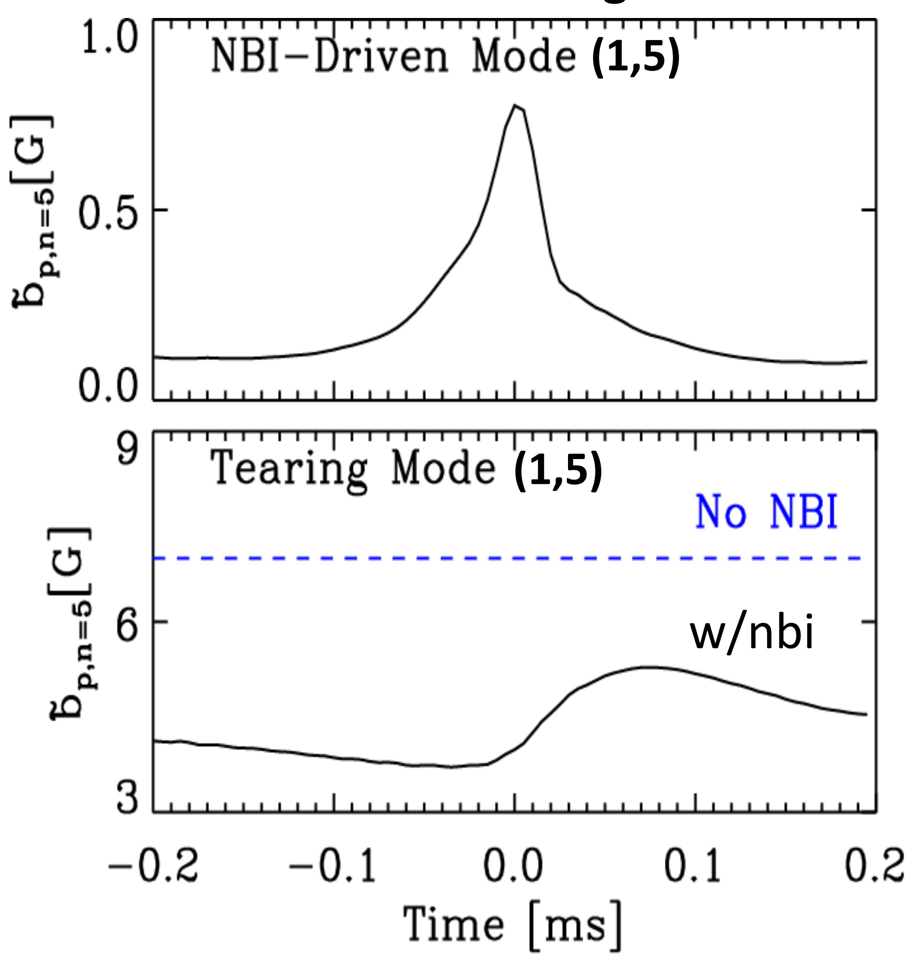
- NBI-driven modes in the reversed–field pinch:
  - spatial structure
  - fast ion-β dependence
  - three-wave coupling

- **NBI reduction of innermost-resonant tearing mode**
  Mechanism of mode stabilization not yet identified:
  (1) current profile change ;
  (2) FLR effect from fast ions at tearing mode layer; …….

- **Evidence for fast ion loss induced by NBI-driven modes**
  - from NBI reduction of tearing mode

Tearing mode suppression is reduced when NBI-driven mode peaks, suggesting loss/redistribution of beam ions.

External magnetic coils



- Suppression of (1,5) tearing mode is reduced when NBI-driven mode peaks

⇩

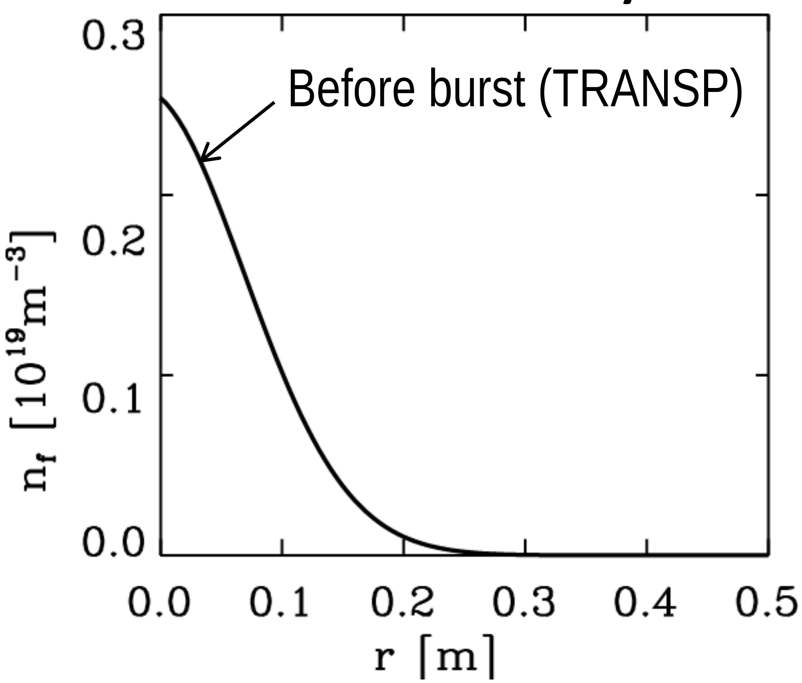
- Effect from beam ions on tearing mode is reduced

⇩

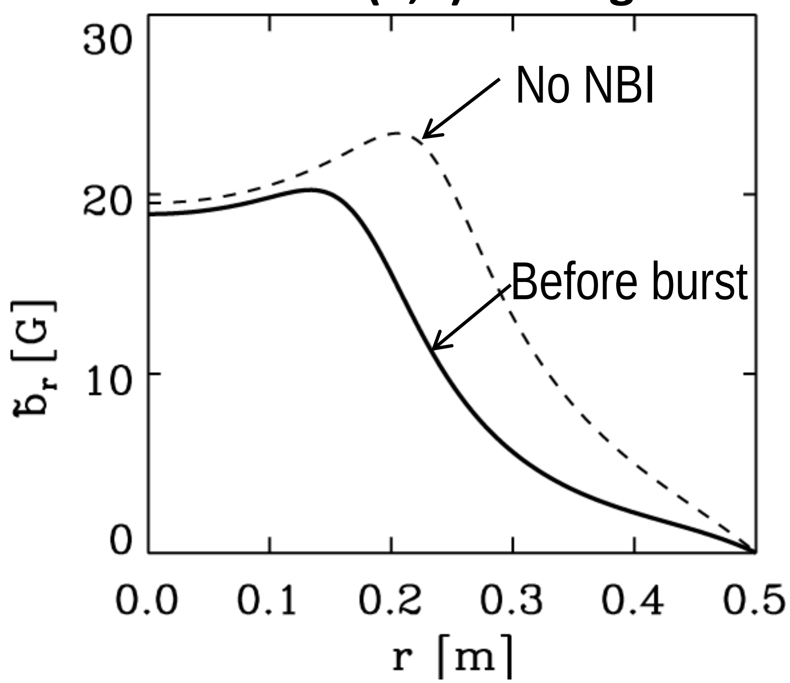
- Loss or redistribution of beam ions

Fast-ions from NBI reduces of innermost-resonant (1,5) tearing mode.

Fast-ion Density

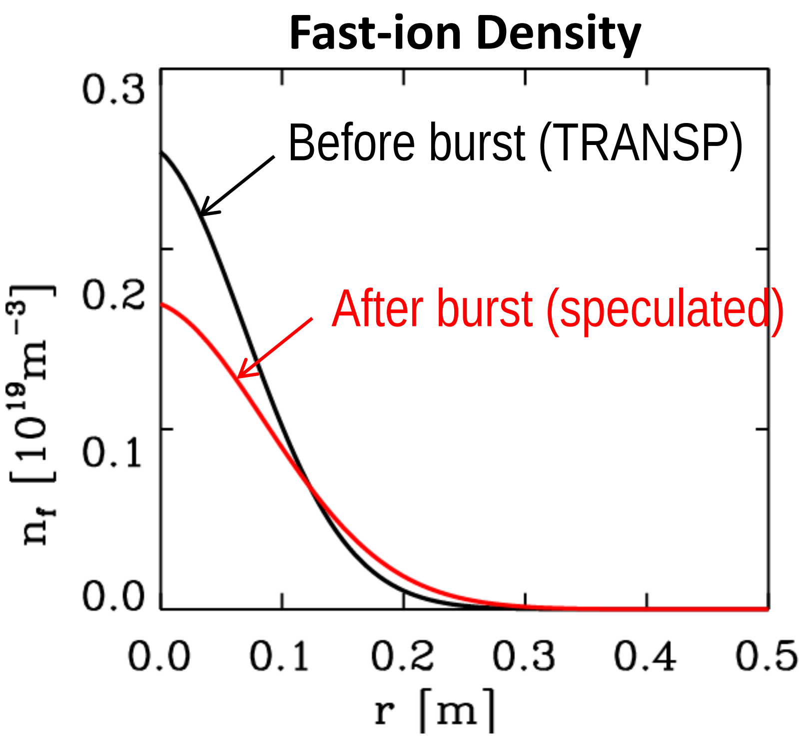


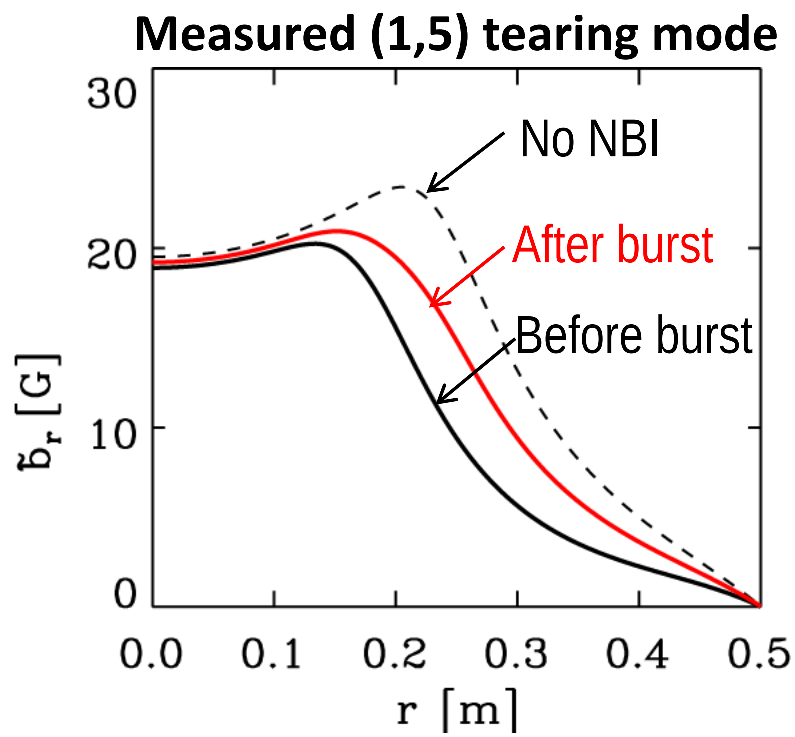
Measured (1,5) tearing mode



- NBI reduces amplitude of innermost-resonant tearing mode.

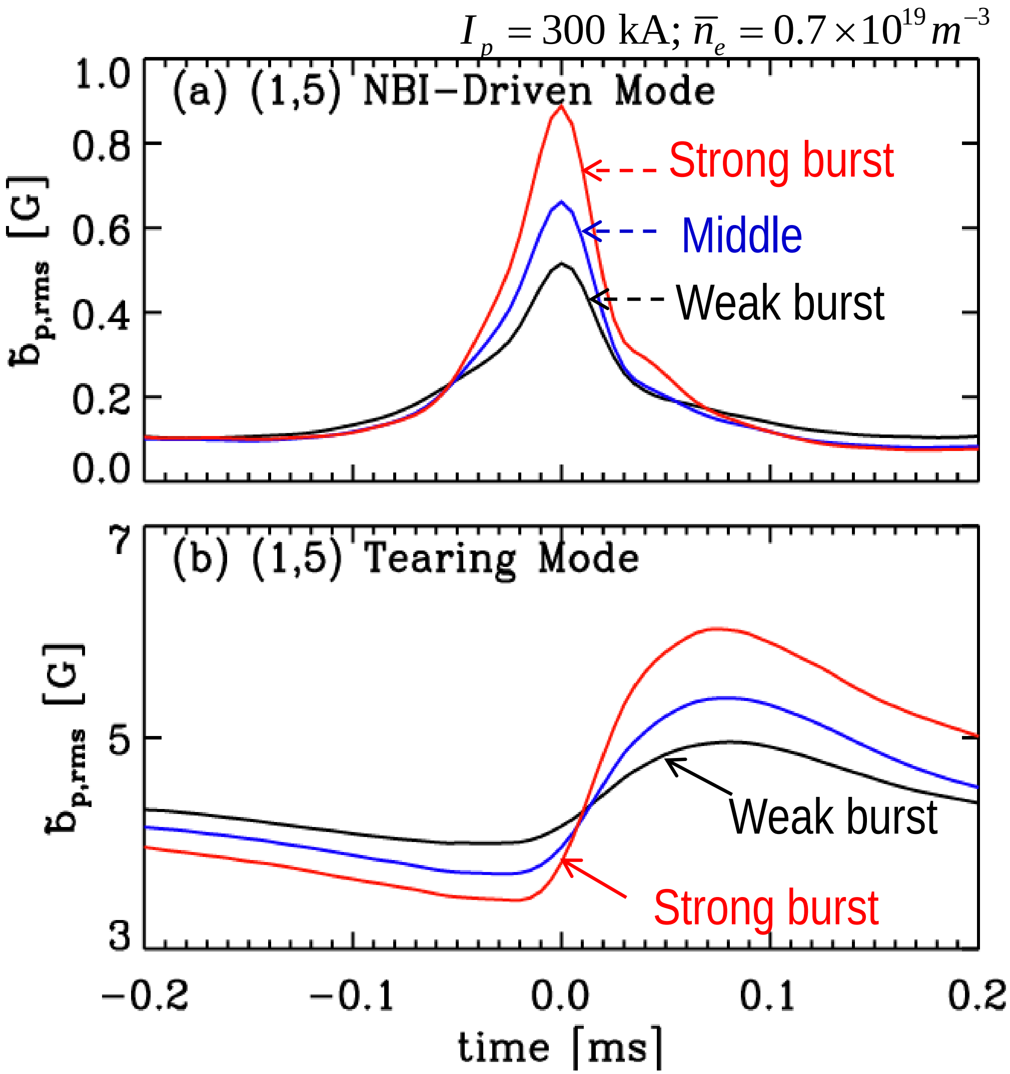
Increase of tearing mode after a NBI-driven burst indicates beam ion loss/redistribution.





- Increase of tearing mode after a burst shows the reduction of beam-ion effect, suggesting a loss or redistribution of beam ions.

Larger NBI-mode induces larger increase of tearing mode, suggesting a larger fast ion loss/redistribution.



- Group NBI-induced modes according to their strength before ensemble analysis.
- t<0, larger tearing mode suppression implies more fast ions, which induces larger NBI mode.
- t>0, larger NBI modes lead to larger fast ion loss, which induces large reduction of tearing mode suppression.

Outline

- NBI-driven modes in the reversed–field pinch:
  - spatial structure
  - **fast ion-β dependence**
  - three-wave coupling

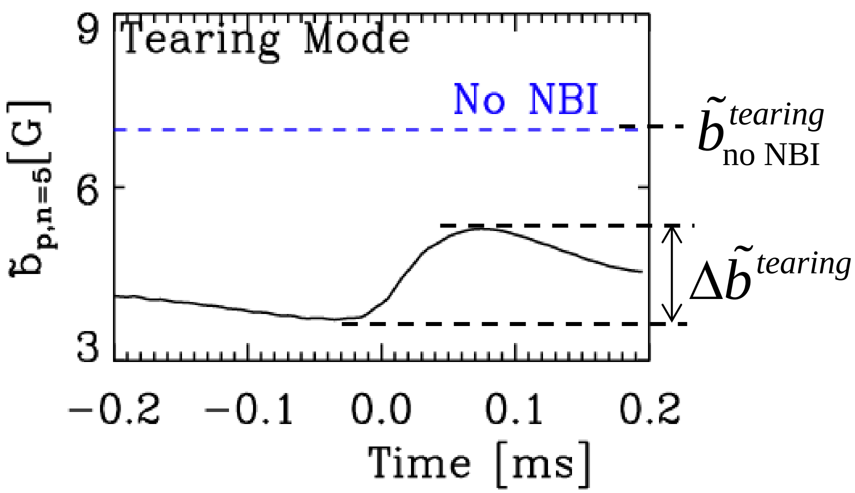
- NBI reduction of innermost-resonant tearing mode

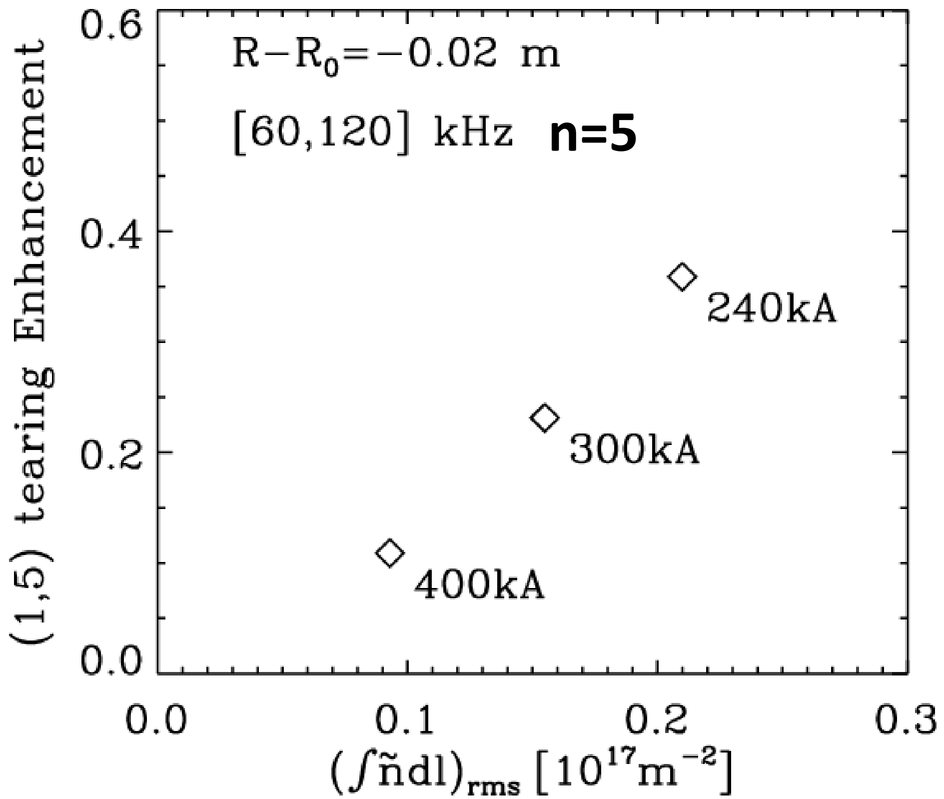
- Evidence for fast ion loss induced by NBI-driven modes

Tearing mode enhancement increases with density fluctuations, as plasma current decreases.

Tearing mode enhancement:

$$\frac{\Delta\tilde{b}^{tearing}}{\tilde{b}^{tearing}_{\text{no NBI}}}$$





- Larger enhancement of tearing mode indicates larger reduction of beam-ion effect, suggesting larger fast ion loss/redistribution.

Summary

- Fast-particle driven instabilities are observed during NBI in a RFP.
  - density fluctuation spatial structure peaks in the core, where fast ions reside.
  - density fluctuation decrease as plasma current increase, suggesting a fast ion β_f dependence.

- Measured bicoherence among multiple NBI modes indicates strong nonlinear three-wave coupling.

- NBI reduces amplitude of innermost-resonant tearing mode.
  - NBI-driven mode reduces suppression of tearing mode,
  - implies loss or redistribution of beam ions.

Discussion Topics

- **Difference between energetic particle physics in RFP and tokamak?**
  - Role of strong magnetic shear
  - Role of tearing modes and 3D magnetic structures

- **Possible application of numerical codes (M3D-K? HINST? NOVA-K? GYRO?) to RFP for study of NBI-driven instabilities and tearing mode suppression?**

- **Possible contributions to code validation effort from a RFP?**

global tearing mode structure measured by interferometry and polarimetry diagnostics