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 equilibrium and fluctuation quantities.

**Standard interferometry:**

\[ \Phi_{\text{int}} \propto \int n_e dz \quad \Rightarrow \quad n_0, \tilde{n} \]

**Polarimetry (Faraday Rotation):**

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

**External magnetic coils:**

\[ \tilde{b}_\phi, \tilde{b}_\theta \]

- 11 chords
- \( \Delta x \sim 8 \text{ cm} \)
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- \( \Delta x \sim 8 \text{ cm} \)

**Phase noise** \( \sim 0.01^\circ \)

**Time response** \( \sim 1 \text{ MHz} \)
Faraday rotation slope change suggests NBI current drive.

\[ I_p = 300 \text{kA}; \bar{n}_e = 0.7 \times 10^{19} \text{m}^{-3} \]

\[ \Psi_{pol} = c_F \int n_e B_z \, dz \]

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

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:**
\[ \left| \frac{\partial \Psi}{\partial x} \right| = 12 \pm 1 \text{ deg/m} \]

**With NBI:**
\[ \left| \frac{\partial \Psi}{\partial x} \right| = 15 \pm 1 \text{ deg/m} \]

- Faraday rotation measurement suggests that NBI increases central plasma current density by \((25 \pm 10)\%\).

- TRANSP shows that central fast ion density is 25% of electron density.
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Bursty modes are observed with NBI.

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

Ip = 300 kA
ne = $0.7 \times 10^{19} m^{-3}$
Single burst of NBI-driven mode

- Each burst has a duration ~0.06 ms (~160 Alfvèn times $a/v_A$) 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
  \[ \frac{\left| \int \tilde{n} dz \right|_{\text{peak}}}{\int n dz} \sim 0.2\% \]

- \( \pi \) 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 \( \nabla n_e \) is small,
  - compressional effect?
  - others?

- Phase shift across \( |R-R_0|\sim 0.3 \text{ m} \), where \( \nabla n_e \) 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.
As plasma current increases, density fluctuations associated with NBI-driven modes decrease.

Increase of current leads to a reduction of $\beta_f$, 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:
  \[
  \beta_{-1,4,5} = \sqrt{ \frac{\langle \tilde{b}_{n=-1} \tilde{b}_{n=4} \tilde{b}_{n=5} \rangle^2}{\langle |\tilde{b}_{n=-1}|^2 \rangle \langle |\tilde{b}_{n=4}|^2 \rangle \langle |\tilde{b}_{n=5}|^2 \rangle} }
  \]

- 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.
  \[
  \frac{|\int \tilde{n}dz|_{peak}}{\int n dz}
  \]

<table>
<thead>
<tr>
<th></th>
<th>( n=5 )</th>
<th>( n=4 )</th>
<th>( n=-1 )</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.21%</td>
<td>0.05%</td>
<td>0.09%</td>
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- 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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Local magnetic and current fluctuations can be obtained from 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.
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- **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.

- 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.

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

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 $\beta_f$ 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