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Interplay between coexisting MHD instabilities mediated by energetic ions in NSTX H-mode plasmas

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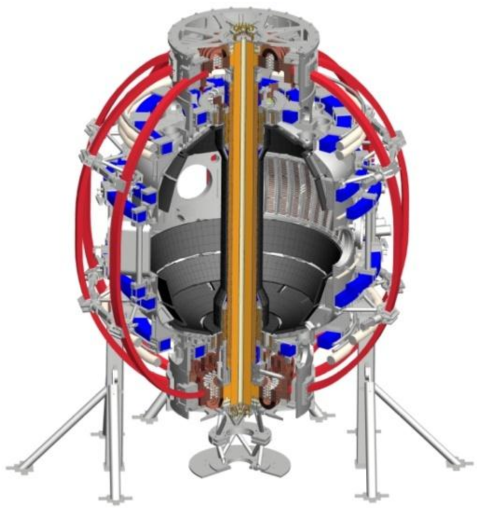

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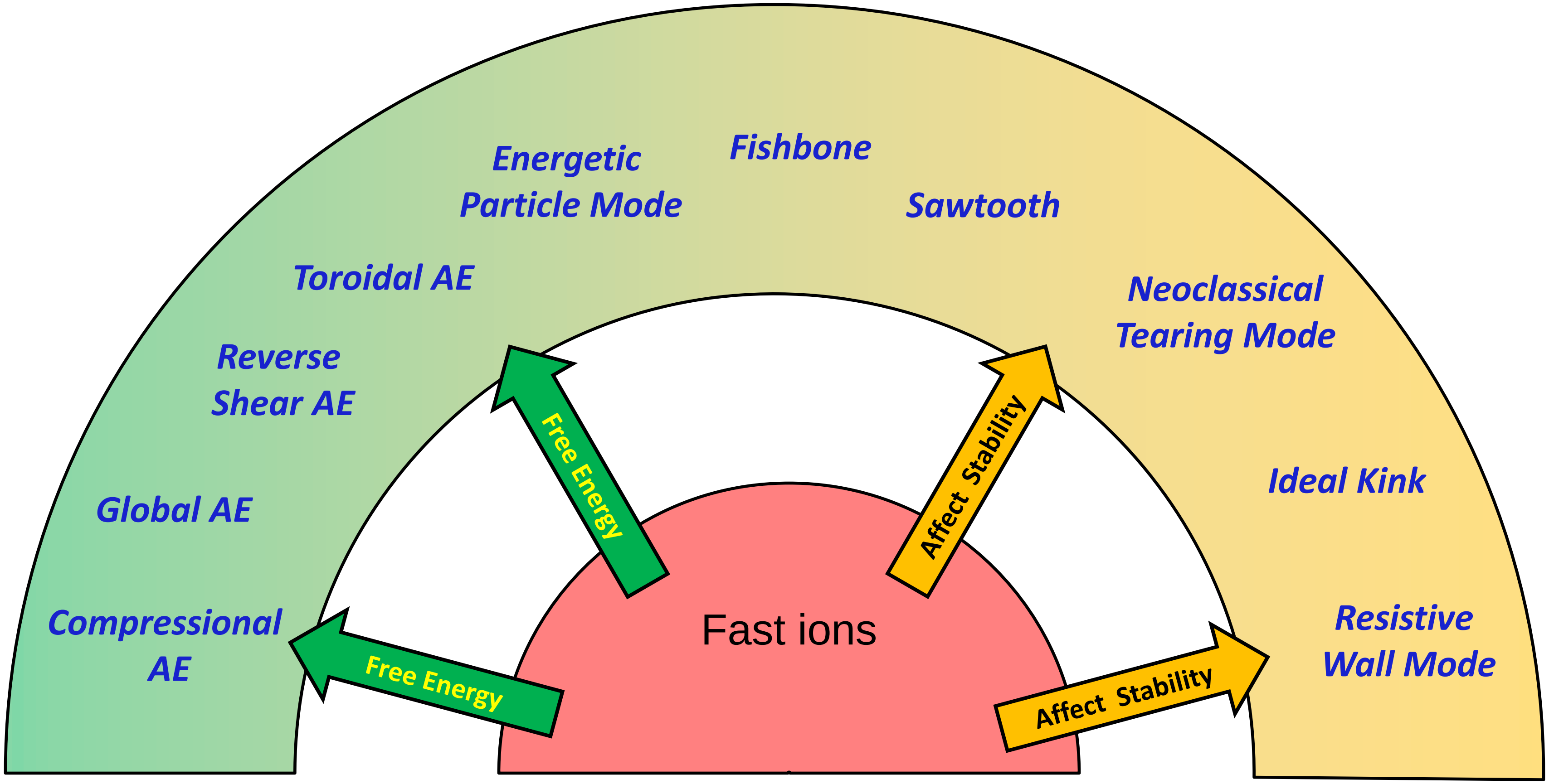
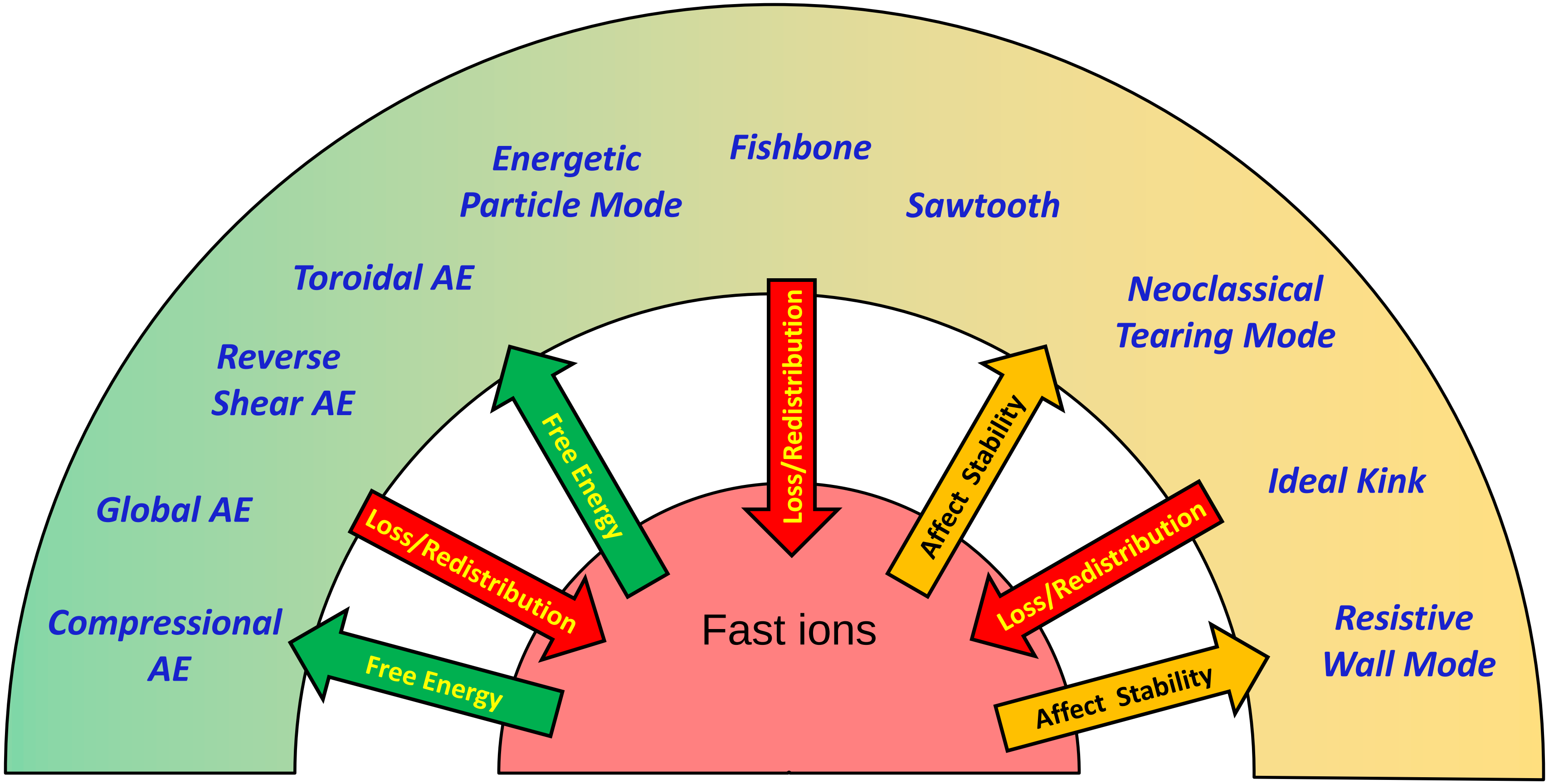
Motivation and observations

- Fast ion confinement is an important element of a fusion device
  - Optimize the plasma heating and current drive
  - Avoid damage from localized particle losses to wall
- Recent focus on the combined effect of multiple fast particle modes
  - Overlap of wave-particle resonances greatly enhances transport
- Direct coupling between modes experimentally documented
  - Non-linear coupling between Toroidal Alfvén Eigenmodes *Podestà NF 2011*
  - 3 wave coupling among TAE and Energetic Particle Modes *Crocker PRL 2006*
  - Simultaneous avalanches of Toroidal and Global AE *Fredrickson NF 2012*
- Fast ions represent a common element of many instabilities

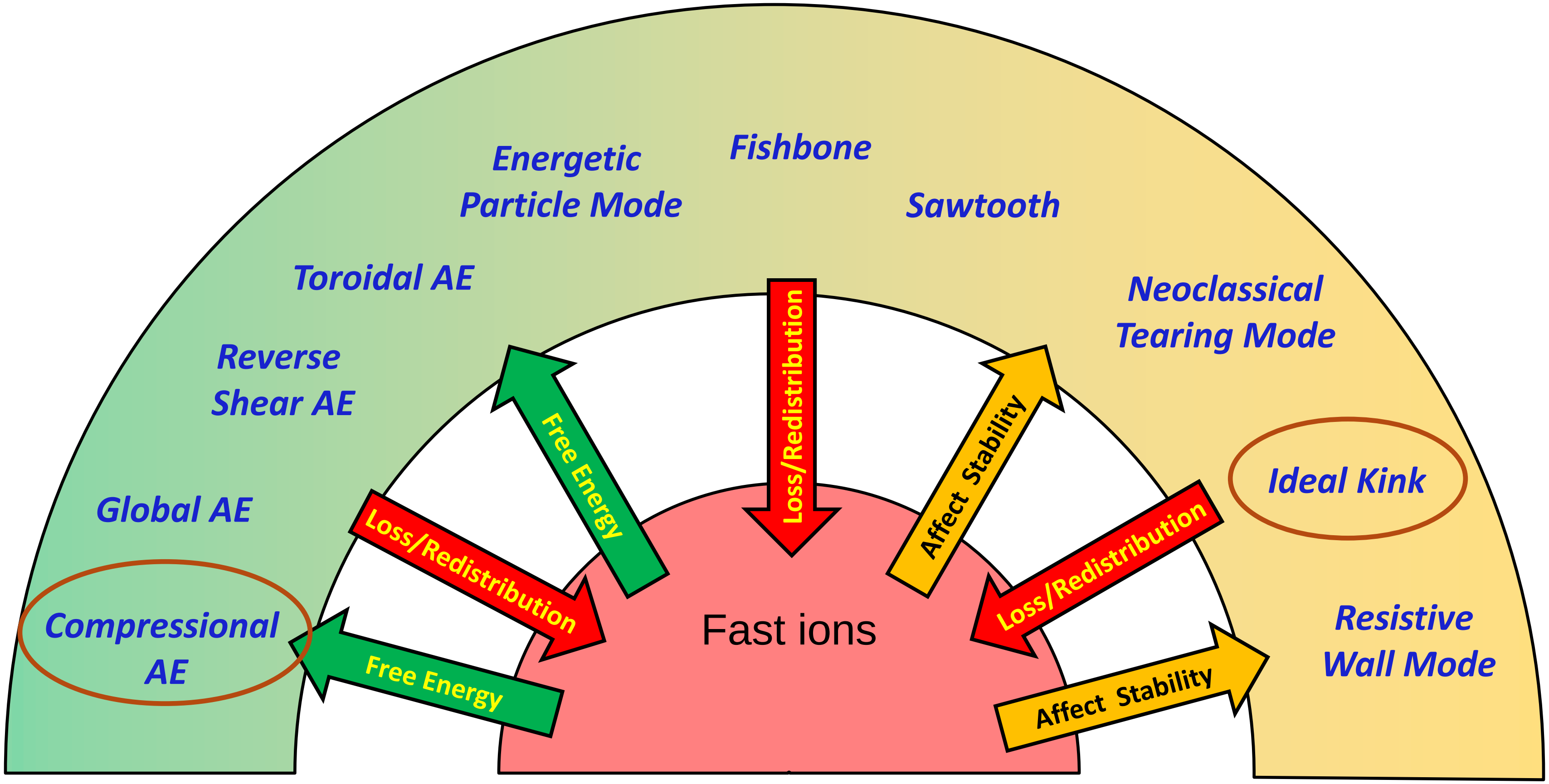
Fast-ions can modify MHD instabilities



Instabilities can modify fast ion distribution

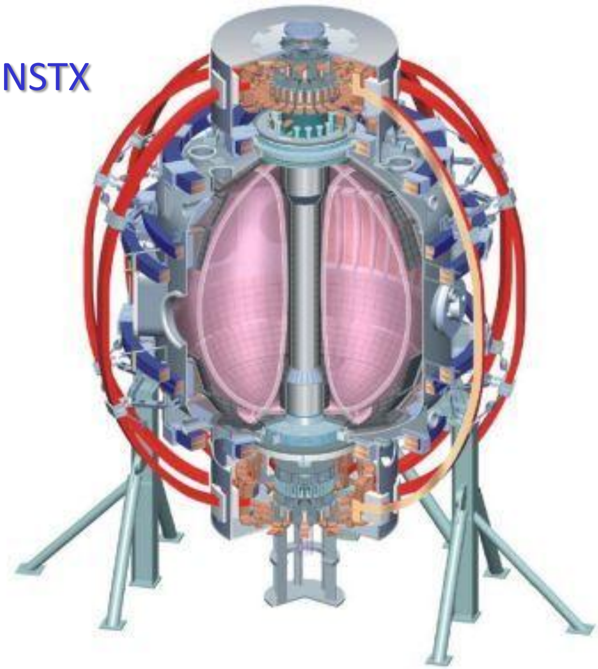


Fast-ions can mediate the interaction between instabilities



The spherical tokamak is an excellent laboratory to study mode interplay

NSTX



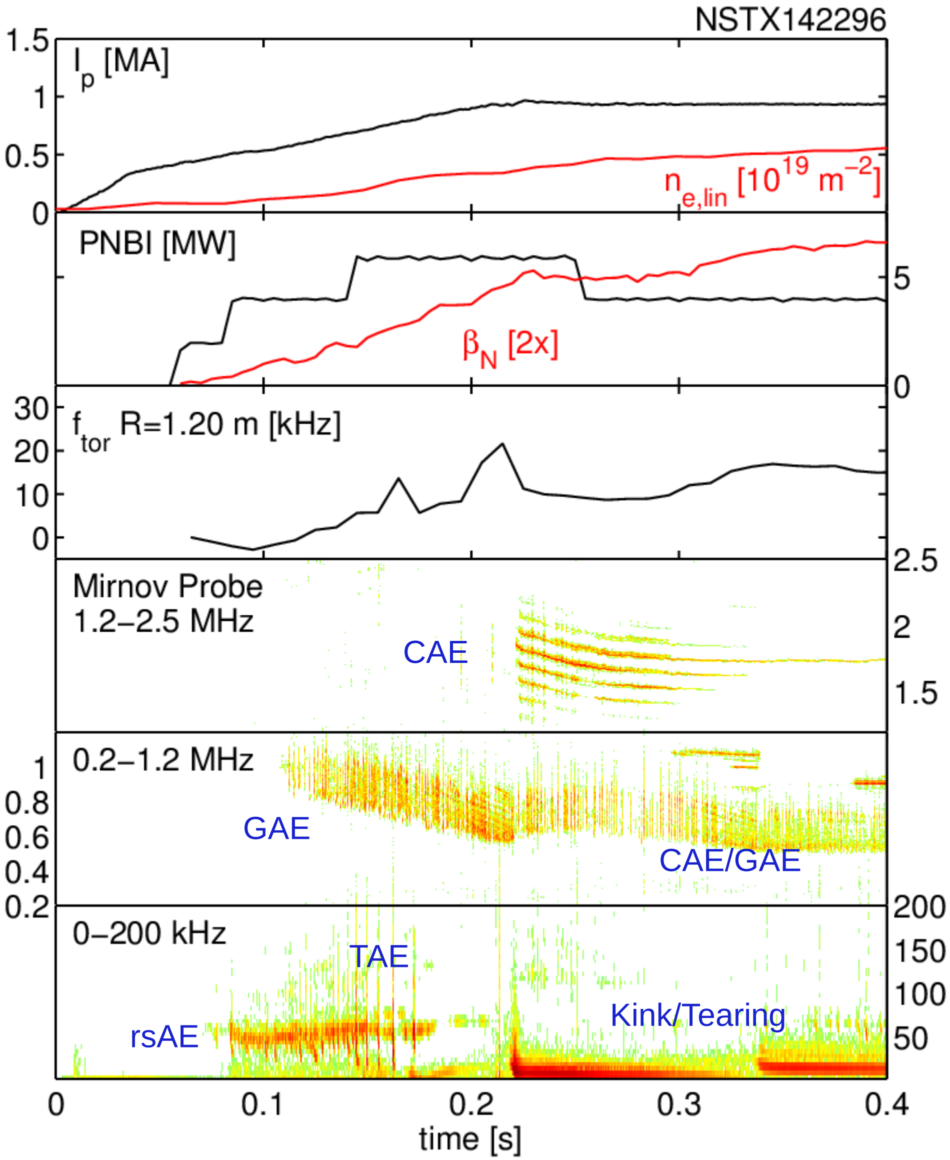
- High β, close to ideal stability limits
  - favors the appearance of ideal kinks, RWM, NTM
- Low $B_{tor,}$ high density → "low" Alfvén speed
  - large population of super alfvénic ions
  - favors the drive of Alfvén Eigenmodes (AE)

NSTX parameters	
Major radius	0.85 m
Aspect ratio	~2
Plasma current	~1 MA
Toroidal field	<0.6 T

Fast Ions from NBI
3 sources, total $P_{NBI} \leq$ 6 MW
$E_{injection} \leq$ 90 keV
1 $< V_{beam}/V_{Alfven} <$ 5
Larmor radius <20 cm

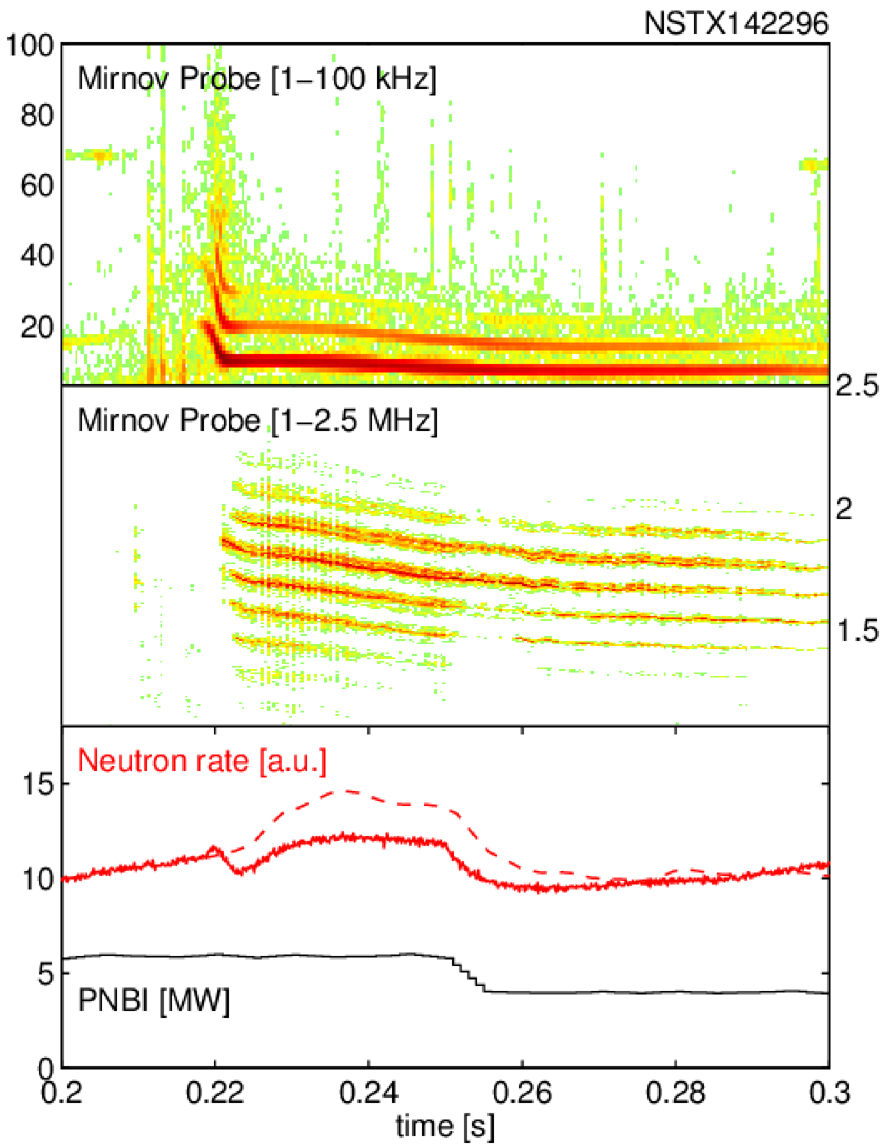
NSTX diagnostics	
Plasma	TS, CX, MSE
Fluctuations	Mirnov ,SXR, Reflectometry, BES
Fast Ions	Neutrons, FIDA, NPAs, Loss detector

Multiple types of modes coexist at the start of current flat top



- H-mode, B_{tor}=0.35T, I_p=900k
  - P_{NBI}=4-6 MW, $\beta_N \approx$ 2.5-3.5
- Multiple types of concurrent MHD activity:
  - Reversed Shear AE
  - Toroidal AE (bursting)
  - Global/Compressional AE (bursting/continuous)
- Onset of Low Frequency MHD at t=220 ms ($2<q_{min}<3$)
  - Rotation collapses (-15kHz)
  - β_N ramp stops
  - High frequency modes react

High frequency modes appear after onset of LF mode

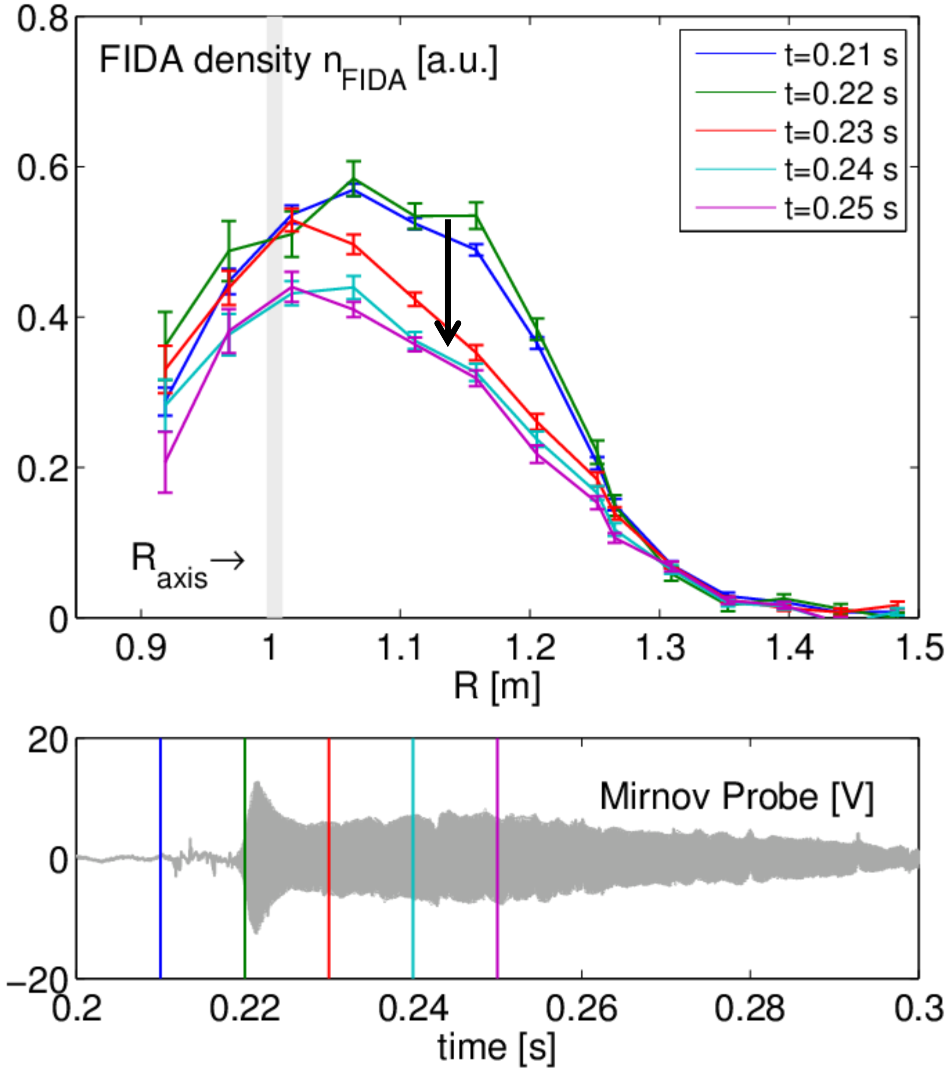


- Low Frequency mode enters with multiple toroidal harmonics
- n=1 (8kHz) and n=2 (16kHz) persist
- Initial chirp associated with the toroidal rotation drop (-15kHz)

- Cluster of Compressional AE in the 1.5-2.2 MHz range (~0.3 Ω_{ci})
- Frequent observation in H-mode
- Driven by coupling with fast ions

- Reduced neutron rate indicates effect on fast ion confinement
  - -8% at mode onset
  - -13% in relaxed phase (TRANSP)

Low frequency mode strongly affects fast-ion population



- Hot Balmer Dα → FIDA density:

$$n_{FIDA} = \frac{1}{n_0}\int_{\lambda_1}^{\lambda_2} s_{FIDA}\, d\lambda$$

- n_{FIDA} provides local information about fast ion density n_{fast}
- Affected by the velocity space response of the diagnostic

- Depletion n_{FIDA} consistently observed after mode onset:
  - up to 30% reduction
  - 10 ms time scale
  - outboard plasma affected first and more strongly

Plan of the work

- What is the amount of fast ion losses and redistribution induced by the low frequency MHD?
- Can redistribution have a role in the destabilization of CAE?

1. Characterization of low frequency MHD
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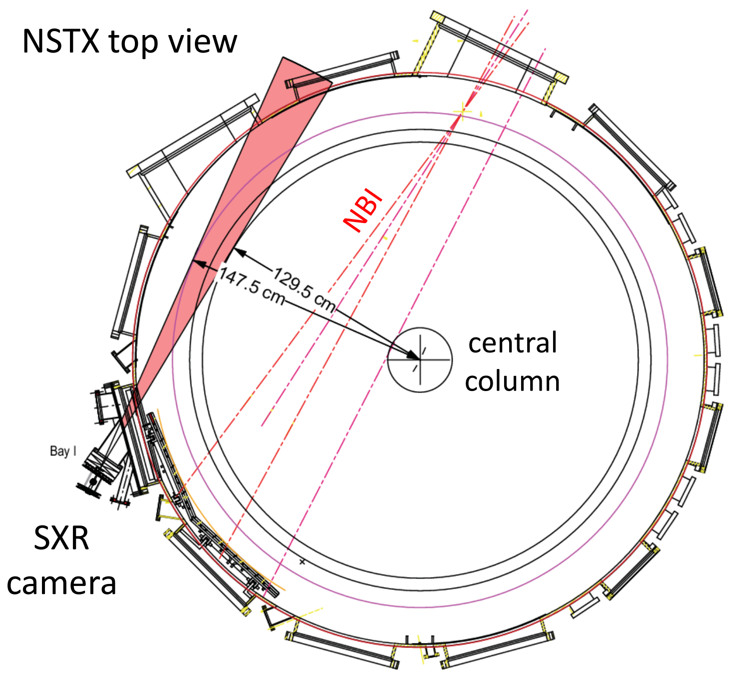
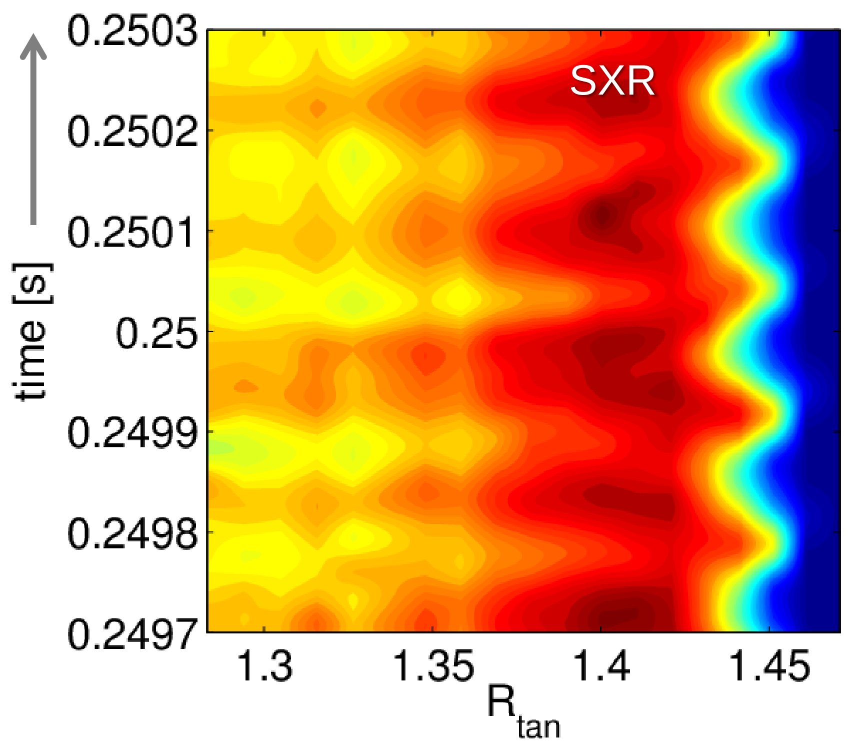
LF-MHD appears as perturbation near the plasma edge

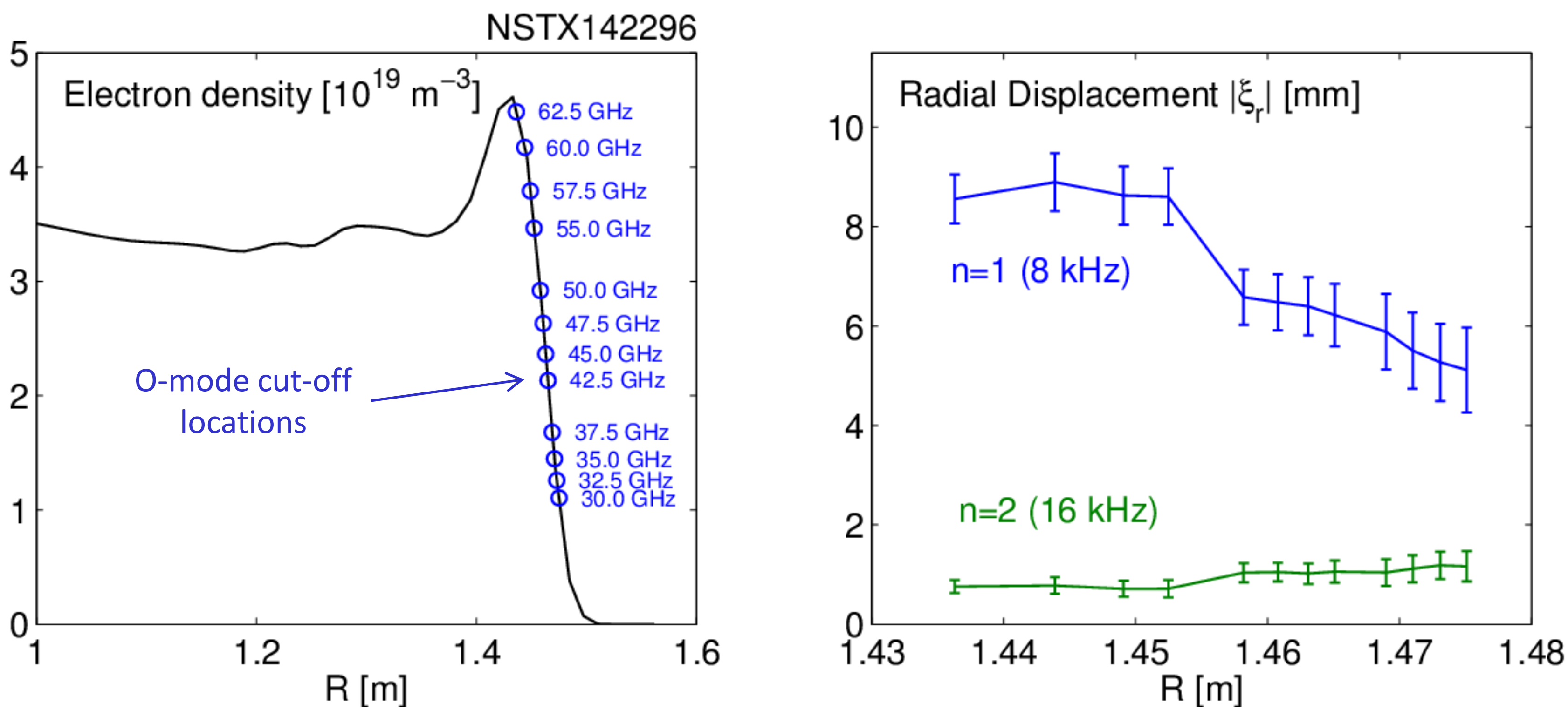
- Tangential SXR camera (20 chords, R_{tan} = 1.3-1.55 m, 50 μm Be)
- Evolution of line-integrated emissivity captures mode dynamics
- Periodic expansion-compression at 8 kHz for r/a>0.6





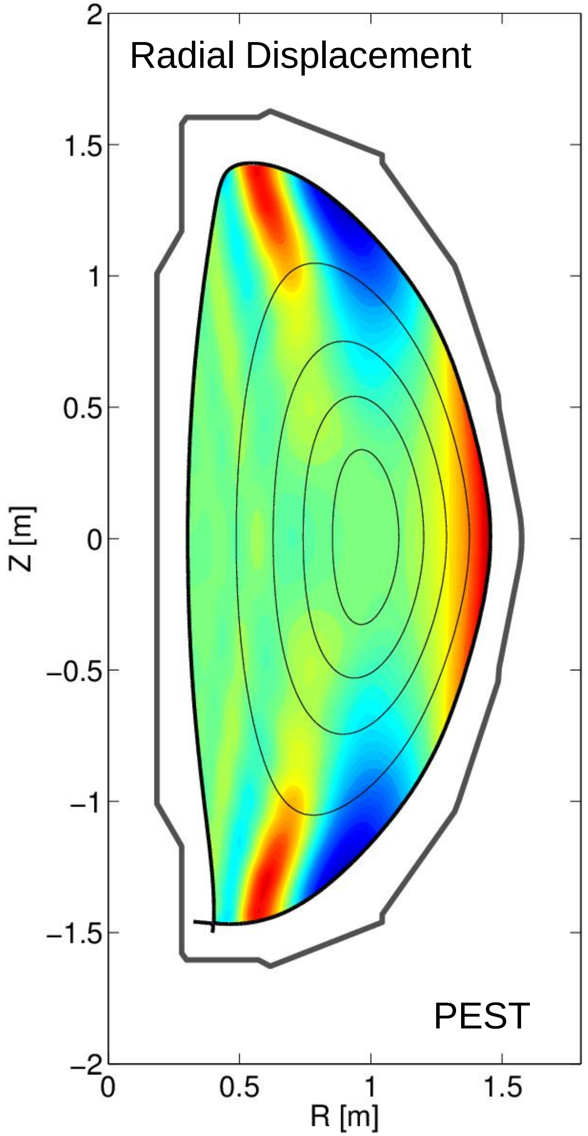
Reflectometer provides local measurement of radial displacement

- Multi channel reflectometer (16 channels, 30-75 GHz)
- Edge density peak → Cut-off locations along plasma pedestal
- Amplitude of radial oscillation ±9 mm (at 8 kHz)



Free boundary PEST simulation predicts instability to n=1 kink

- Ideal MHD code PEST used to determine mode structure
- Configuration is ***linearly*** unstable to n=1 kink under these conditions:
  - Pedestal pressure gradient
  - Reversed shear in plasma core
- Solution is a global kink
  - Large amplitude at plasma periphery
  - Radial displacement indicates compression of outboard plasma edge



Developed a synthetic diagnostic for Soft X-rays

1. n_e and T_e perturbation from radial displacement:

$$\delta n_e = -n_e \nabla \cdot \xi_r - \nabla n_e \cdot \xi_r$$

$$\delta T_e = (1-\gamma) T_e \nabla \cdot \xi_r - \nabla T_e \cdot \xi_r$$

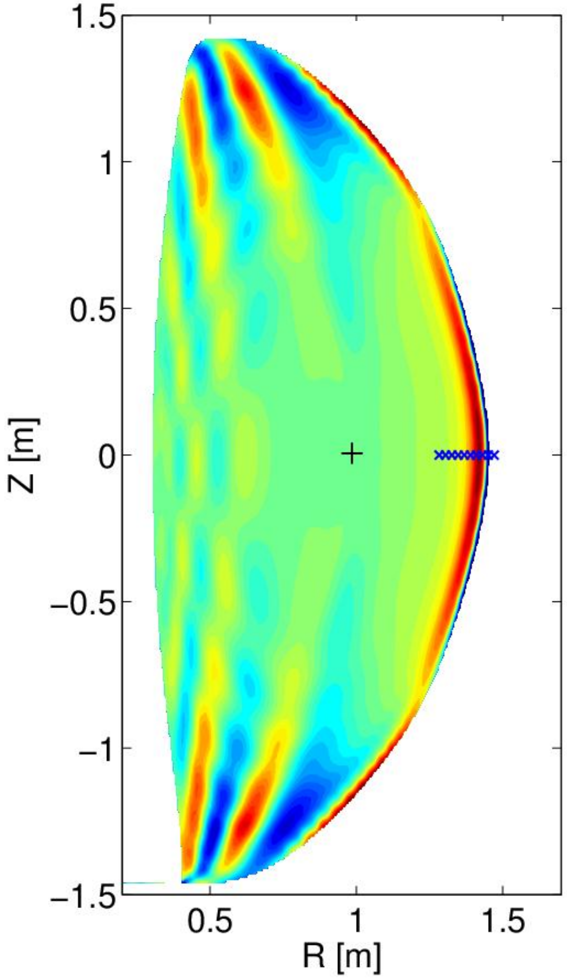
2. SXR emissivity assuming carbon impurity only:

$$E_{SXR} = n_e^2 R_C(T_e) \rightarrow \delta E_{SXR}$$

3. Integration along view lines
4. Rigid toroidal rotation at mode frequency (8 kHz)

Assumption: structure to linear solution is preserved in the saturated phase

Simulated density perturbation

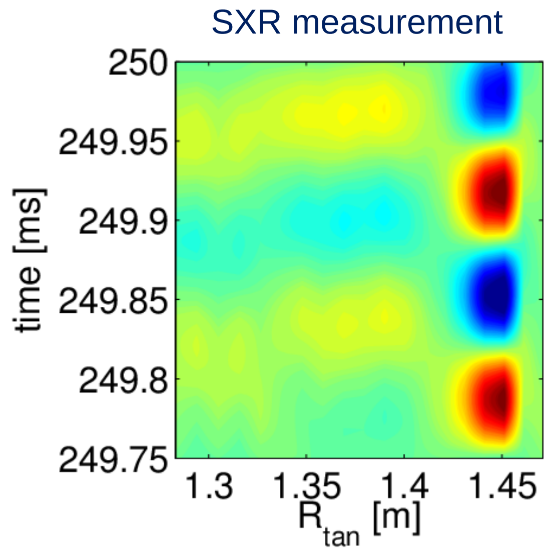


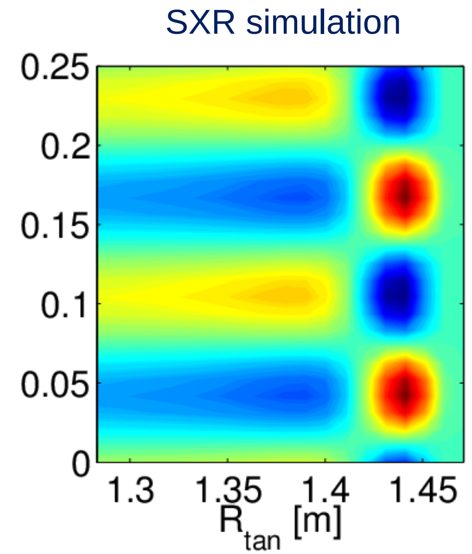
Kink structure validated against SXR measurements

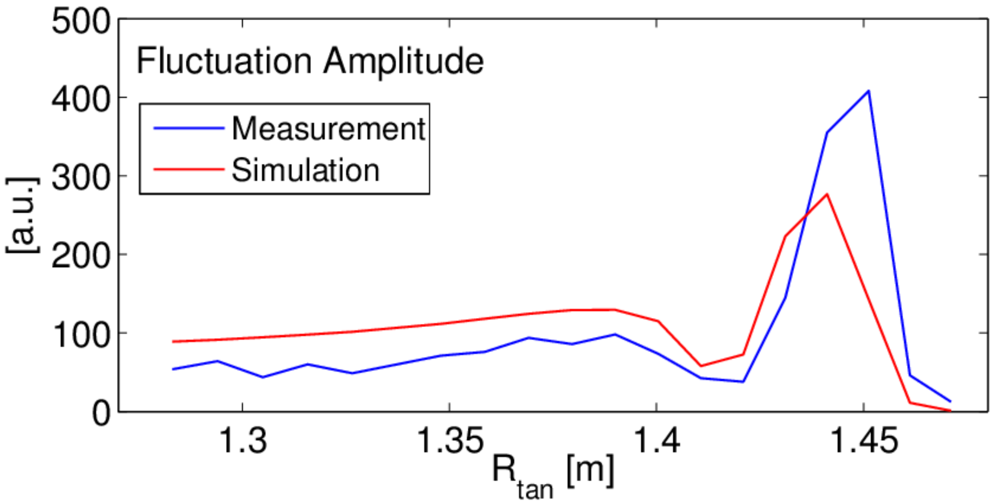
- Linear solution does not provide saturated amplitude

- Normalize PEST radial displacement to reproduce ΔR_{edge}=±9 mm excursion measured by reflectometer

- Reasonable agreement obtained with:
  - B_z at Mirnov coil ≈ 15G
  - Profile of SXR fluctuation







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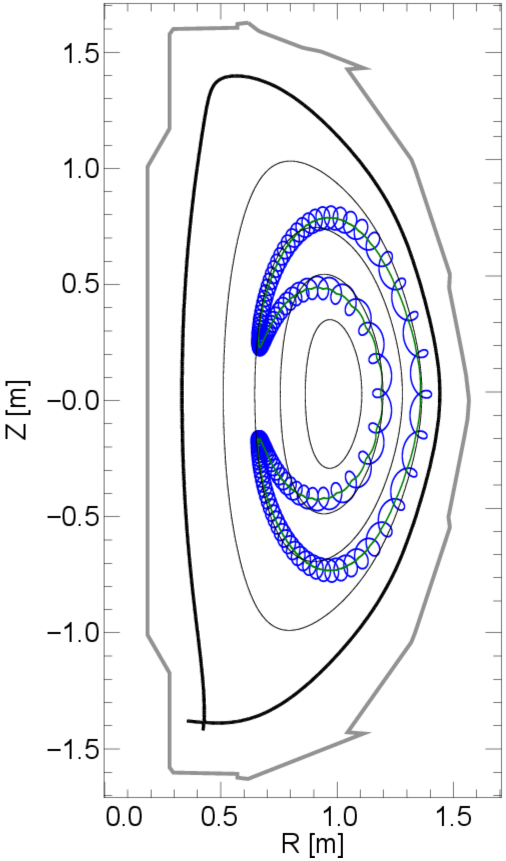
Full-orbit Monte-Carlo code SPIRAL predicts fast-ion redistribution and small particle losses

- Beam ions introduced at uniform rate along a 25 ms simulated time window using ***birth profile from NUBEAM*** code
- Fast ion orbits computed including collisional ***slowing-down*** and ***pitch angle scattering***
- Energy slowing down time <20 ms for 90keV ion → final state represents the ***stationary distribution***
- Computation performed ***with*** and ***without*** kink at t=0.25 s (relaxed state)

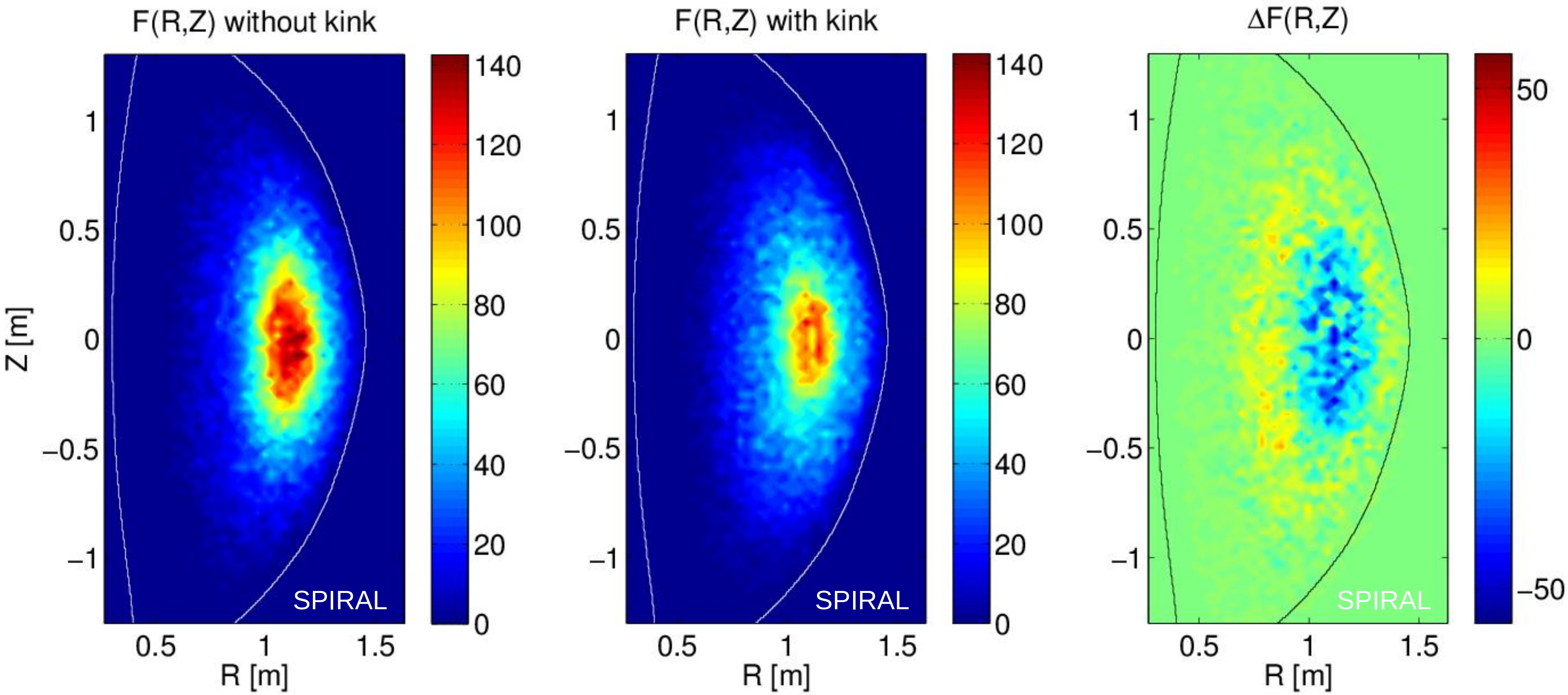


- Small increase of fast-ion losses (-3% confined particle)
- 8% decrease in neutron production rate

Confined fast-ions are redistributed by the kink in real space (R,Z)

- Differential distribution function: $\Delta F(R,Z) = F_{kink} - F_{nokink}$

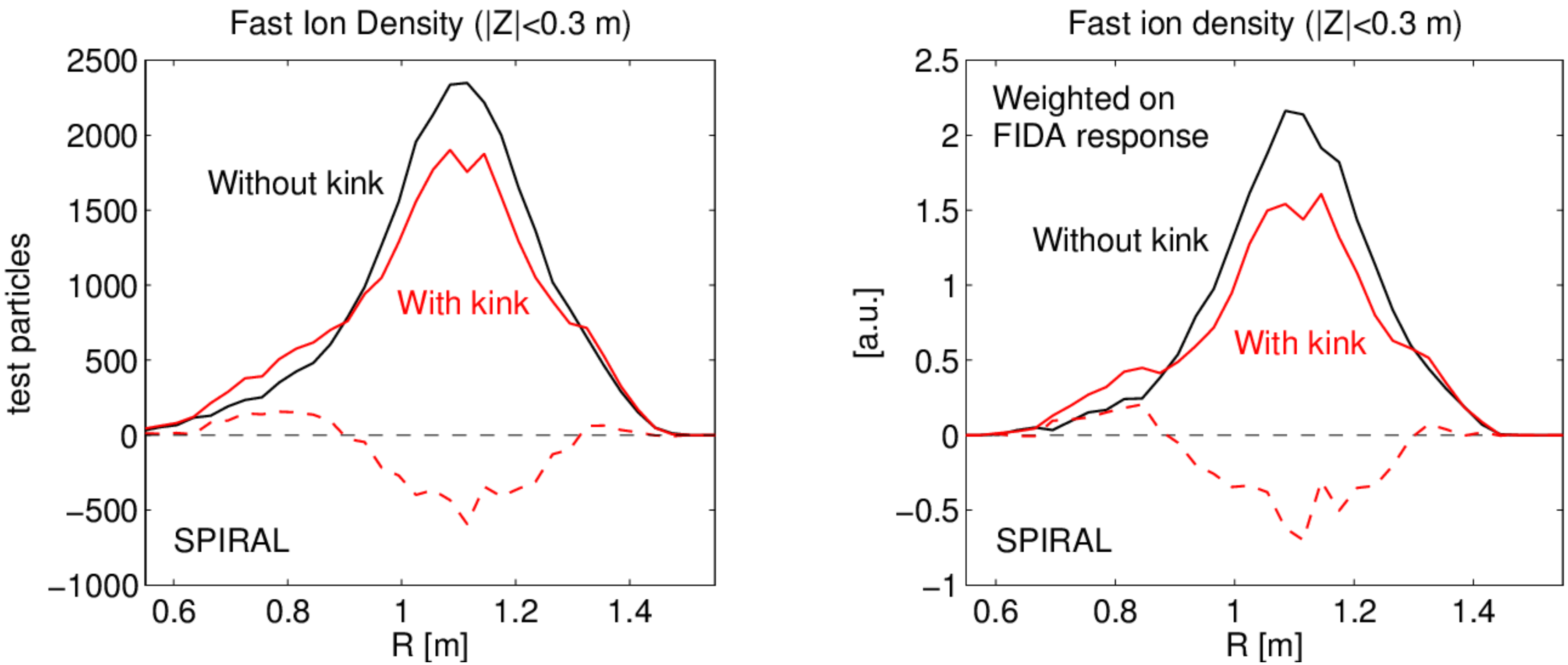
Integrated over velocity space



In presence of the kink:

- depletion of n_{fast} in the core
- increase of n_{fast} in the outer regions

Kink effect on radial profile of fast-ion density

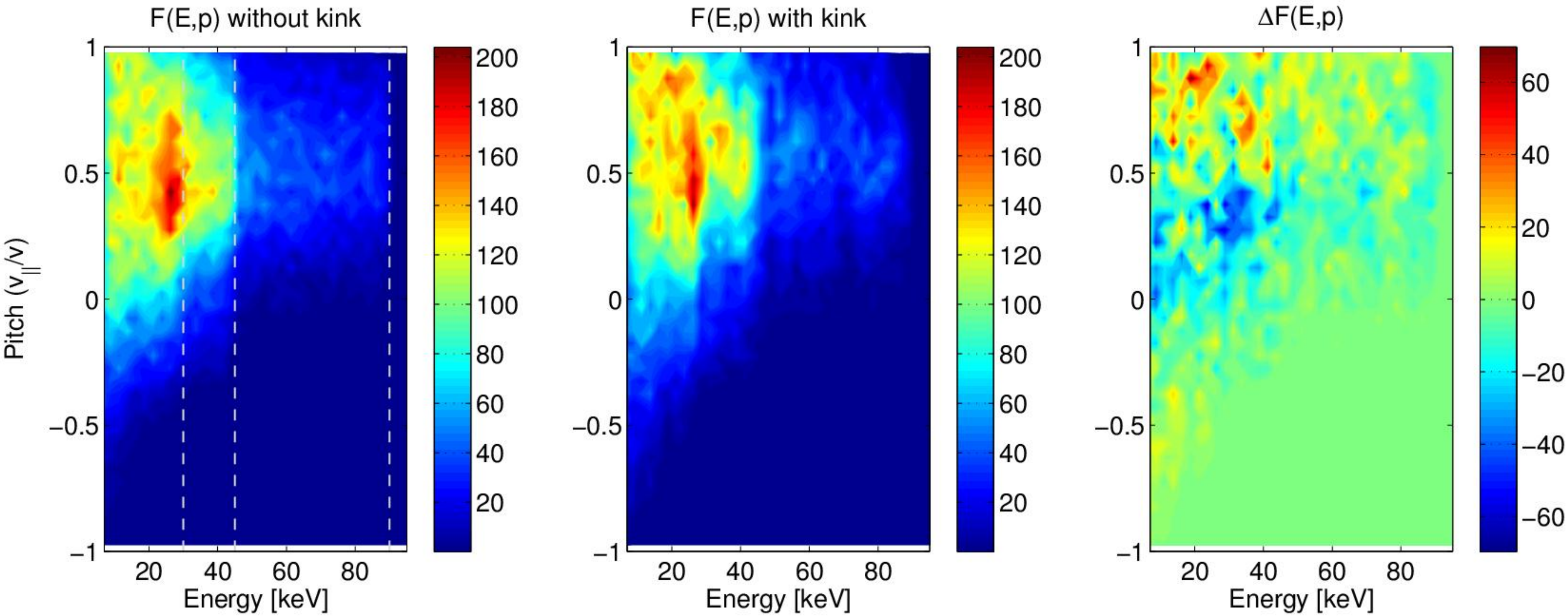


- Decrease of n_{fast} by ~20% in the core
- Increase of n_{fast} for R<0.9m (inboard) and R>1.3m (outboard)
- Accounting for the FIDA weight function (λ=653nm, R=1.2m) leads to an apparent collapse of -25% in the core

Confined fast-ions are redistributed by the kink in velocity space (energy, pitch)

- Differential distribution function: $\Delta F(E,p) = F_{kink} - F_{nokink}$

Integrated over plasma volume



- Slowing down distribution
- Strong anisotropy

In presence of the kink:

Slowing down distribution shifts towards $V_{||}/V = 1$

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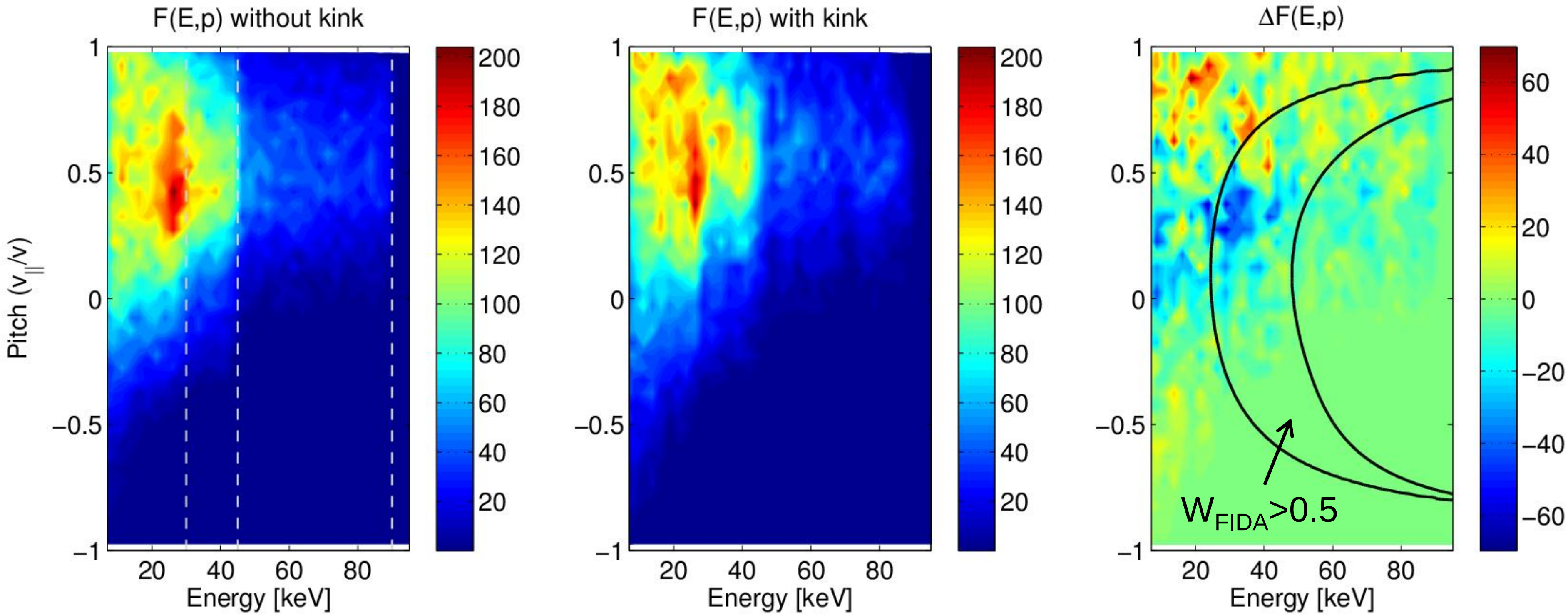

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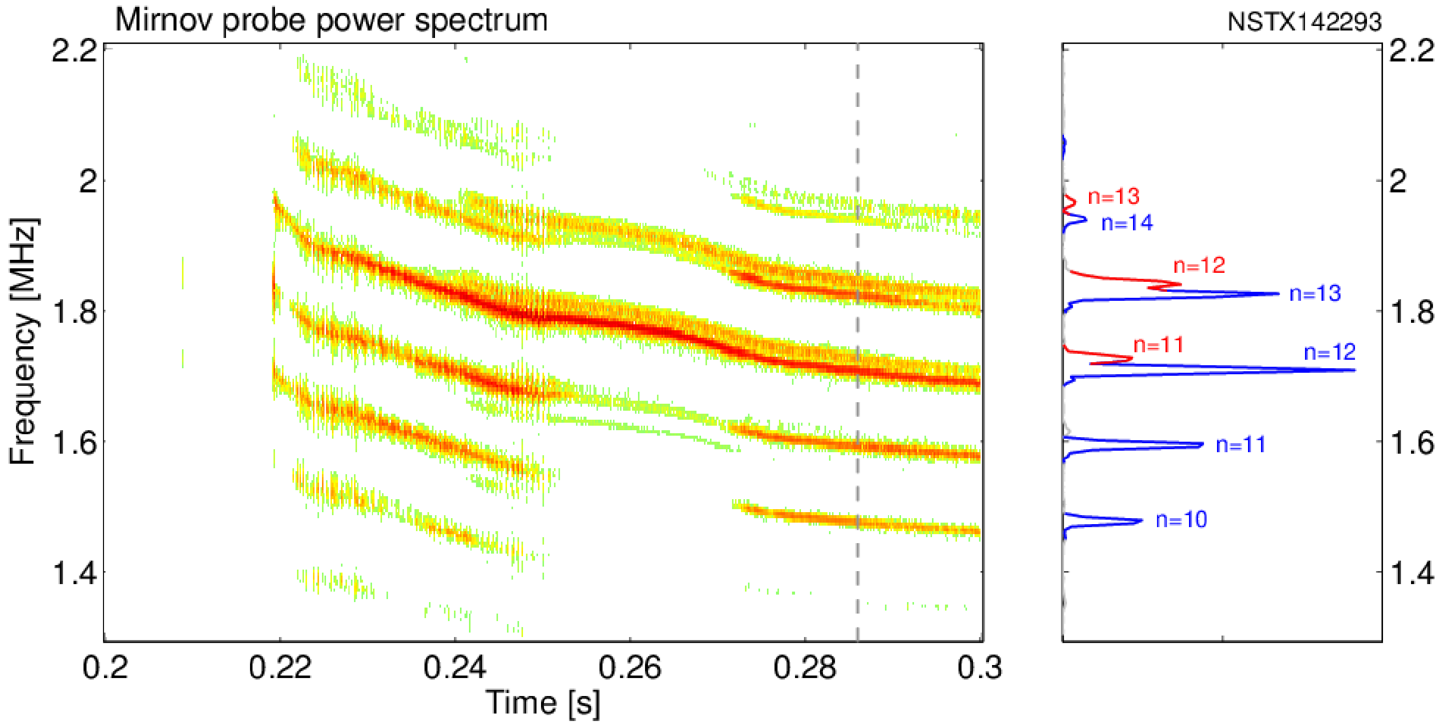
Mirnov array measurements show multiple sequences

- Clusters of modes with $0.3<\omega/\Omega_{ic}<1$ identified as CAE
- Toroidal mode numbers n=9-13, $\tilde{B}_{||} > \tilde{B}_{\perp}$
- Propagating in direction of neutral beam injection



2 sequences of modes ascending *frequencies* and *n* are present

CAE are expected to be localized in the outboard region

- CAE wave equation for electric field

$$\left(\nabla^2_{R,Z} - V\right) E_Z = 0 \qquad V(R,Z) = k_\varphi^2 - \frac{\omega^2}{v_A^2}$$

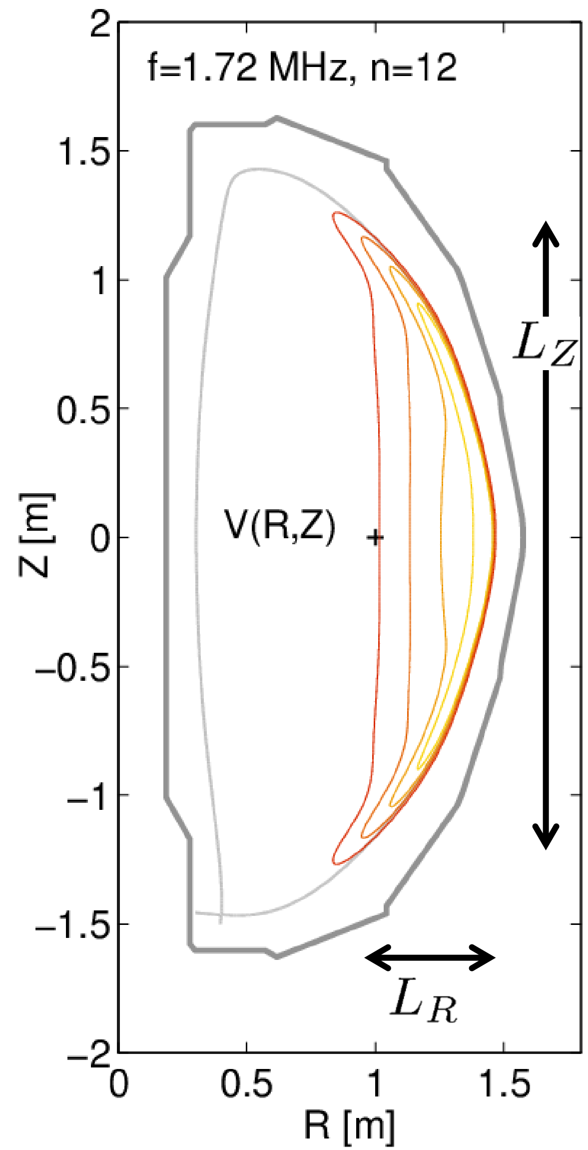
Wave in a box form (Schroedinger-like) — Effective Potential Well (equilibrium and toroidal structure)

- Solutions will be standing waves localized within the potential well V(R,Z,ω)

- Eigenmodes can be classified according to effective quantum numbers:

$$\vec{k} = \left(\frac{n}{R}, \frac{2\pi m}{L_Z}, \frac{2\pi s}{L_R}\right)$$

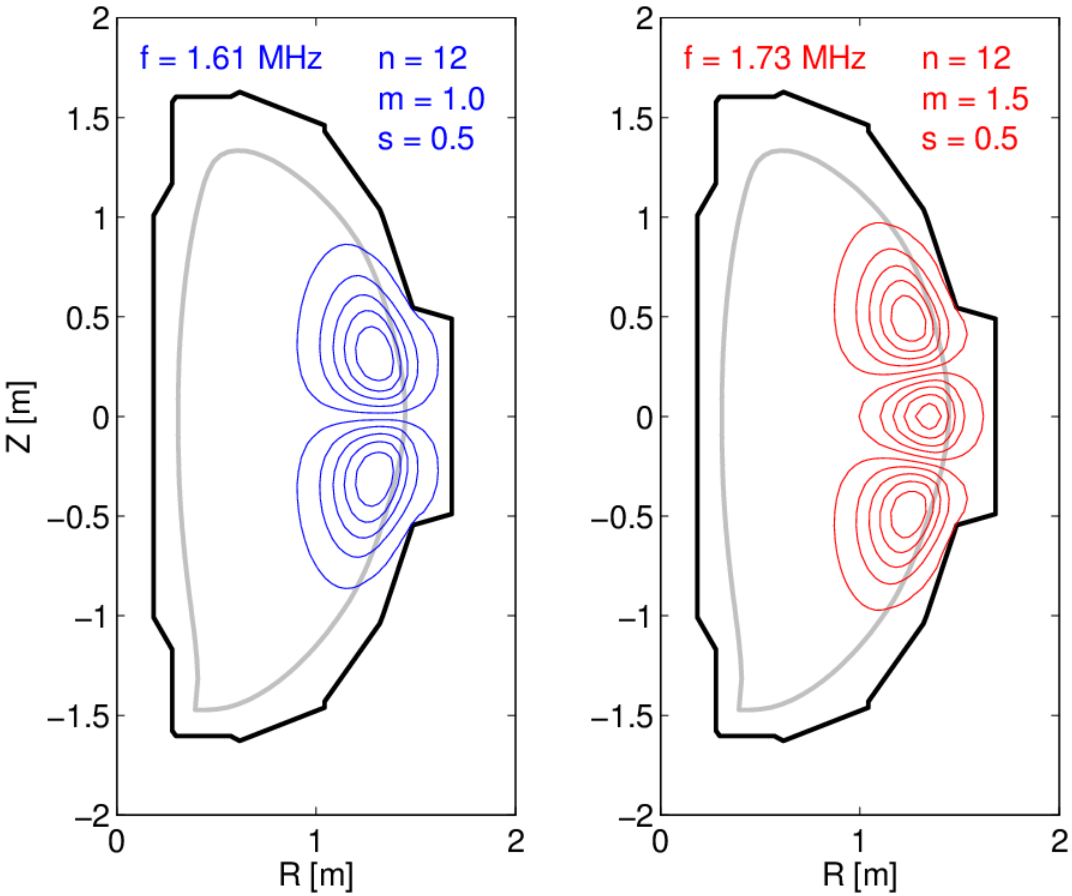
- n, m , s number of wavelengths in toroidal, vertical, radial direction

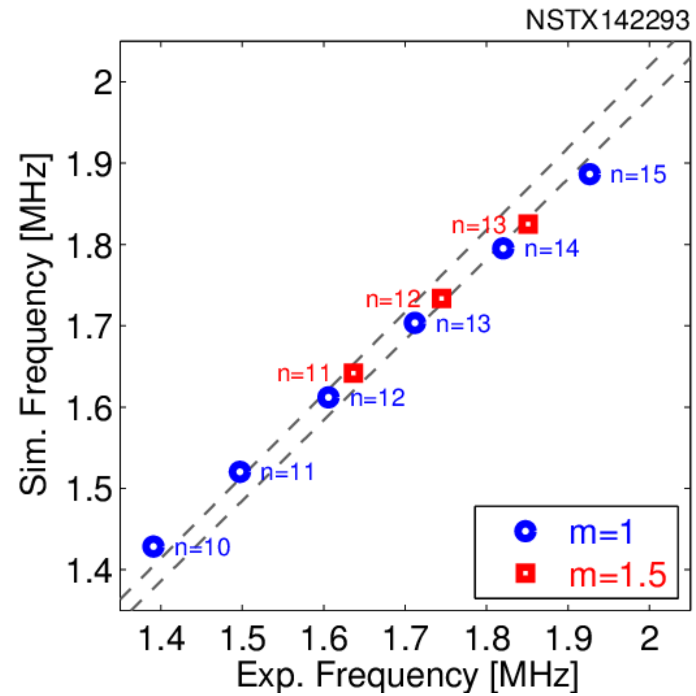


Eigenvalue equation solved numerically in realistic 2D equilibrium

- Sequences of low-m solutions found
  - s=0.5, **m=1**, n=9-13 (odd poloidal parity)
  - s=0.5, **m=1.5**, n=9-13 (even poloidal parity)

Fredrickson PP8.00022
Wednesday PM





Good agreement between experimental and simulated frequencies

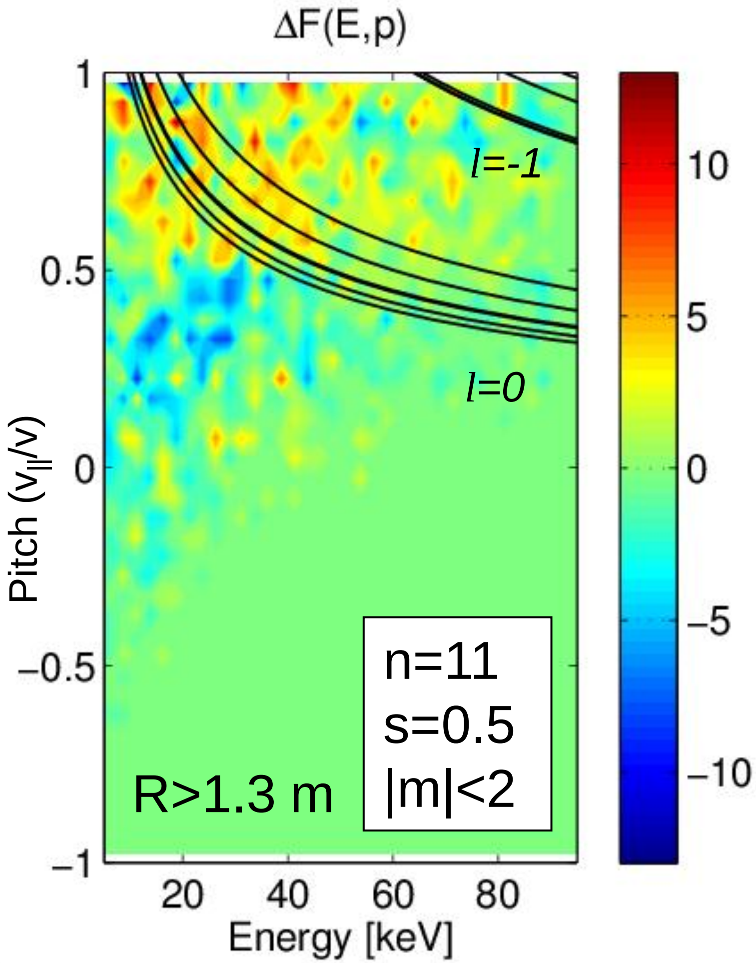
Fast-ion redistribution by kink populates CAE resonances

- Fast ions couple with CAEs through Doppler shifted ion cyclotron resonance

$$\omega = k_{\|}^{nms}\, v_{i,\|} + l\,\Omega_{ci}, \quad l = -1, 0$$

- Knowledge of the mode structure (n,m,s) allows to identify fast ions that resonate with the wave
- Determine resonance curves for the observed modes (in velocity space)
- Self-consistent MHD simulations (HYM) of co-propagating CAE in progress to determine fast ion drive

Belova PP8.00022
Wednesday PM



Conclusions

- Fast ions can mediate the interaction between instabilities that differ by localization, timescales and underlying physics
  - Complex integrated analysis is required to investigate these processes experimentally
- In NSTX H-modes, kHz-frequency ideal kinks can induce substantial fast ion redistribution in real and velocity space
  - Redistribution to resonant phase space regions could explain the destabilization of CAEs observed in presence of kinks
- In simulations, fast ion redistribution with small losses obtained in presence of low-f peripheral fields
  - Conceivable to use of 3D perturbations to affect stability of AE

Resonance conditions for co-propagating CAE

- CAE are driven by bump-on-tail fast ion distribution function
- Excited through Doppler shifted ion cyclotron resonance

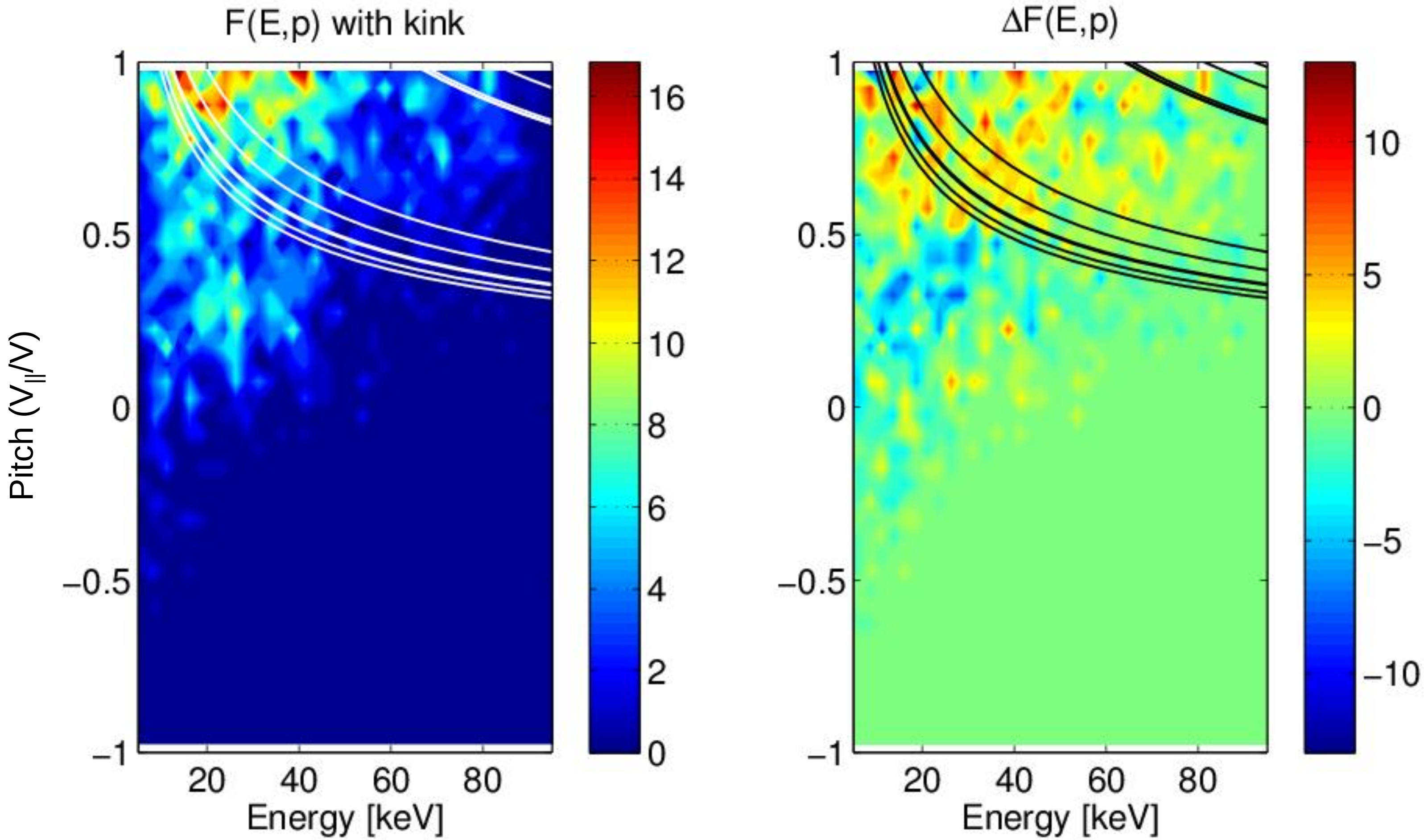
1-3.5x10^6 m/s (→ $v_{i,\parallel}$) **15 MHz** (→ Ω_{ci})

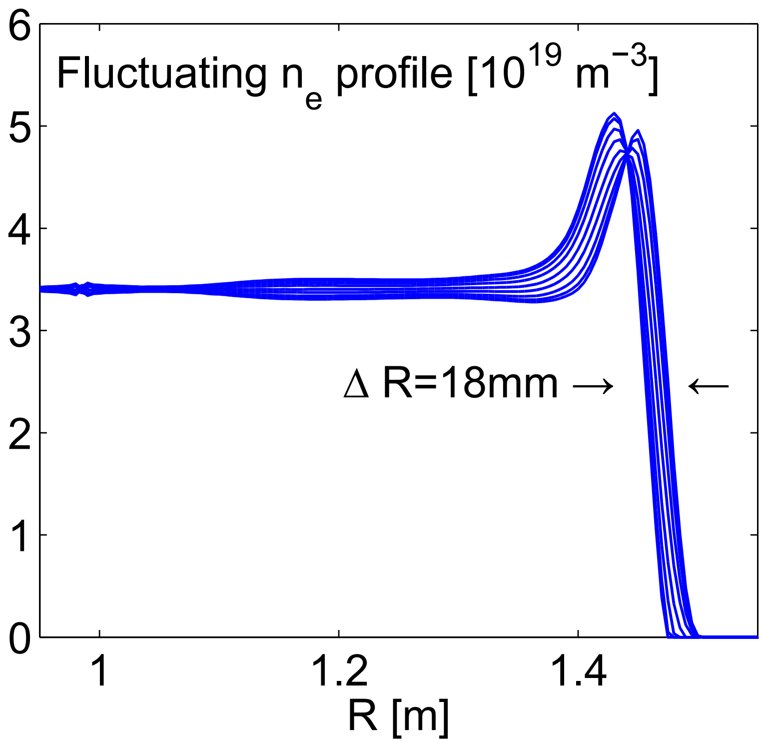
10 MHz → $$\omega = k_\parallel v_{i,\parallel} + l\,\Omega_{ci}, \qquad l = -1, 0, 1$$

$$k_\parallel \approx 8 - 10 > 0 \Leftarrow \begin{cases} k_\varphi = n/R, & n = 9 - 13 \\ k_\vartheta \approx \frac{2\pi M}{L_\vartheta}, & |M| \leq 2 \end{cases}$$

- Co-propagating CAE can couple with fast ion through:
  1. Direct Resonance (l=0) $\quad \omega = k_\parallel v_{i,\parallel}$
  2. Anomalous Doppler Shifted IC (l=-1) $\quad \omega = k_\parallel v_{i,\parallel} - \Omega_{ci}$

Distribution function at CAE location (R>1.3)





Simulated fluctuating density profile (midplane)