NSTX

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Fast Ion Redistribution and CAE Destabilization in Presence of Low Frequency MHD in NSTX

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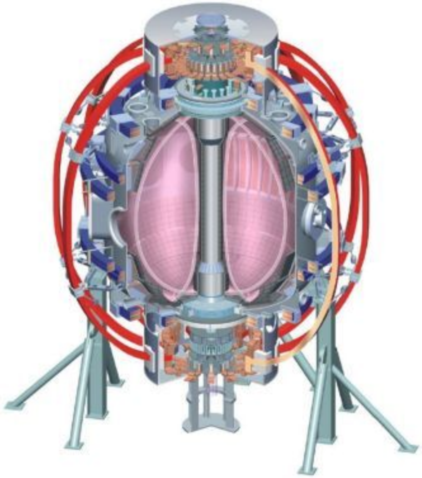

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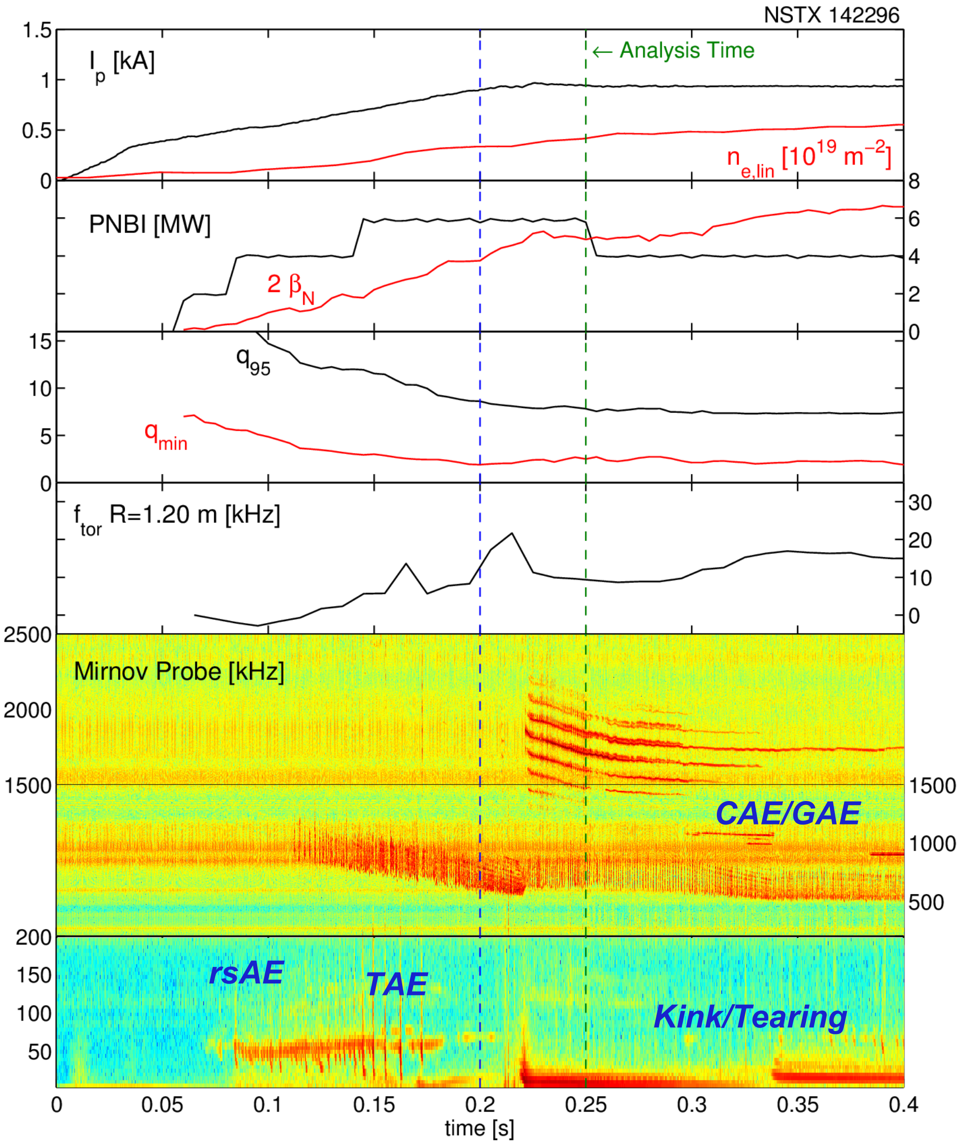
Introduction

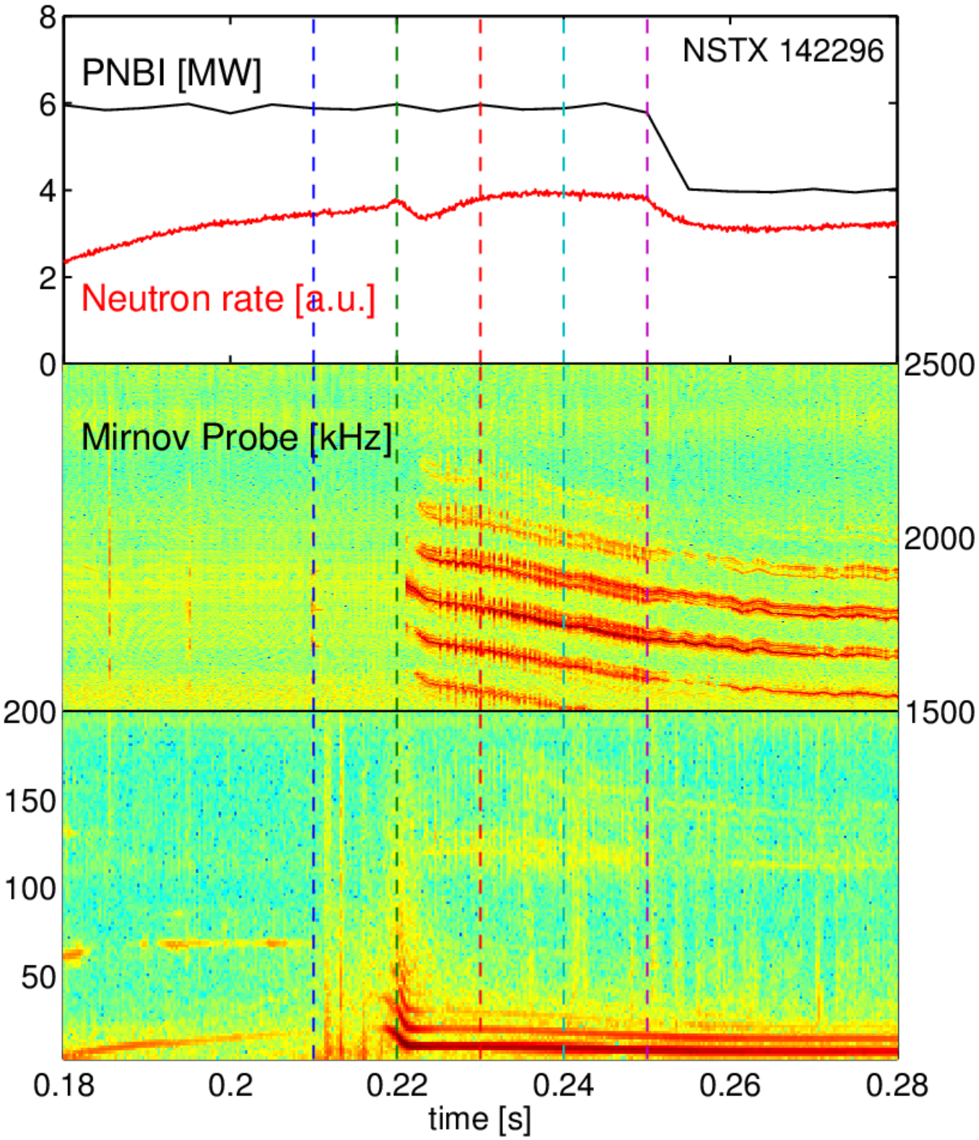
- Fast particle transport and losses in presence of Low Frequency MHD modes has been long studied (TFTR, DIII-D, ASDEX, NSTX, …)
- Often core modes have been addressed, well described by single helicity radial perturbation (Tearing Mode, Neoclassical TM, internal kink)
- Former studies [1,2] on NSTX focused on (m=2,n=1) internal kink
  - Depletion at particle energies below the injection energy (NPA)
  - Passing particles ($E<E_{inj}$) are preferentially affected and lost
- This work addresses ***early*** low frequency MHD activity on NSTX
  - Extends to the plasma periphery
  - Strongly affects fast ion population
  - Appears to be an important element for the destabilization of High Frequency Alfvénic modes

Experimental scenario: H-mode, B_t=0.4T, I_p=900kA



- "Fiducial" configuration, t<300 ms
  - P_{NBI}=4-6 MW
  - β_N~2.5-3.5
- MHD activity at different frequencies:
  - Toroidal AE (bursting)
  - Reversed Shear AE
  - Global/Compressional AE (bursting/continuous)
- Onset of LF mode at t=220 ms
  - Rotation collapses (-15kHz)
  - β_N ramp stops
- Mode vanishes after 100 ms, as density increases

High Frequency MHD associated with LF mode



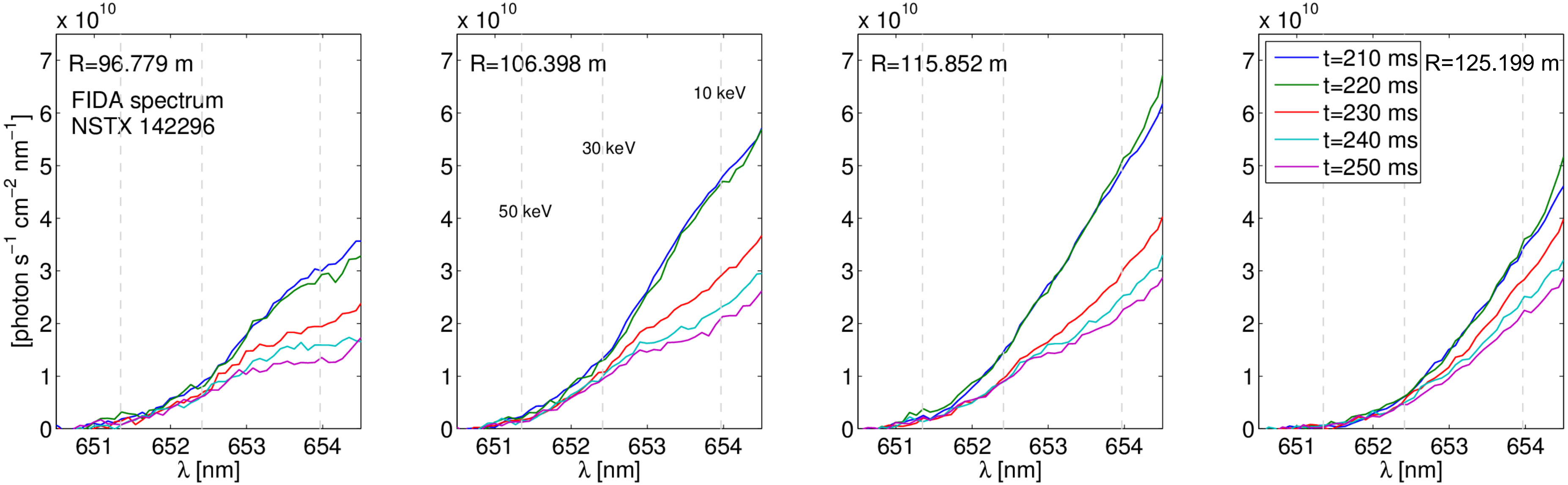
- Low Frequency mode enters with multiple toroidal harmonics
- n=1 and n=2 persist
- Initial chirp follows the toroidal rotation drop (-15kHz)

- Compressional AE cluster in 1-2.5 MHz frequency range
- Co-propagating modes, n=9-13
- Appear ***after*** onset of LF MHD
- Associated with *bump-on-tail* beam ion distribution function

- Small effect on neutron rate
- Losses <5% estimated from SFLIP Scintillator Loss Detector [5]

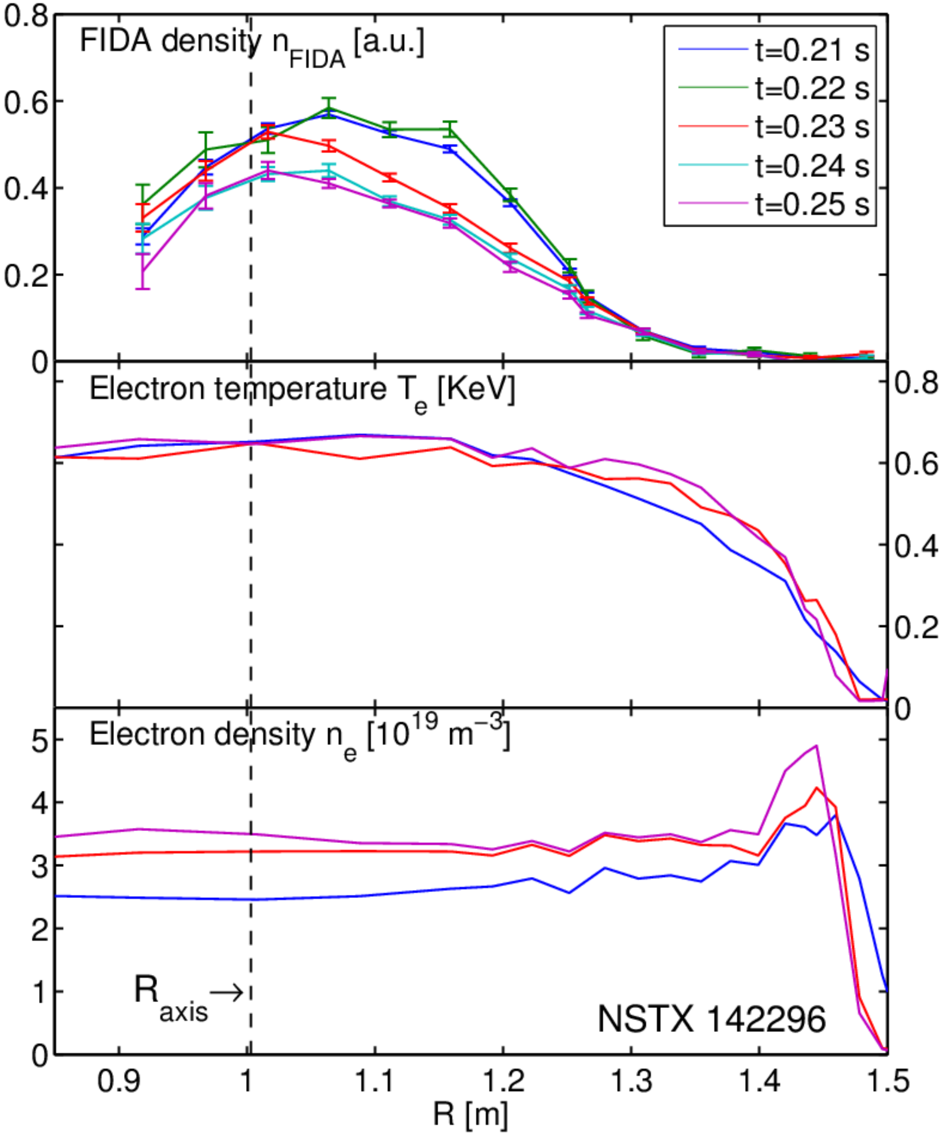
FIDA Spectra Show Strong Effect on Fast Ions

Fast Ion D-Alpha diagnostic observes the hot tail of Deuterium Balmer-α spectral line (656.1nm) emitted by recombined fast ions [3,4]



- Spectral signal decreases in a broad range of wavelength/energies
- Vertical view → sensitive to low pitch ($p=|v_{||}/v| <0.6$, E~20-60 keV)
- Low Frequency MHD activity affects the trapped population

Strong Depletion of FIDA Density at Mode Onset



- FIDA density:

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

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

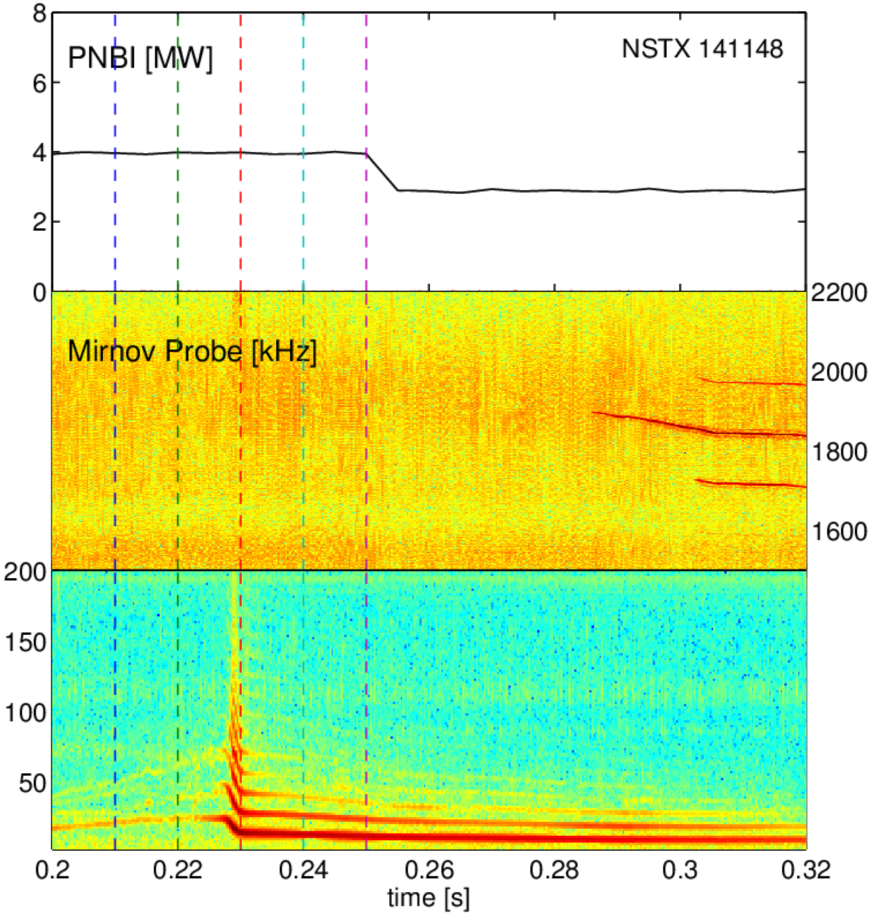
Depletion n_{FIDA} consistently observed after mode onset:

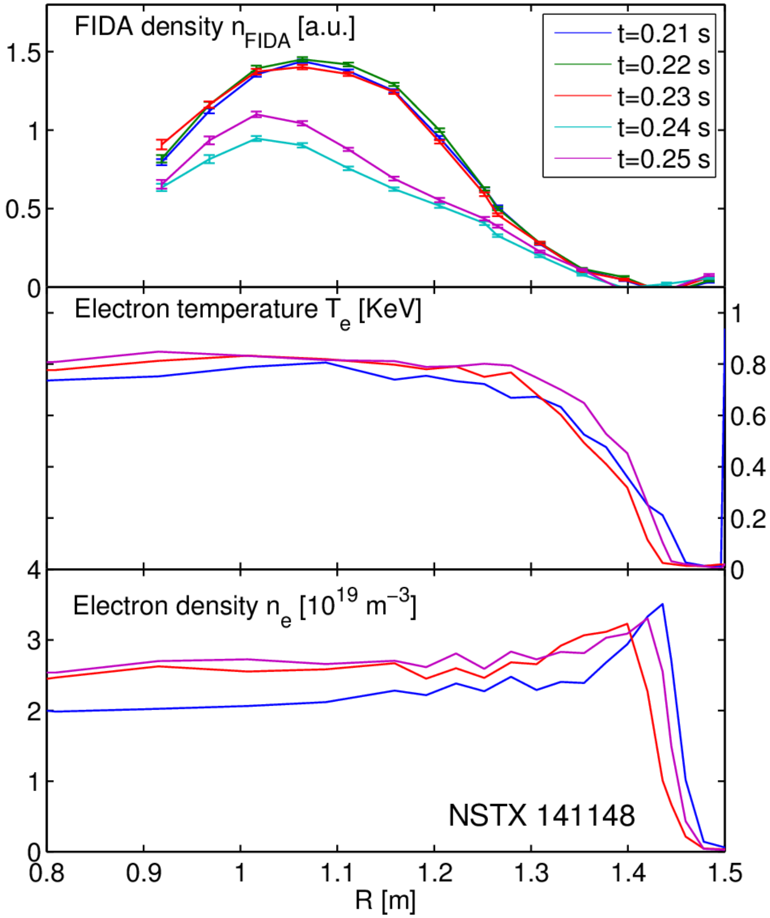
- *up to 30% reduction*
- *10 ms time scale*
- *outboard plasma is affected first and more*

Redistribution in real/velocity space ?

Fast Ion Redistribution is not Associated with CAEs

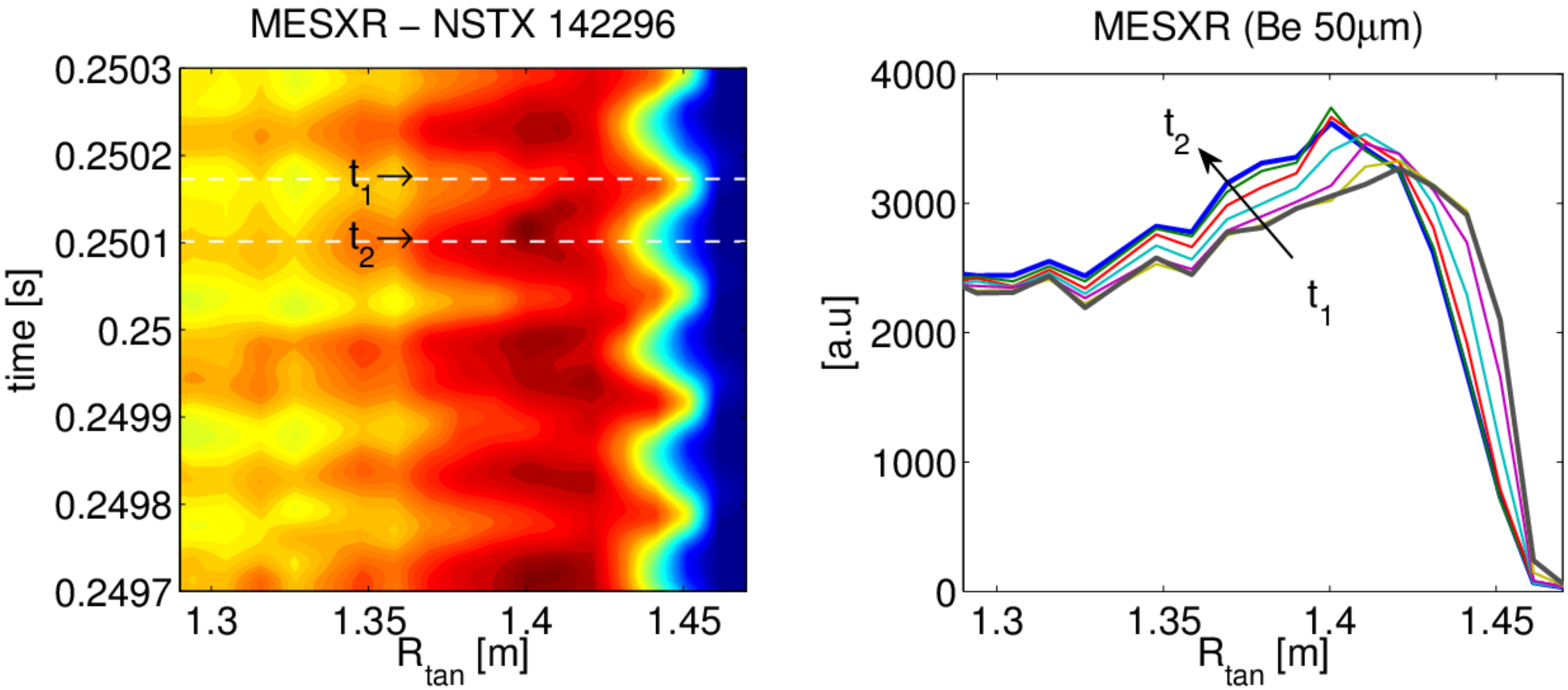
- In some discharges HF-CAEs are absent or destabilized later
- n_{FIDA} collapse observed without concurrent CAE activity





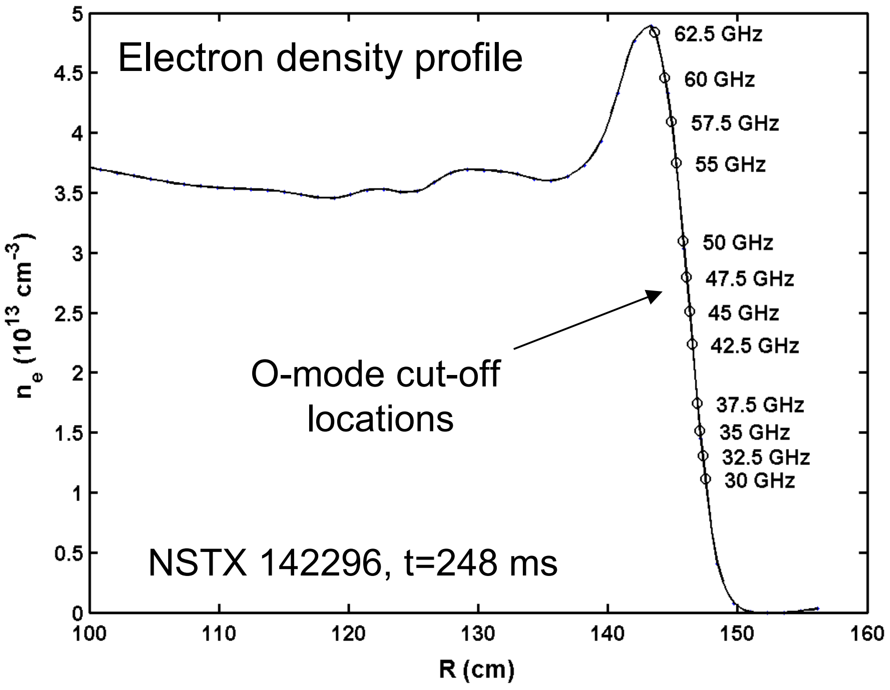
Low Frequency Mode Extends to Plasma Boundary

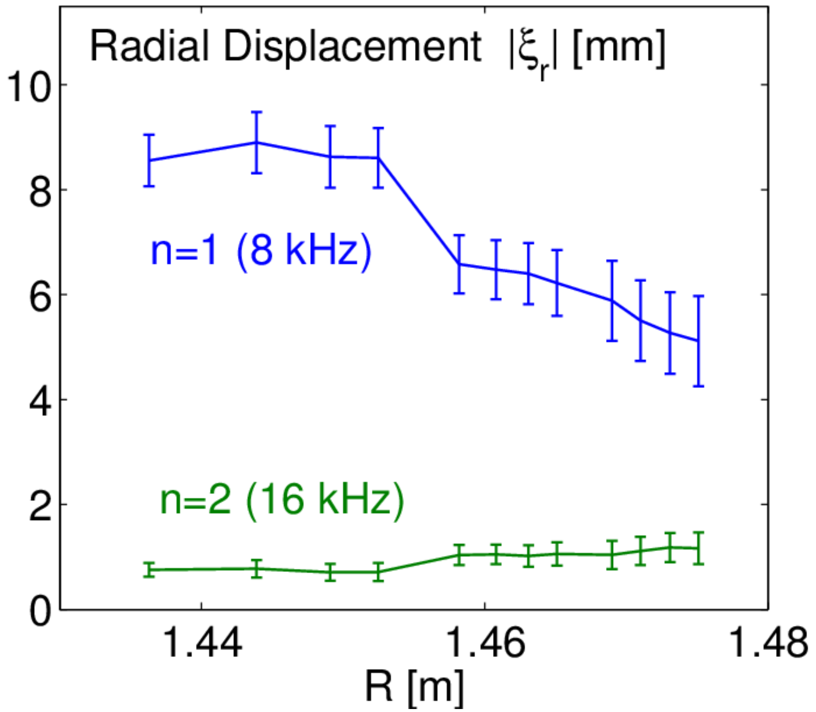
- Mirnov array indicates n=1 (B_z~15G at probe location), weaker n=2
- No clear evidence of magnetic island (e.g. in T_e or v_{tor} profiles)
- Edge Toroidal SXR array (MESXR) captures peripheral dynamic



Periodic expansion-compression peripheral region (8 kHz, r/a>0.6)

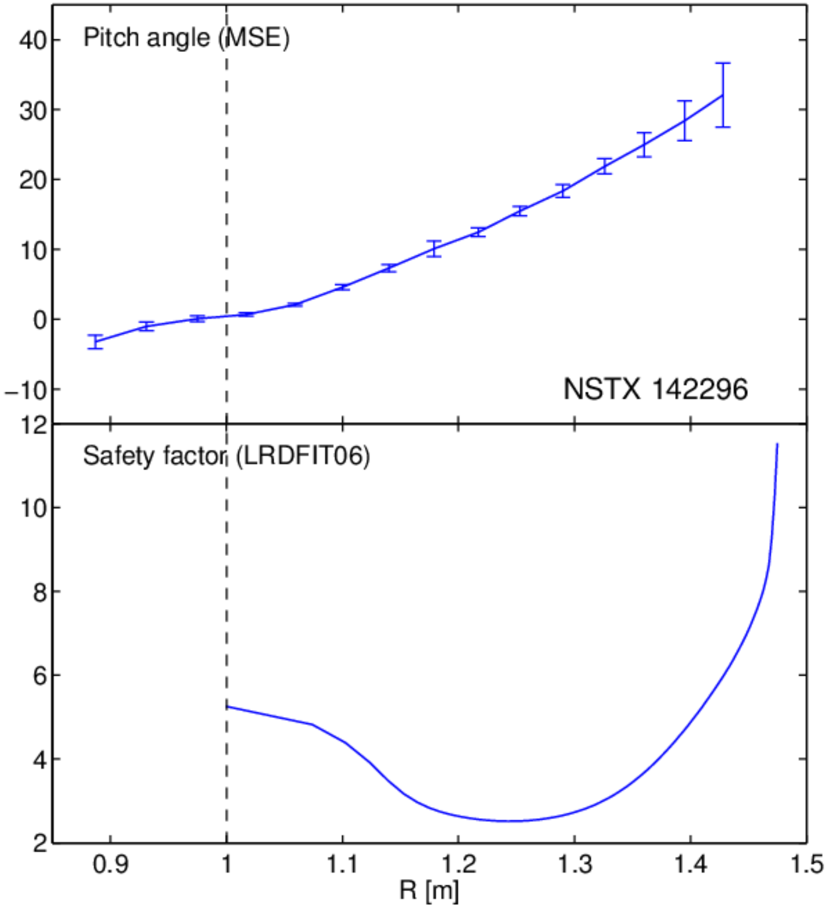
Reflectometer Measures Pedestal Displacement





- Reflectometer [6] provides local measurement of radial displacement at selected mode frequencies
- No access to internal mode structure, due to the n_e pedestal.
- Radial in-out oscillation measured at 8kHz (n=1): **ΔR~17 mm**

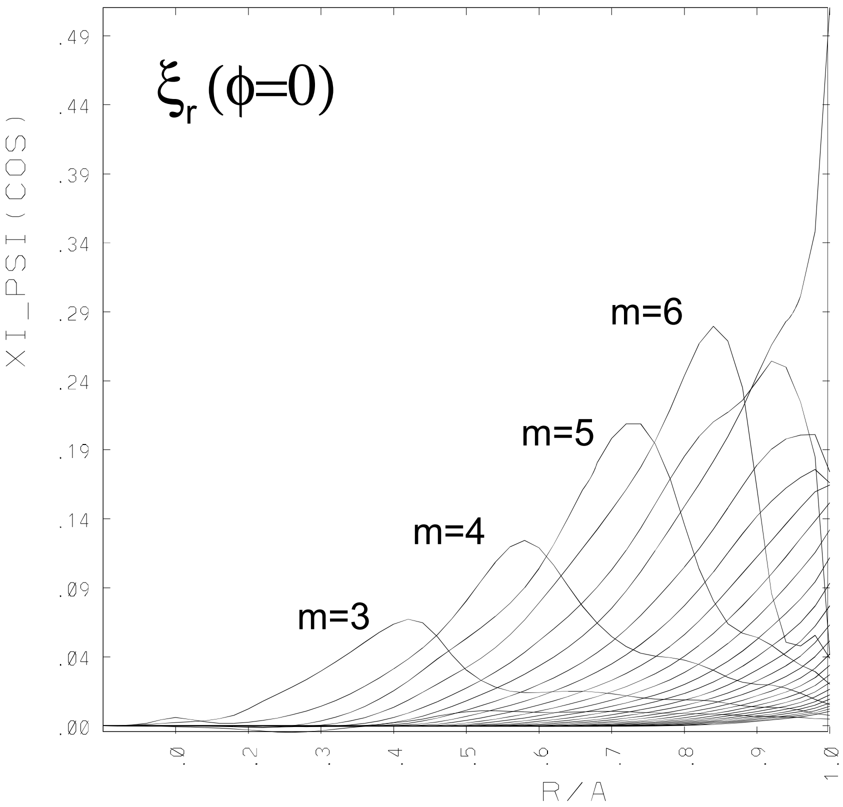
PEST Code Predicts Instability to n=1 Kink

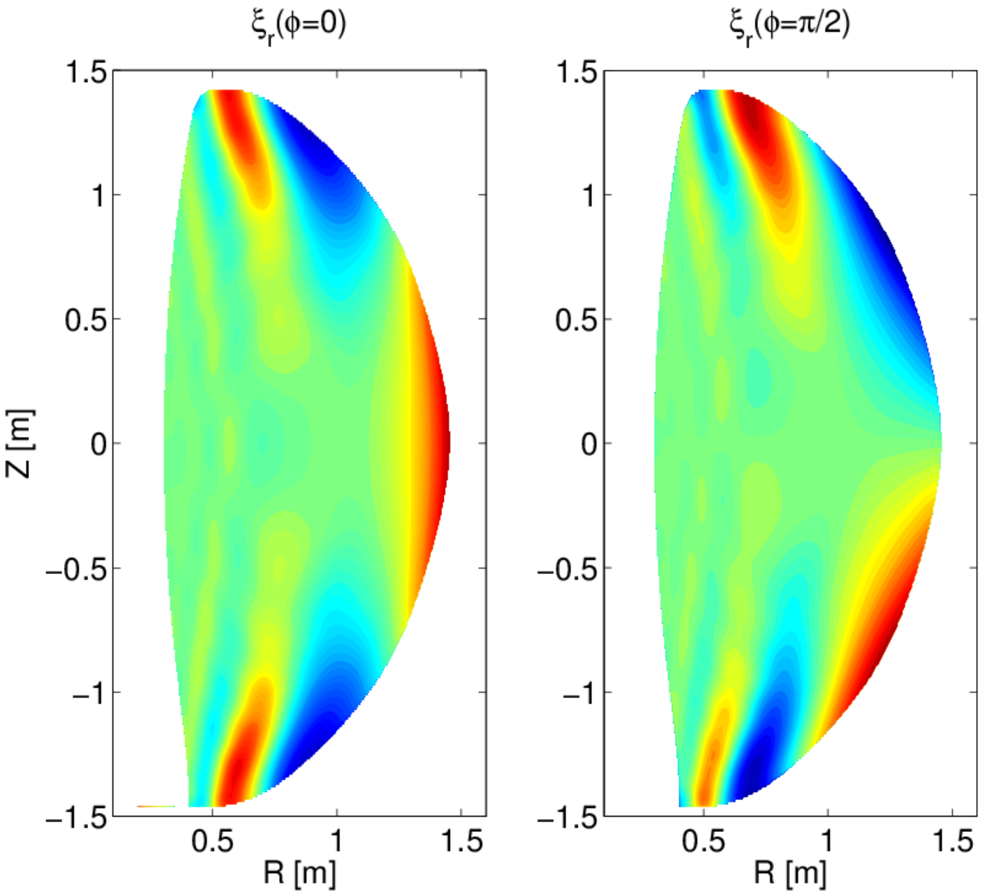


- Consider t=250ms, saturated phase, 30 ms after onset
- Plasma configuration from LRDFIT equilibrium reconstruction code
  - constraints on measured profiles of pressure and pitch angle
- Only n=1 component considered
- |m|<40 poloidal harmonics included
- Computation up to 99.98% of ψ_e

- Configuration is ***linearly unstable*** to n=1 kink under these conditions:
  - Free boundary
  - High pressure gradient at pedestal
  - Reversed shear in plasma core

Kink Amplitude Maximal at Outboard Plasma Periphery





- High order poloidal harmonics contribute in the peripheral region
- Mode amplitude is larger in the LFS (m=3-4 *effective* structure)
- Fine structure in the HFS, but smaller amplitude

Kink Structure Validation Procedure

Mode structure is checked against measurements assuming saturated structure is similar to linear computation

- 3D n_e and T_e perturbation from radial displacement:

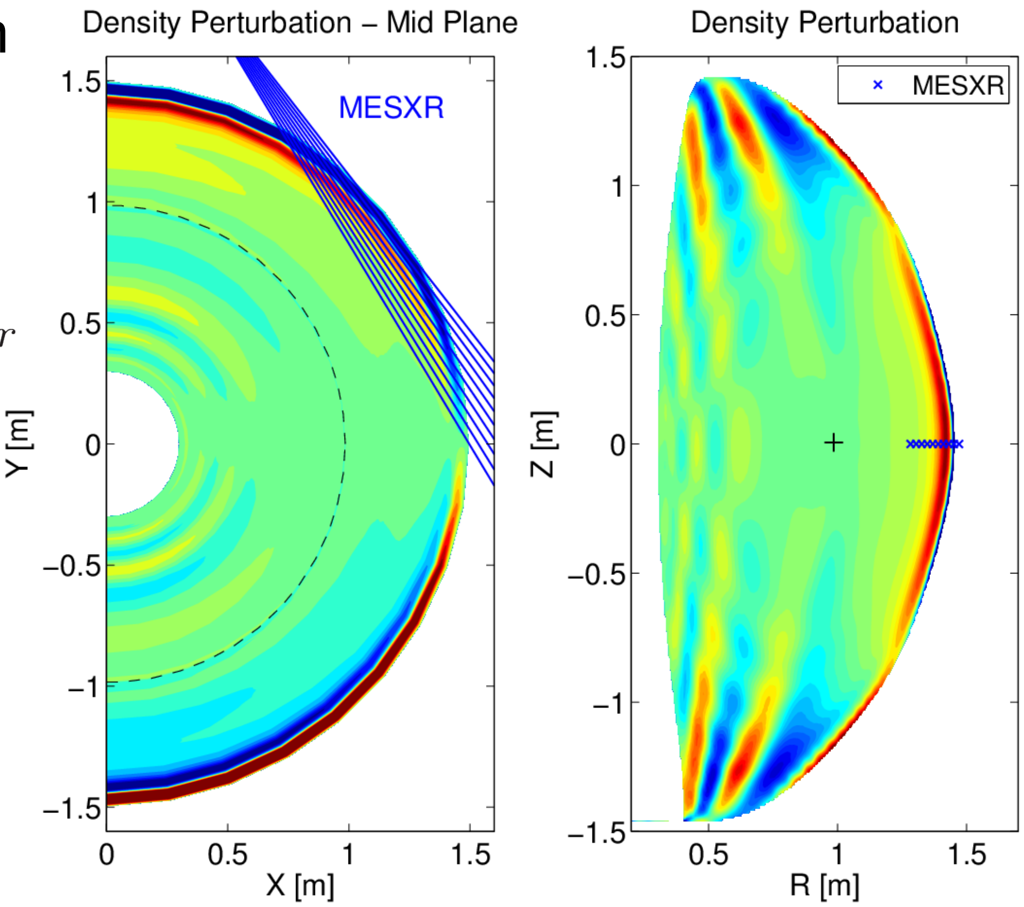
$$\delta n_e = -n_e \nabla \cdot \xi_r - \nabla n_e \cdot \xi_r$$

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

- SXR emissivity assuming carbon impurity only:

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

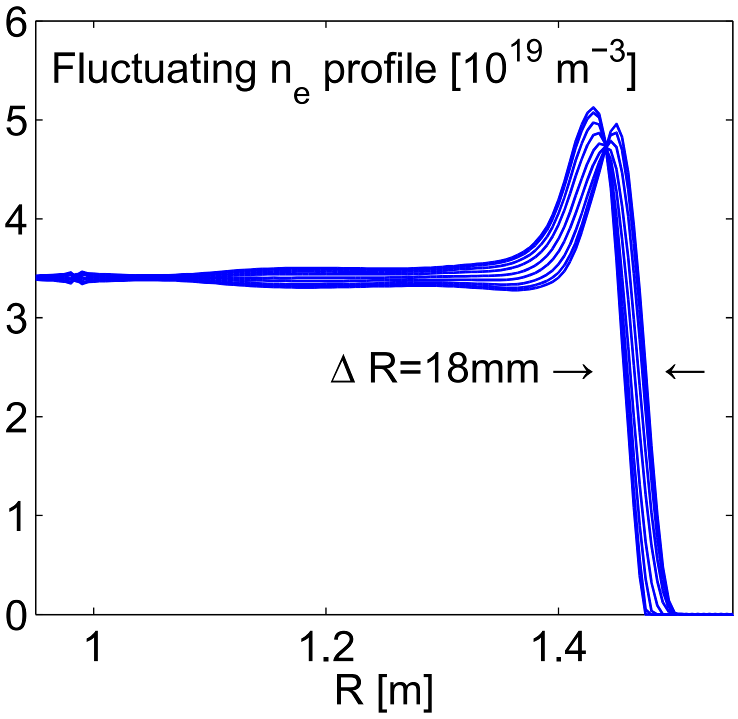
- Rigid toroidal rotation at mode frequency (8 kHz)

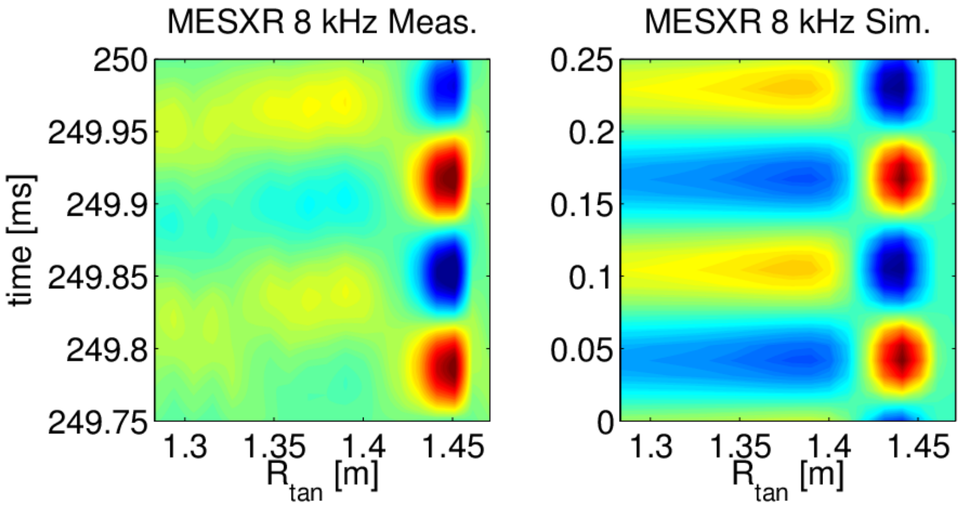


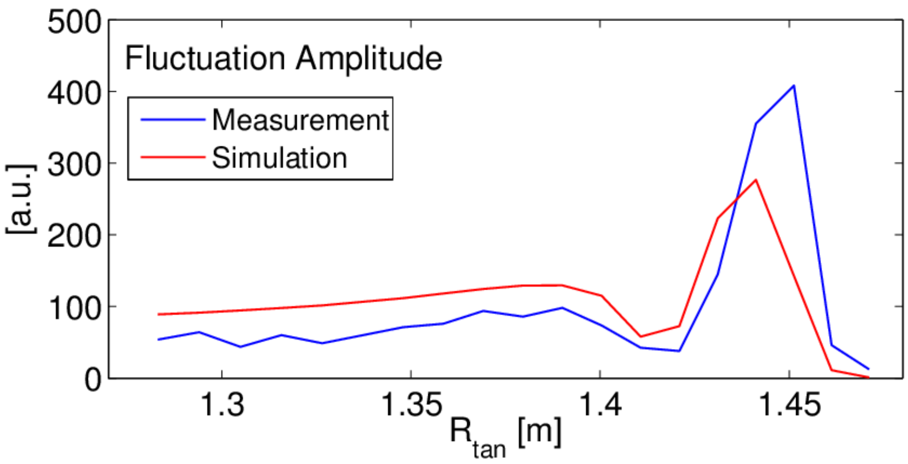
Kink Structure Validated against Experimental Data

Good agreement with data when **ξ is scaled to 2%** of PEST output

- δB_z at Mirnov coil ~ 15G
- Fluctuating MESXR profile
- Pedestal displacement ±9mm







Full-Orbit Monte-Carlo Code SPIRAL Used to Predict the Perturbed Ion Distribution Function and Particle Losses

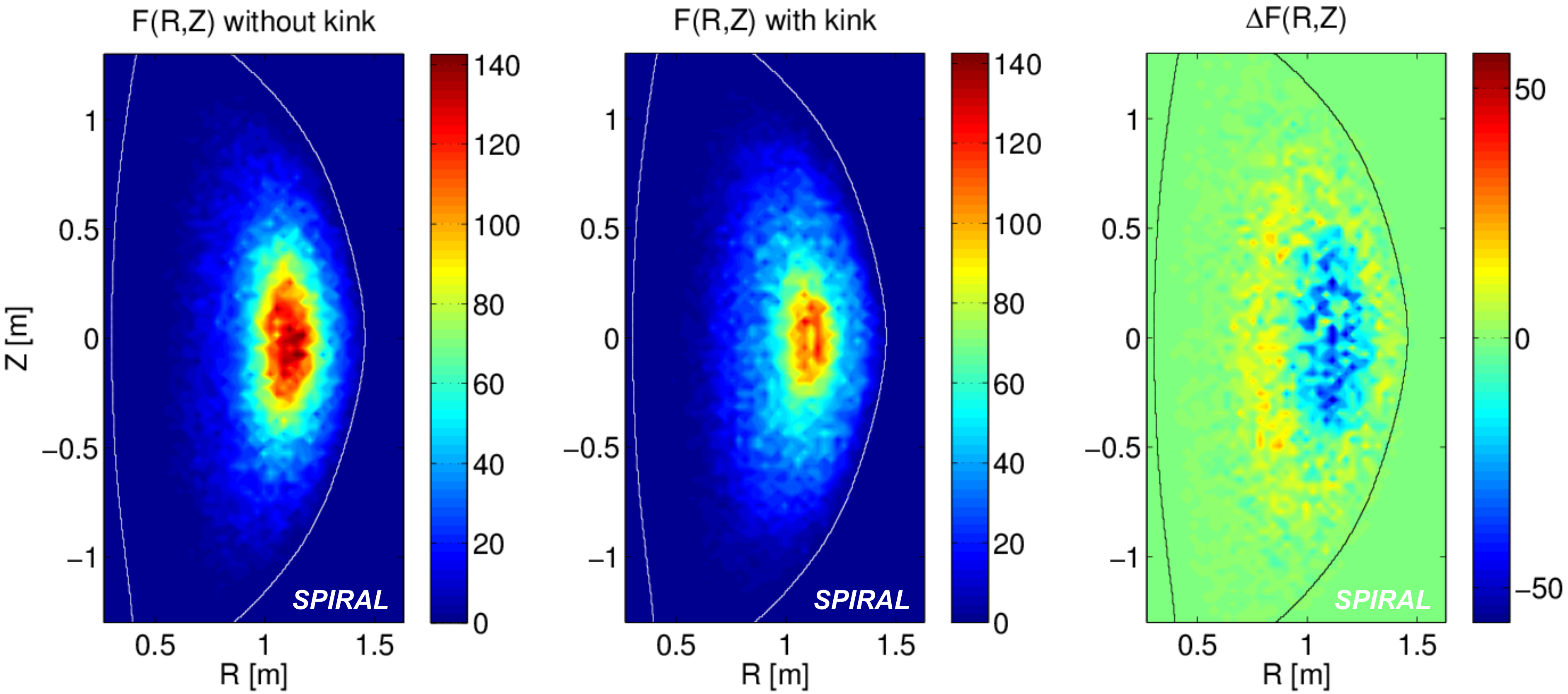
- SPIRAL [7] is adequate for NSTX gyroradii (~19cm for 90 keV D ion)
- Beam ions orbits solved in 2 magnetic configurations
  - **Perturbed** fields (PEST n=1 kink, scaled) + **unperturbed** ref. case
  - Random selection of ionizing neutrals introduced at **uniform rate** along **25 ms simulated time window** (birth profile from NUBEAM)
  - Energy slowing down time ~15ms for 90keV ion → **final distribution assumed representative of the steady state**
  - Particles hitting the **realistic wall model** are considered lost

	Without kink	*With kink*	*Increment*
Total Beam Ion Losses	*17.4 %*	*20.6 %*	*+ 3.3 %*

Predicted losses consistent with fast ion loss detector (SFLIP)
Total losses extrapolated from SFLIP observations: <5%

Confined Fast Ions are Redistributed in *Real* Space

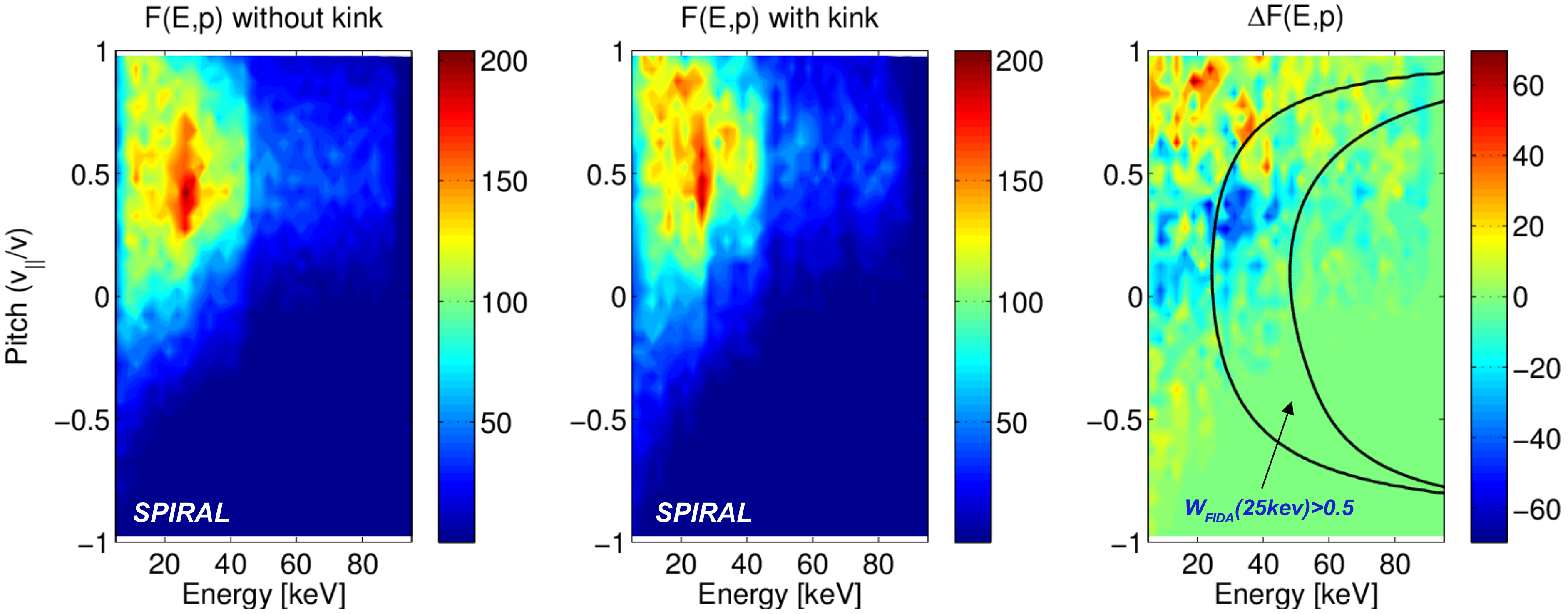
Kink effect from differential distribution function: $\Delta F = F_{kink} - F_{equi}$



Unperturbed
Fast Ion density n_{FI}
peaks in the core

- ***With kink fast ion depletion in the core***
- ***Increase of n_{FI} in the outer regions***

Confined Fast Ions are Redistributed in ***Velocity*** Space



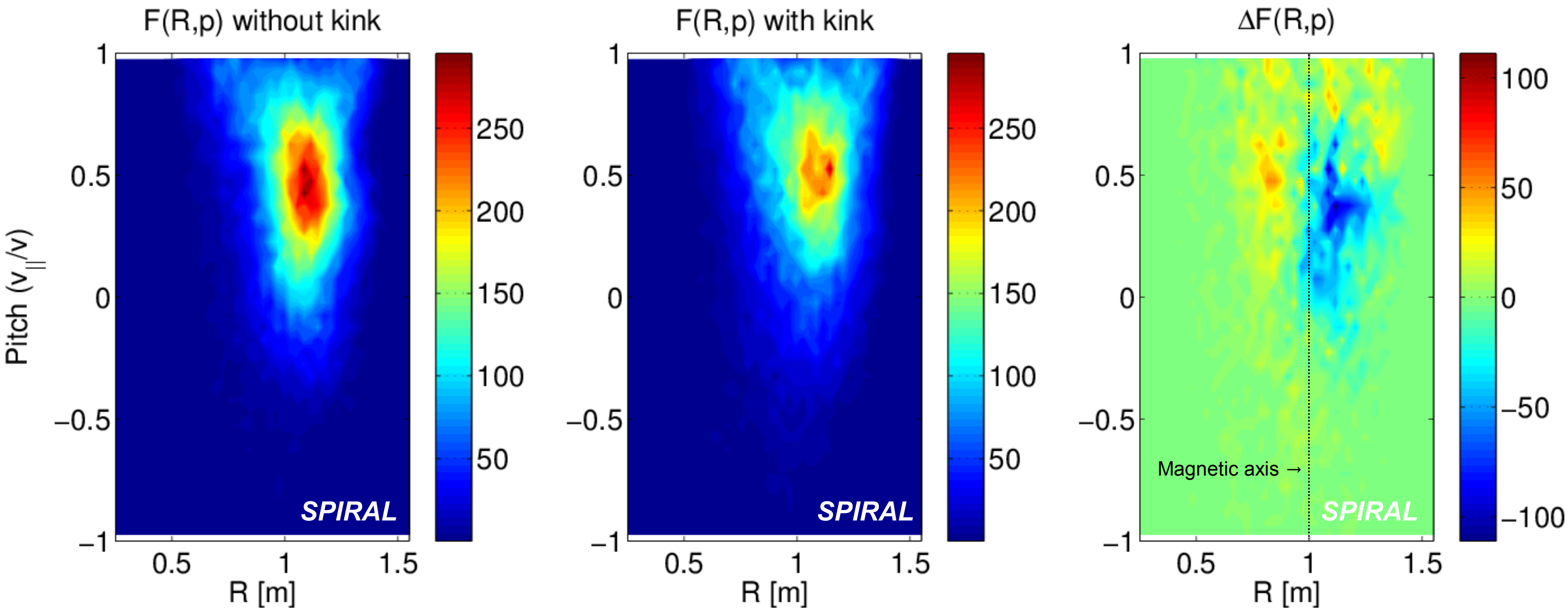
Slowing down distribution function

E_{inj}=90, 45, 30 keV

Enhanced pitch angle scattering in presence of kink

Slowing down distribution shifts towards $v_{||} / v = 1$

Radial Profile of Pitch Angle Distribution

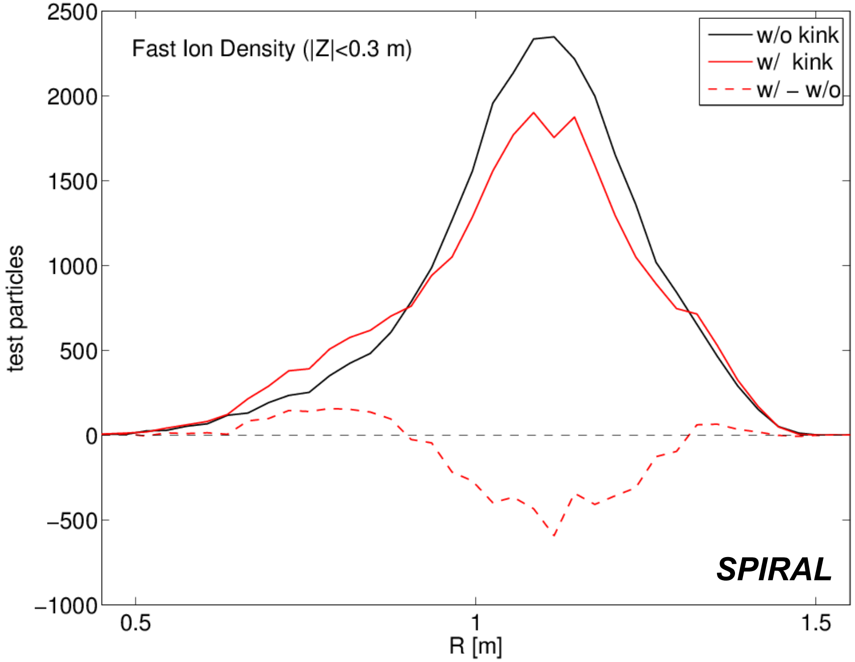


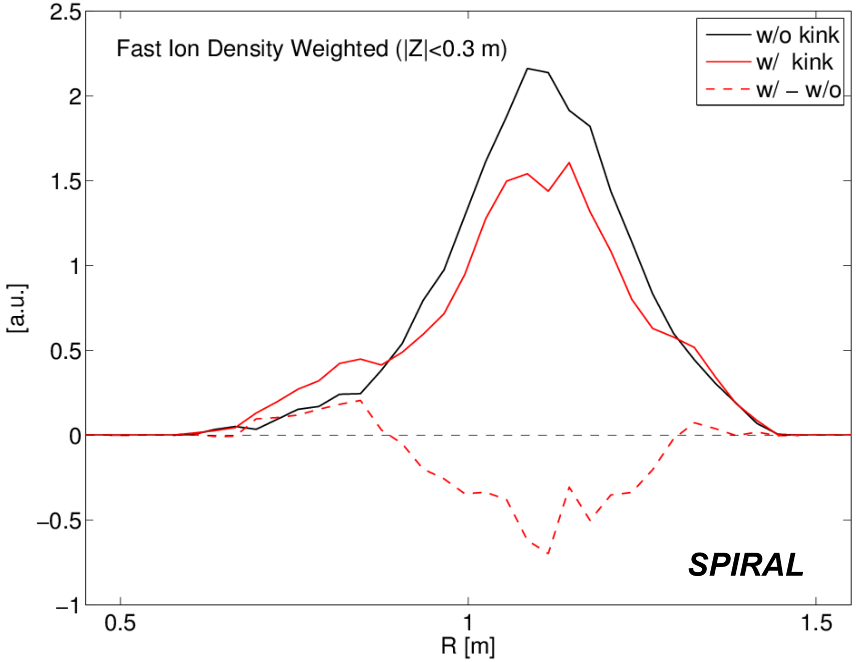
LFS → increase of ions with $v_{\parallel} / v > 0.5$ (more parallel)

HFS → increase of ions with $v_{\parallel} / v < 0.5$ (more perpendicular)

Kink Effect on Radial Profile of Fast Ion Density

Radial n_{FI} profile obtained by summing all particles in the strip |Z|<0.3 m





- ***Decrease of n_{FI} by ~20% in the core***
- ***Increase of n_{FI} for R<0.9m (HFS) and R>1.3m (LFS)***
- ***Including the effect of a typical FIDA weight function (E_λ=25keV, R=1.2m) leads to an apparent collapse of -25% in the core***

Compressional Alfvén Eigenmode Resonance

- Alfvén waves from the compressional branch $\tilde{B}_{||} > \tilde{B}_{\perp}, \quad \omega = v_A k$

- CAE are observed at frequencies fraction of the thermal ion cyclotron frequency [8,9]: $\omega_{ic}/3 < \omega < \omega_{ic}$

- Excited through Doppler shifted ion cyclotron resonance condition with beam ions:

$$\omega = k_{||} v_{||,b} + l\omega_{c,b}, \quad l = \pm 1$$

In the ion frame the wave oscillates at the ion cyclotron frequency

- For modes propagating in the beam ion direction only direct resonance is possible:

$$\omega_{CAE} = k_{||} v_{||}$$

The ion parallel velocity is equal to wave phase velocity

CAE are Localized Within an Effective Potential Well

$$\frac{\partial^2\xi}{\partial t^2} = v_A^2\nabla^2\xi \quad \Rightarrow \quad (\nabla_\perp^2 - V)\xi = 0$$

"Wave in a box" equation

Eigenvalue equation for plasma displacement

$$V = \left(k_\phi^2 - \frac{\omega^2}{v_a^2}\right)$$

Effective Potential Well

Heuristic geometrical model [10] gives:

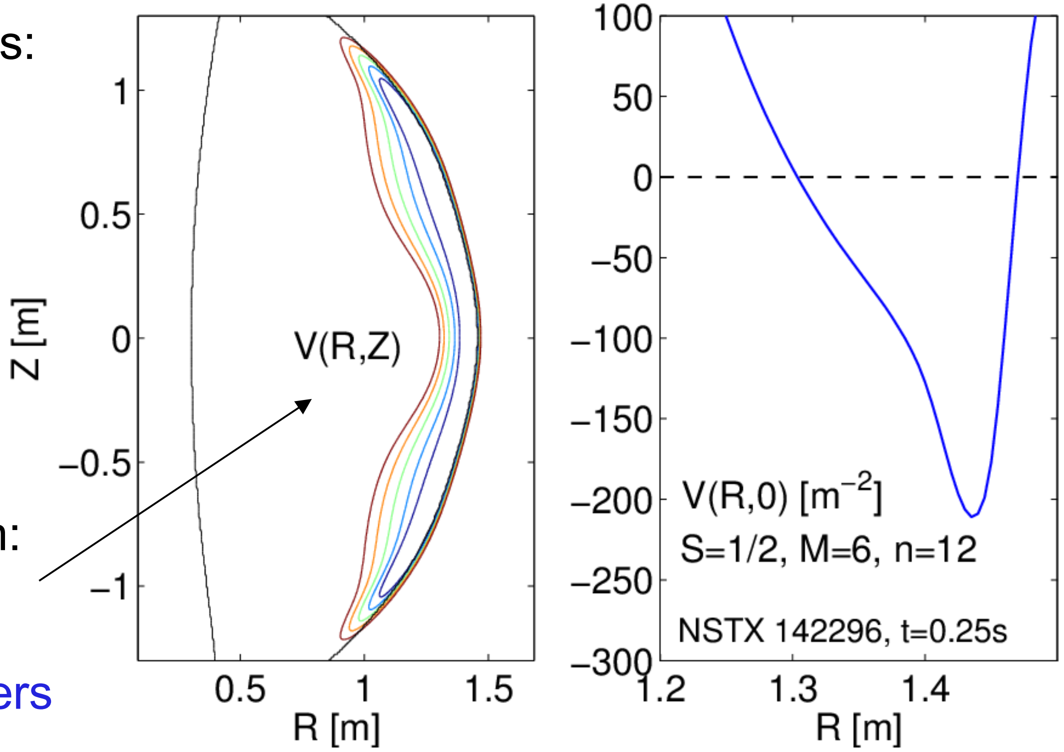
Mode "quantum" numbers

$$\omega_{CAE}^2 \approx v_A^2\left(\frac{M^2}{r^2} + \frac{n^2}{R^2} + \frac{S^2}{L_r^2}\right)$$

Potential well parameters

Well structure can be evaluated from:

1. Experimental profiles (B, n_i)
2. Selected mode/well parameters

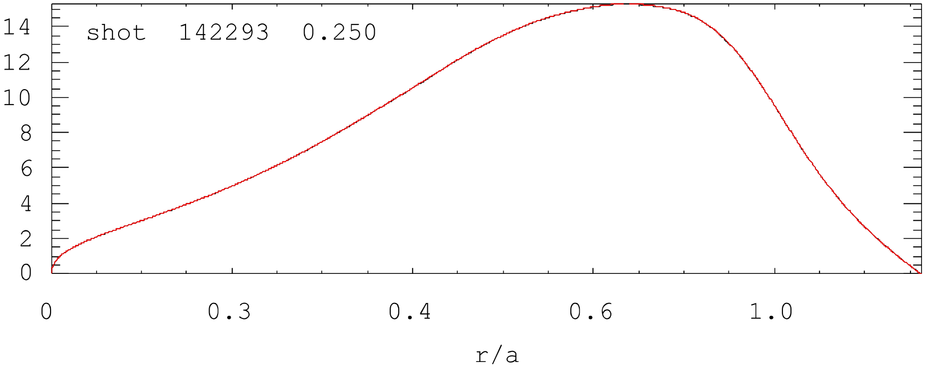


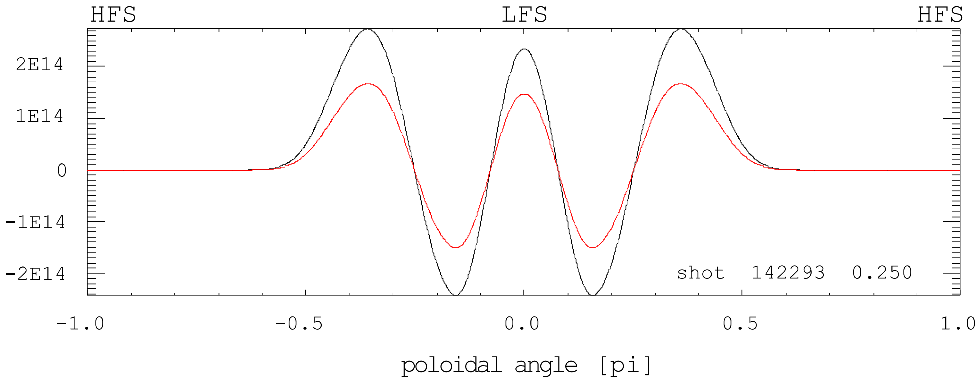
In Kink Scenario CAEs are Localized on the LFS

- Eigenvalue equation can be solved [11] separating radial and poloidal structure assuming

$$V(r,\theta) = V_r(r) + V_\theta(\theta)$$

- Calculation performed for a single mode observed in the experiment:
  - n=12, co-propagating
  - f_{EXP}=1.79 MHz, f_{SIM}1.75 MHz



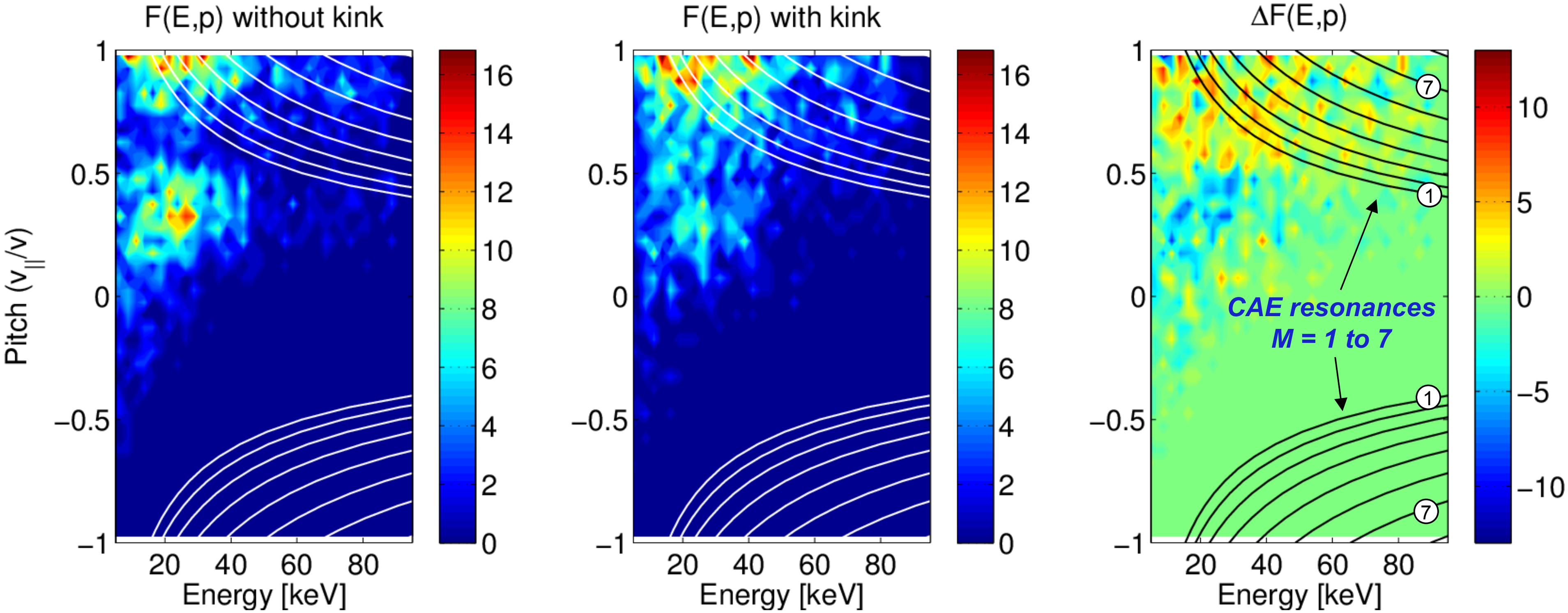


- ***Mode extends radially from the axis to the edge***
- ***Max amplitude at r/a~0.6***

- ***Even poloidal structure, localized at LFS***
- ***Low poloidal number (M<10)***

With n=1 Kink More Fast Ions are Resonant with CAEs

- Resonances evaluated from heuristic model, assuming realistic mode parameters (S=1/2, n=12, M=1-7)
- Select d.f. F(E,p) in the region of mode location: R>1.2 m



CAE resonances
M = 1 to 7

Substantial increase of fast ions in the phase space region sampled by CAEs resonances

Conclusions

- ***LF MHD is observed to affect strongly the fast ion population***
  - FIDA density reduced as much as 30%
  - Small effect on neutron emission rate
- ***LF mode nature and structure inferred by coupling ideal MHD stability calculations to experimental observations***
  - global kink nature, finite edge amplitude, associated to a residual reversed shear
  - a kink perturbed equilibrium has been constructed consistent with SXR emission and reflectometry observations
- ***Full-Orbit simulations with SPIRAL indicate FI redistribution***
  - Fast ion losses in presence of the kink increase by a small amount ~3%
  - Redistribution in both real and velocity space is predicted
- ***FI redistribution may explain the observed CAE destabilization***
  - Kink perturbation is associated with an increase of ions resonating with the modes at mode location
  - Need to evaluate the actual drive, and estimate growth and damping rates

References

Effect of low frequency MHD modes on fast ions on NSTX

[1] Medley et al. Nucl. Fusion 44 (2005) 1158

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Diagnostics and codes

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[6] Crocker et al. Plasma Phys. Contr. Fus. 53 (2011) 105001

[7] Kramer et al. Proc. of Fusion Energy Conference (Geneva, 2008) CD-ROM file IT/P6-3

Compressional Alfvén Eigenmodes on NSTX

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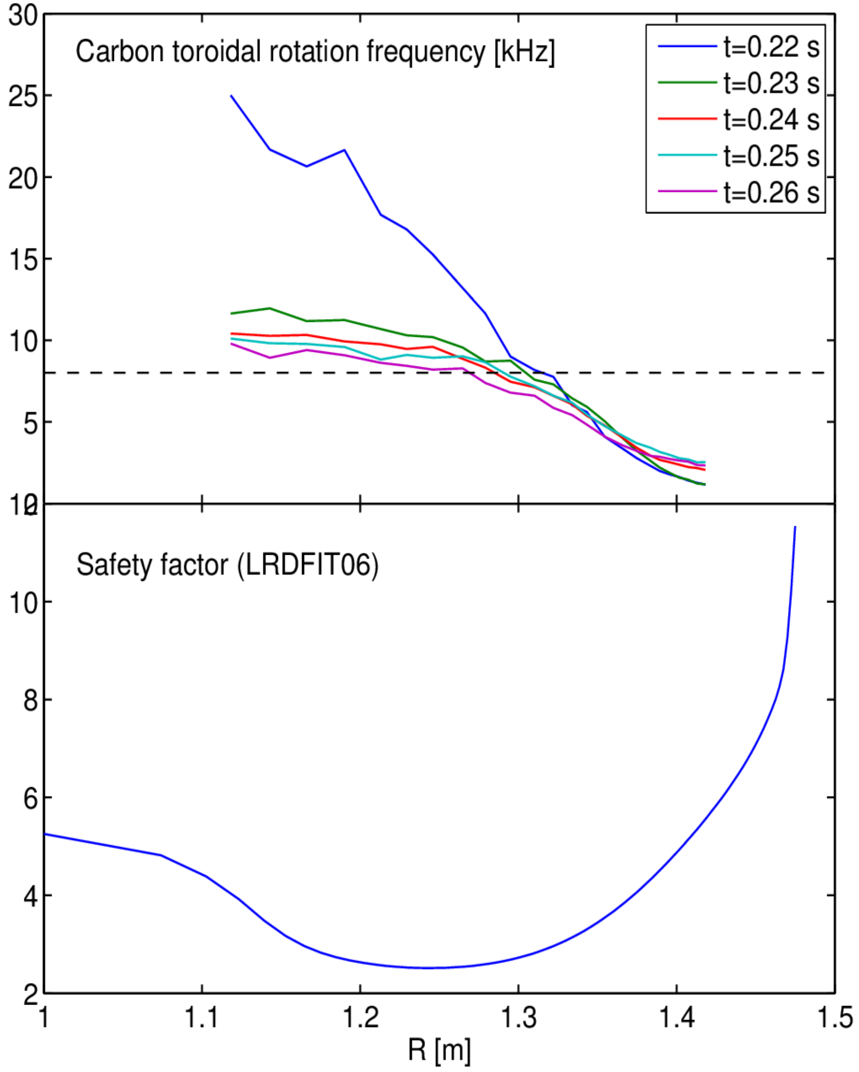
[10] Gorelenkov et al. Nucl. Fusion 46 (2006) S933

[11] Fredrickson et al. Phys. Plasmas 11 (2004) 3653

Sign-up sheet

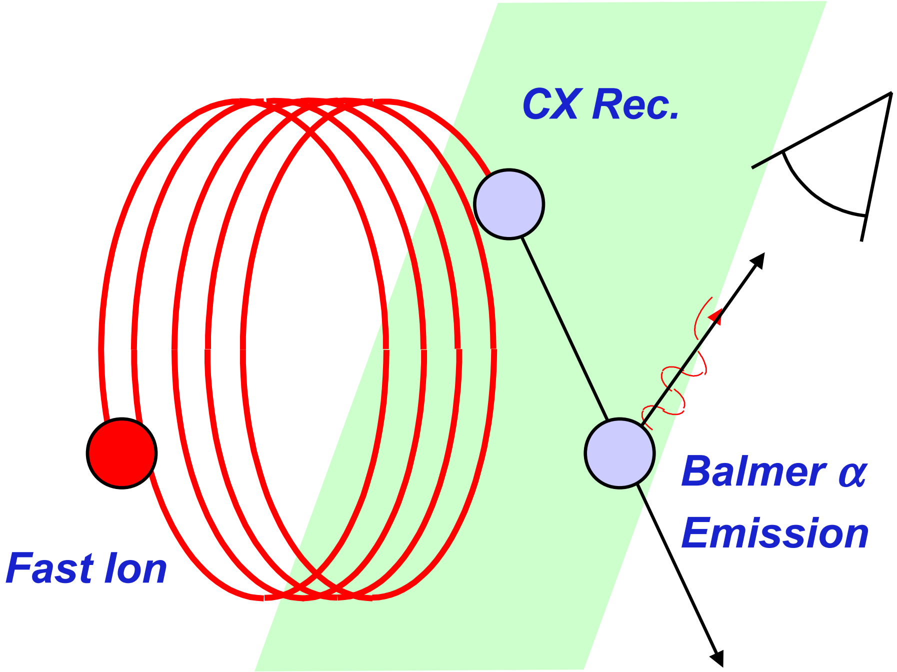
Rotation braking at kink onset



- Kink locked at the plasma rotation of q_{min} location

← Kink frequency 8kHz

FIDA measurement concept



An approximate Fast Ions Density n_{FIDA} can be obtained from

$$\int_{\Delta\lambda} s_f d\lambda \propto n_f n_b \langle \sigma_{cx} \bar{v} \rangle$$

- Active Charge eXchange
  - Measures hot tails of Balmer alpha
  - Large Doppler shift of recombining fast ions
  - Background subtraction is crucial
- Effective average over velocity space
  - Viewing angle
  - NBI geometry
  - Effective CX cross section
- Weighting $W_\lambda(E,p)$ function gives the sensitivity to different velocity space regions (pitch parameter $p=v_{||}/v$)

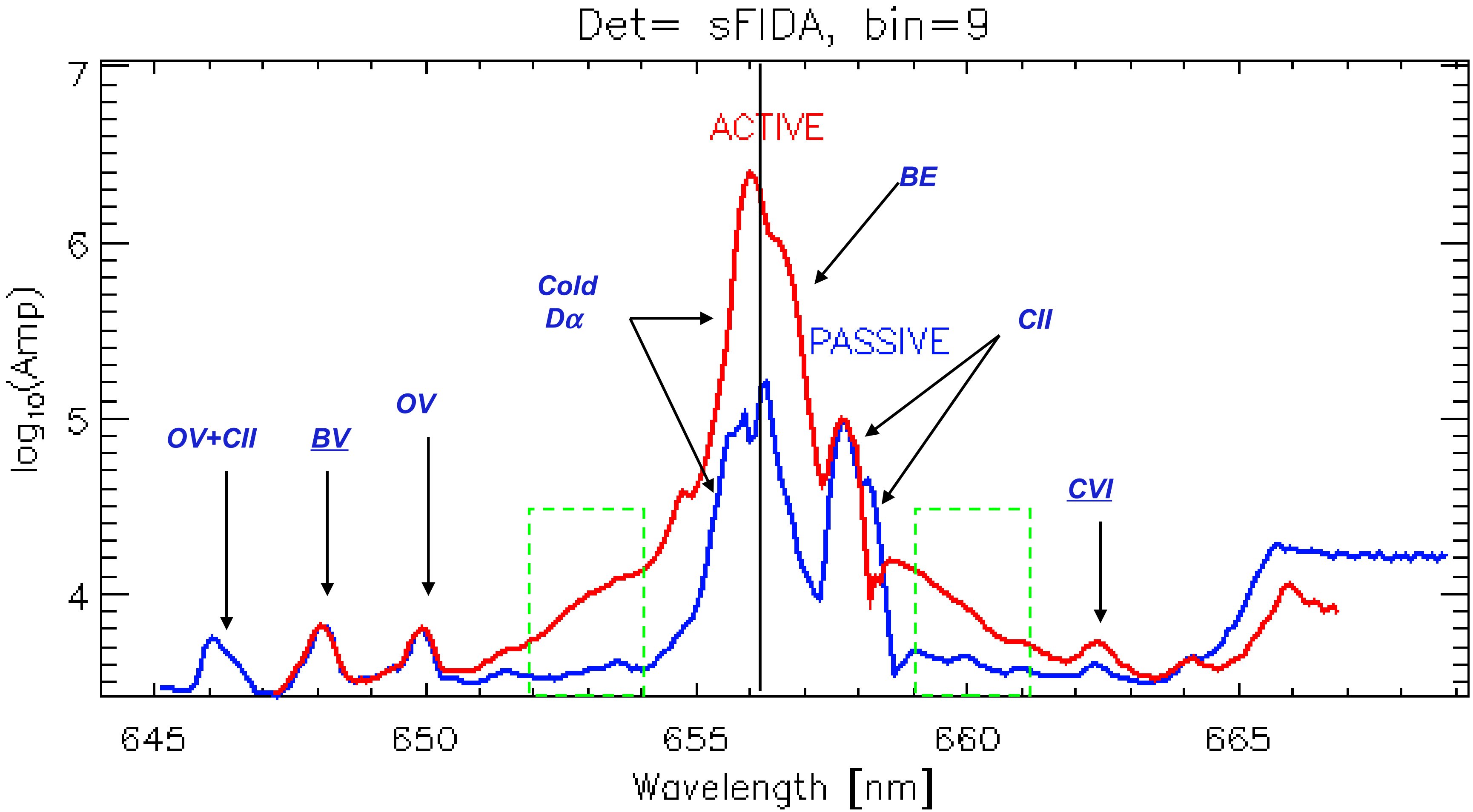
Weight function

FIDA spectrum

FI distribution function

$$s_f(\lambda) \equiv \int\int W F_f dE dp$$

Example of FIDA spectrum (NSTX vertical view)



NSTX FIDA response

- $W_\lambda(E,p)$ evaluated at
  - R=1.2 m,
  - E_λ=35 keV (652.1 nm)