NSTX-U

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U.S. DEPARTMENT OF ENERGY | Office of Science

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

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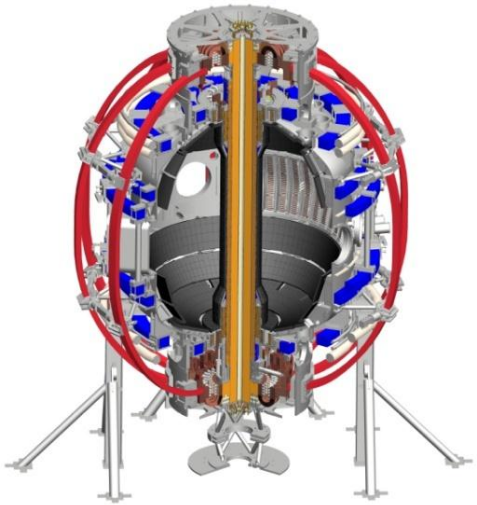
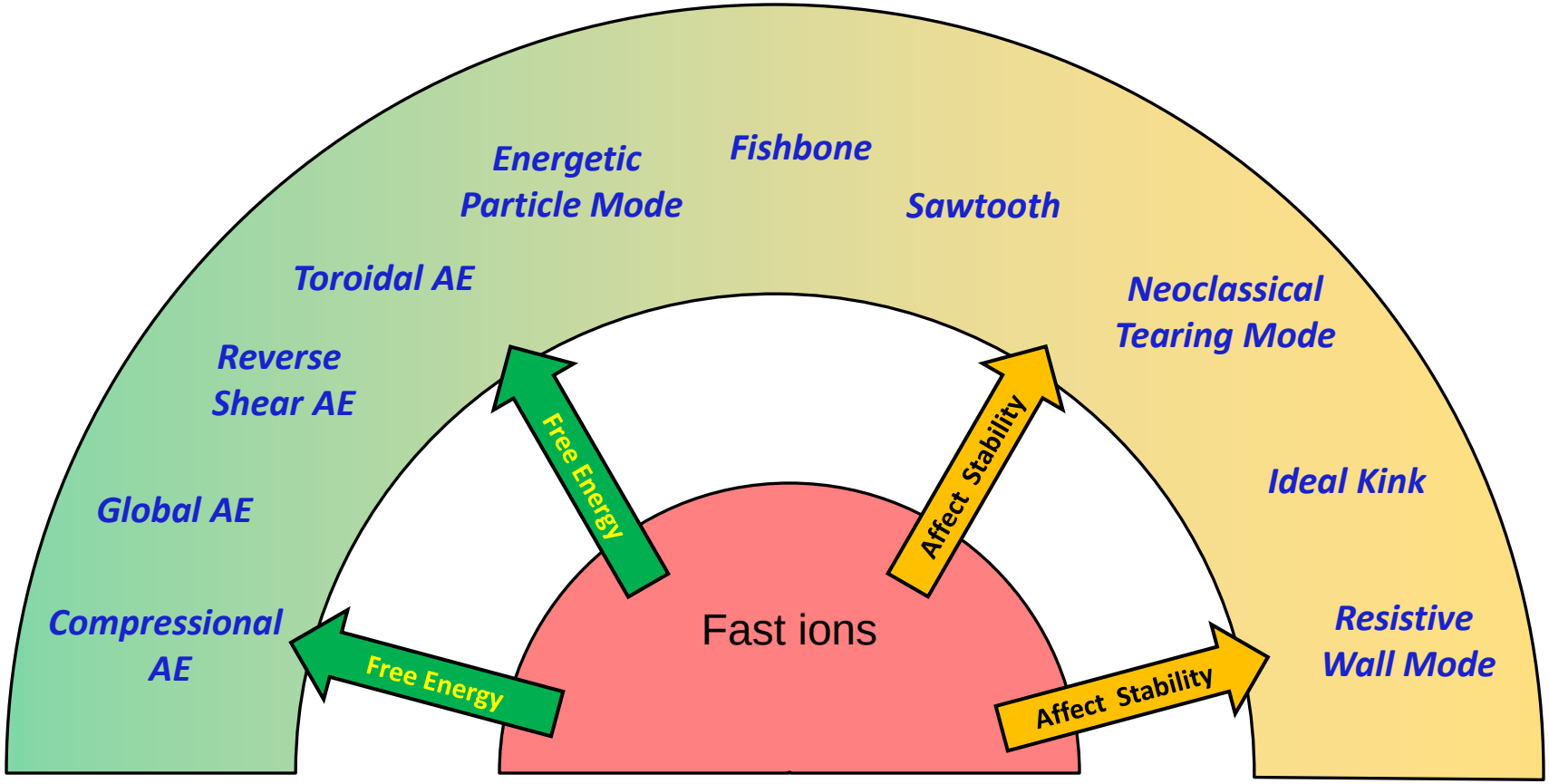


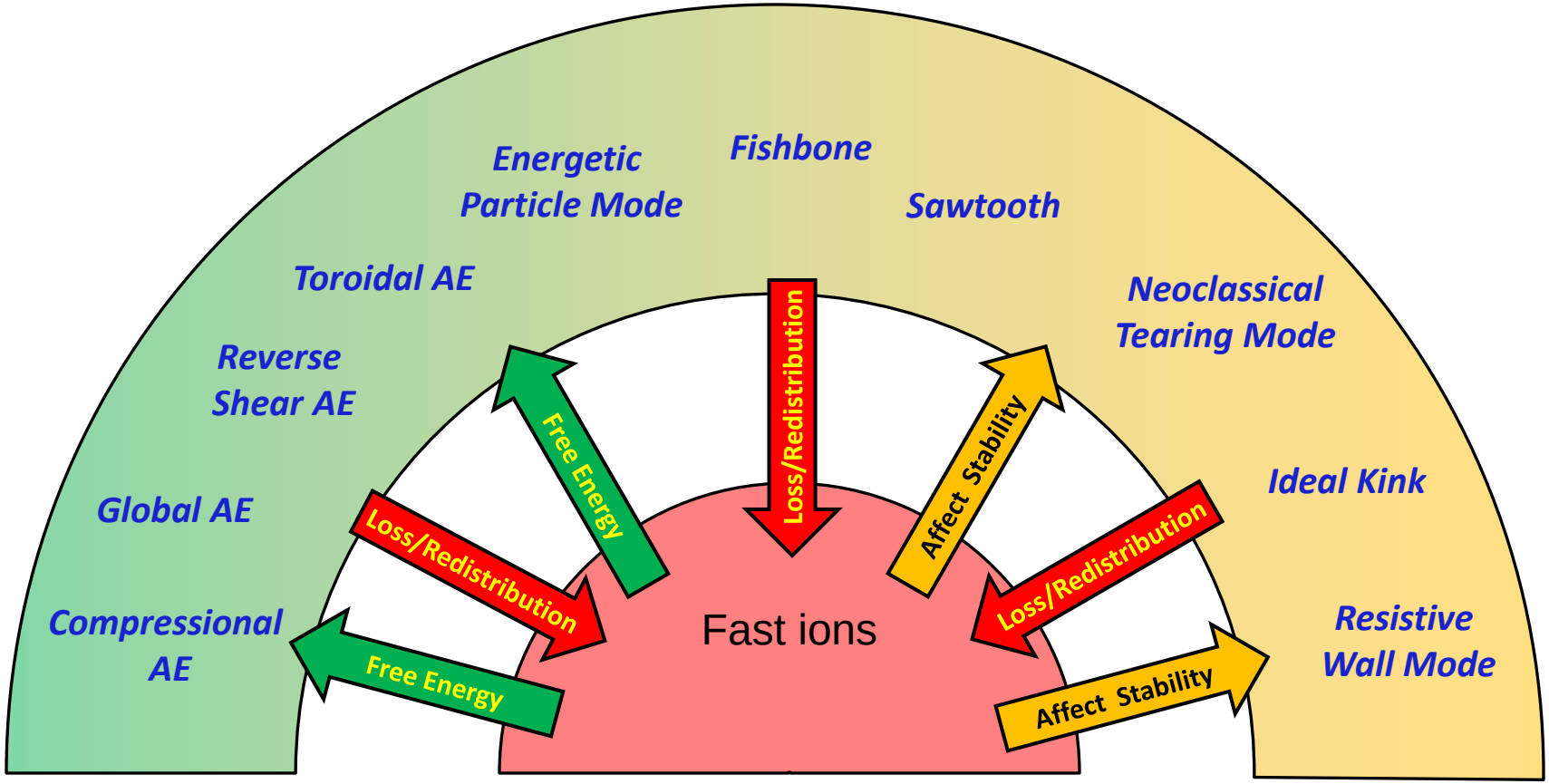
Motivation and observations

- 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

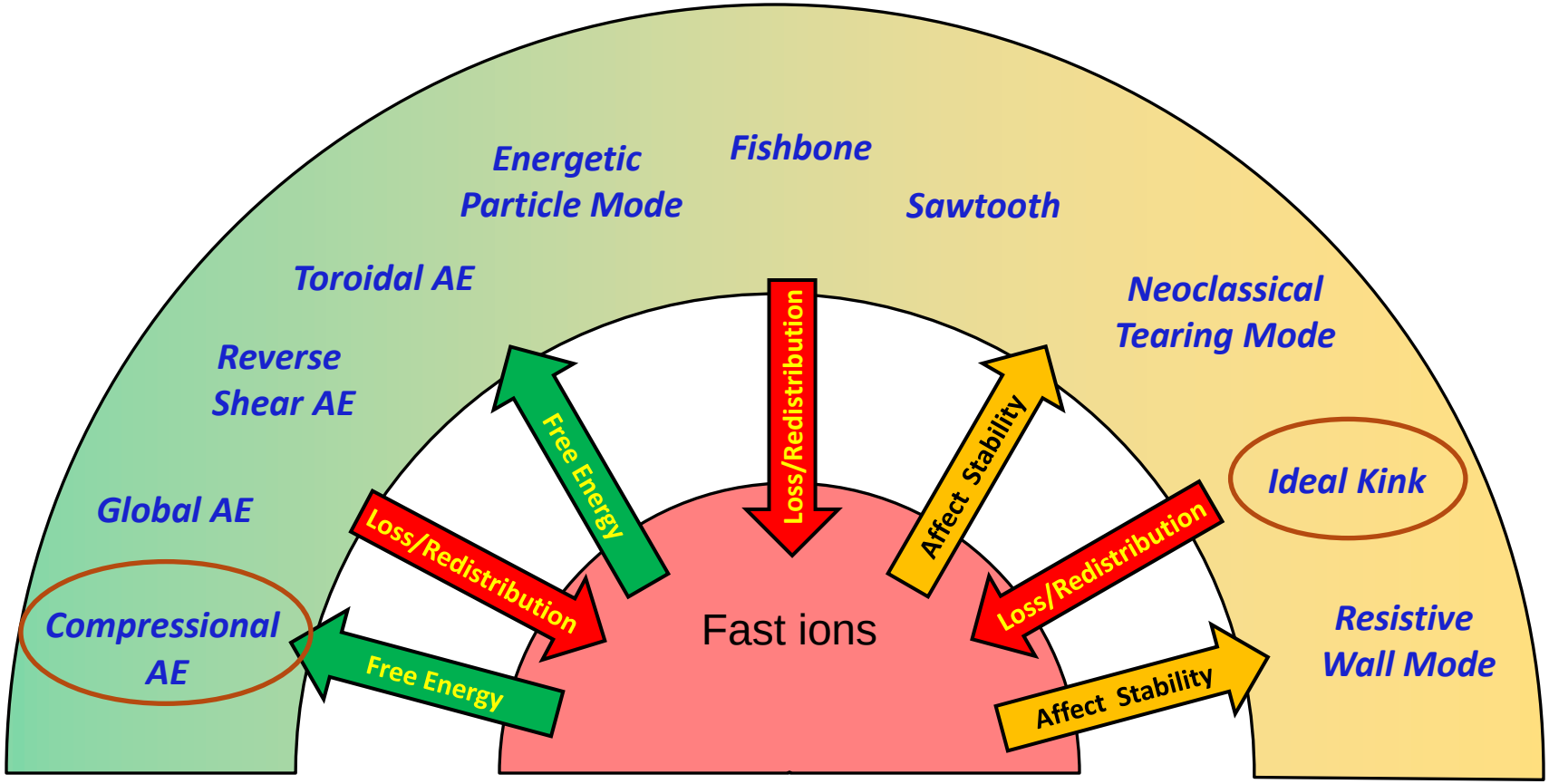
Fast-ions can modify MHD instabilities



Instabilities can modify fast ion distribution

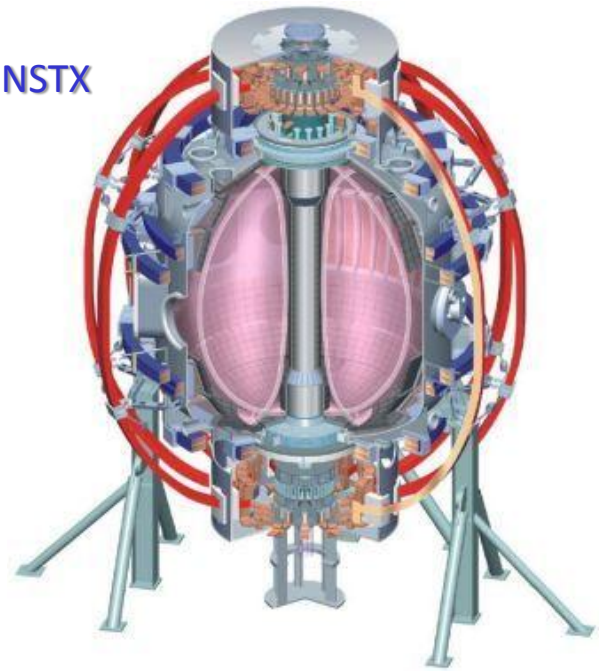


Fast-ions can mediate the interaction between instabilities



The spherical tokamak is an excellent laboratory to study mode interplay

NSTX



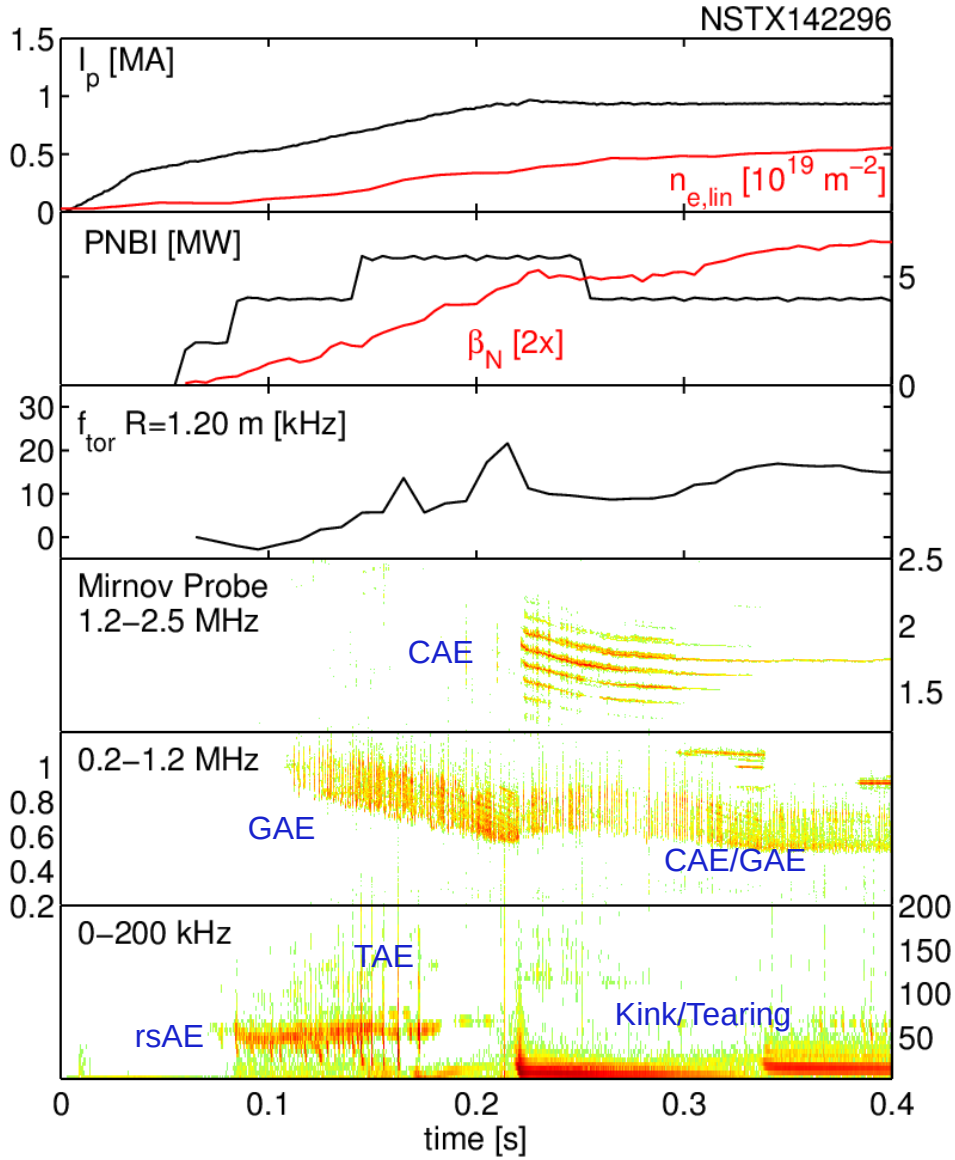
- High β, close to ideal stability limits
  - favors the appearance of ideal kinks, RWM, NTM
- Low B_{tor}, high density → "low" Alfvén speed
  - large population of super alfvénic ions
  - favors the drive of Alfvén Eigenmodes (AE)

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

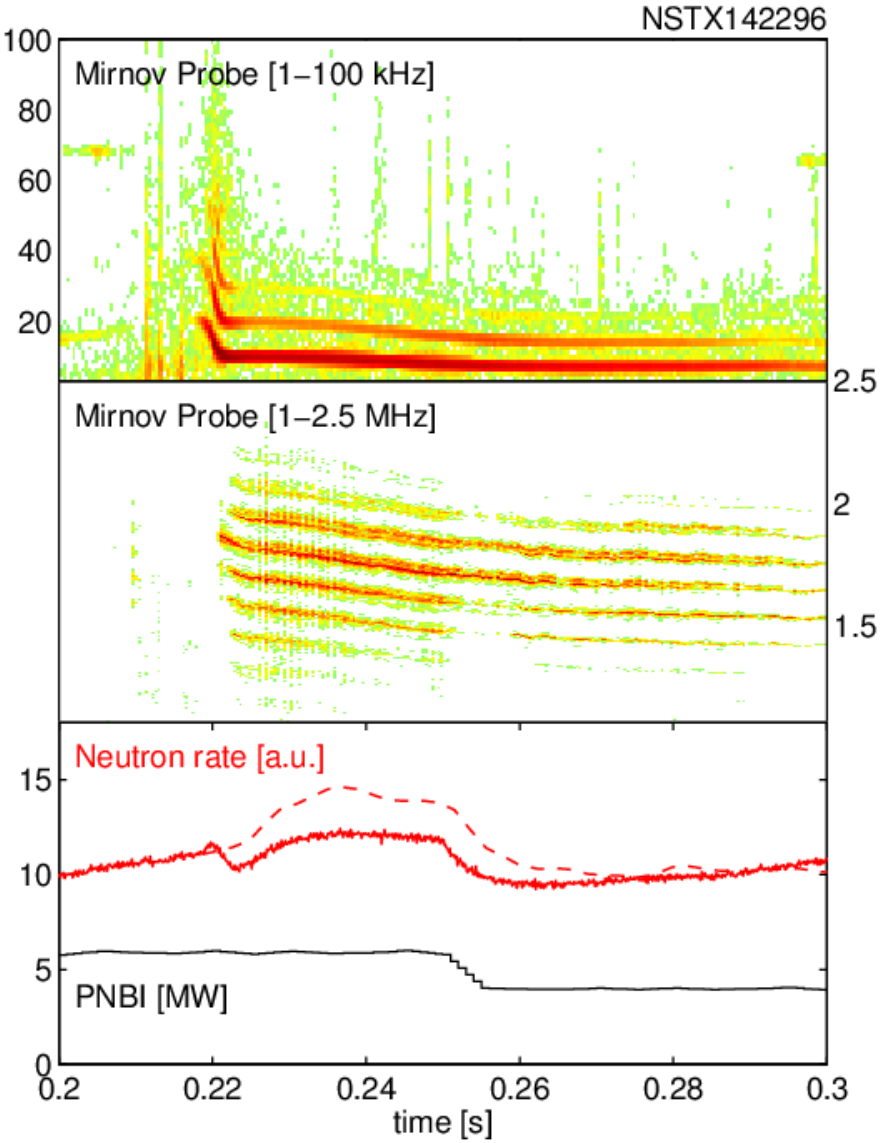
NSTX diagnostics	
Plasma	TS, CX, MSE
Fluctuations	Mirnov ,SXR, Reflectometry, BES
Fast Ions	Neutrons, FIDA, NPAs, Loss detector

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



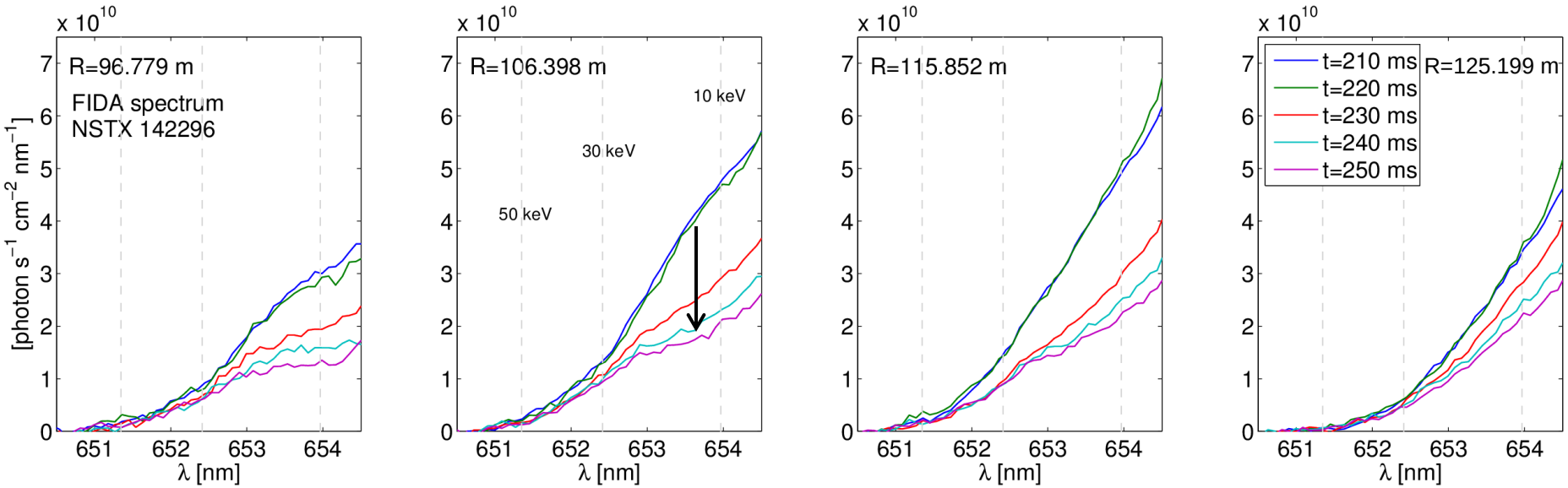
- Low Frequency mode enters with multiple toroidal harmonics
- n=1 (8kHz) and n=2 (16kHz) persist
- Initial chirp associated with the toroidal rotation drop (-15kHz)

- 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)

FIDA spectra show strong effect on fast ions

Fast Ion D-Alpha diagnostic observes the hot tail of Deuterium Balmer-a spectral line (656.1nm) emitted by recombined fast ions



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

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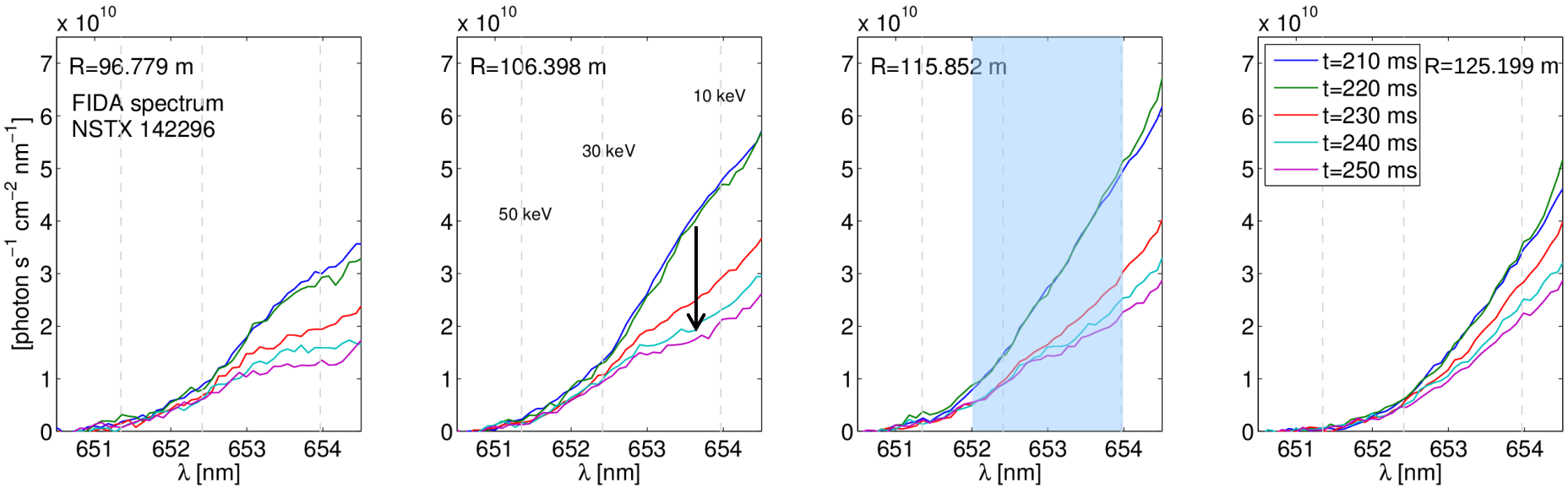
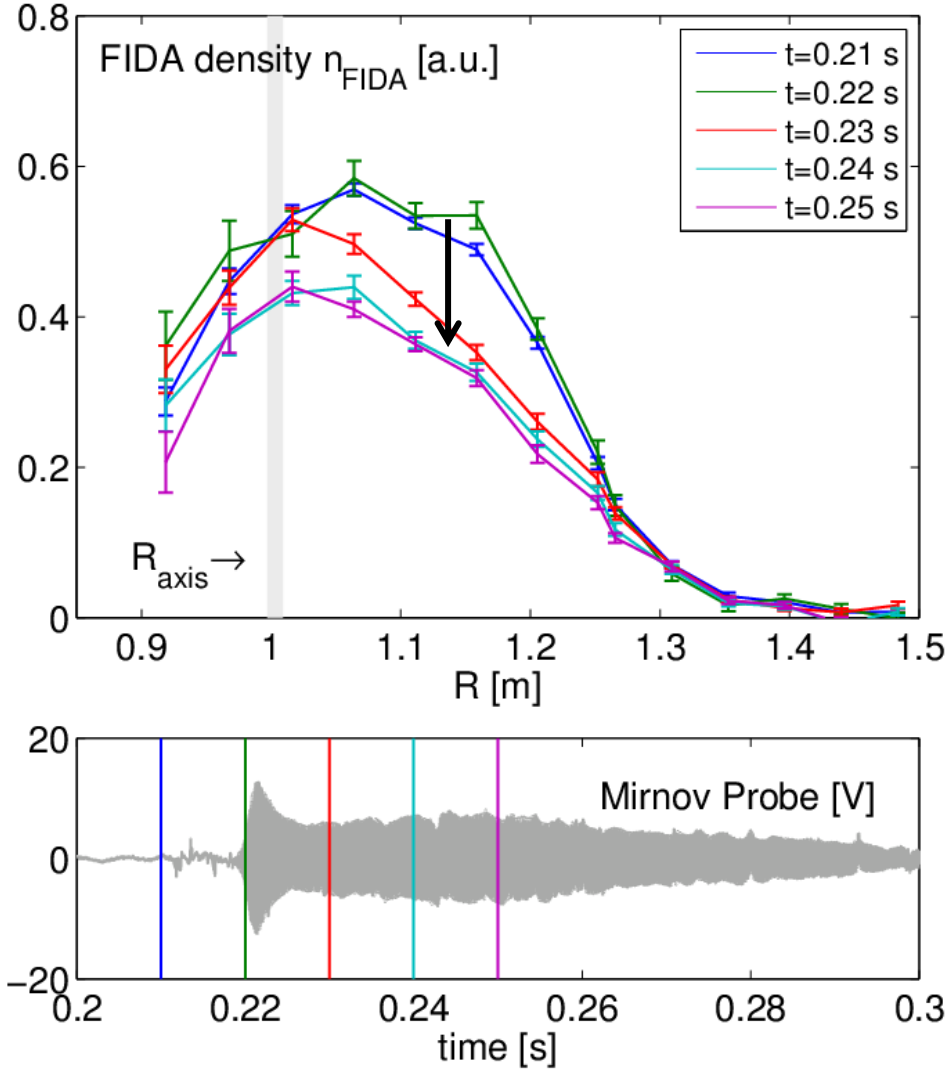


- Spectral signal decreases in a broad range of wavelength/energies
- Vertical view → sensitive to low pitch ($p=|v_{||}/v|$ <0.6)
- Low Frequency MHD activity affects the trapped population

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} <u>consistently</u> 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

2. Computation of losses and redistribution caused by the low frequency MHD

3. Characterization of CAE and coupling with fast ions

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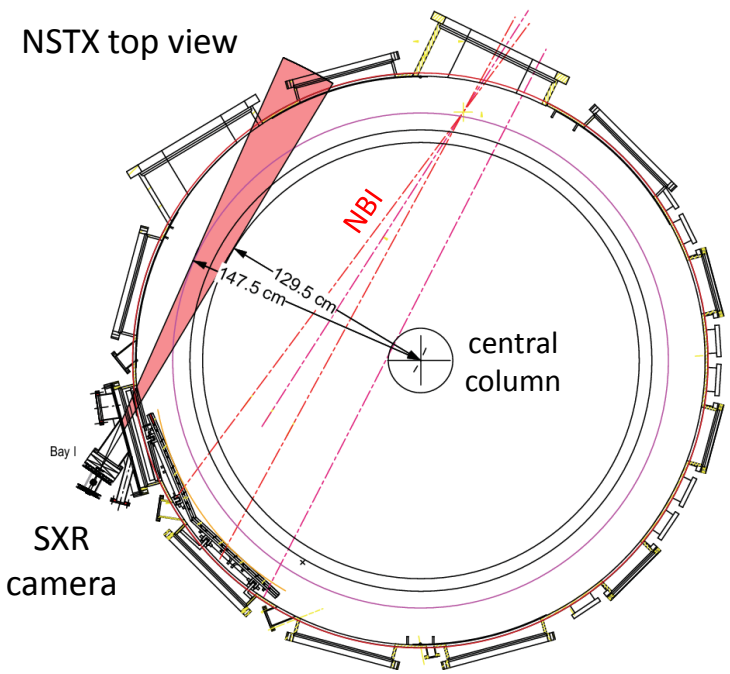
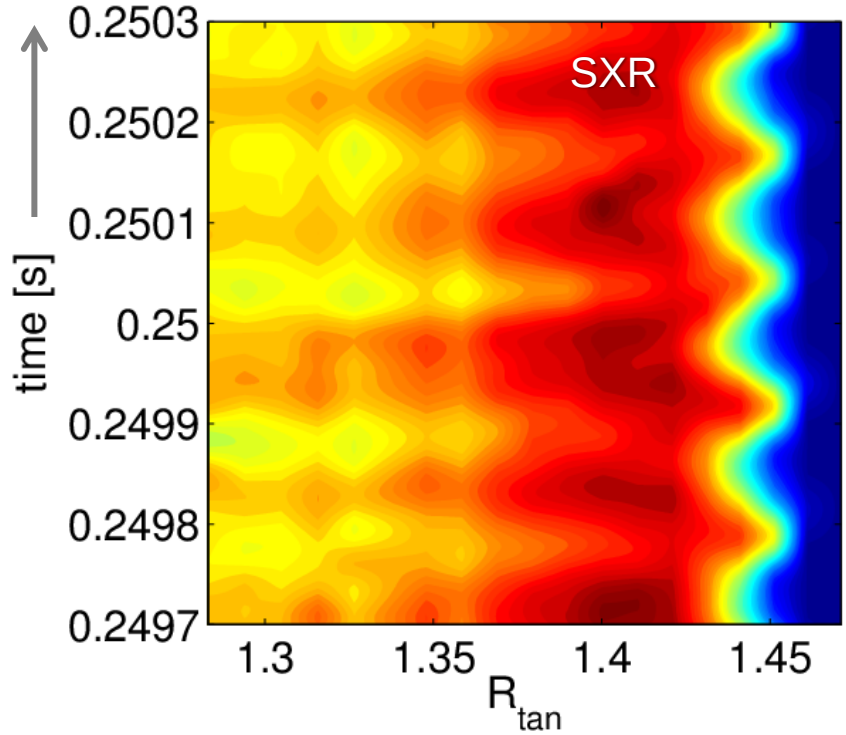
LF-MHD appears as perturbation near the plasma edge

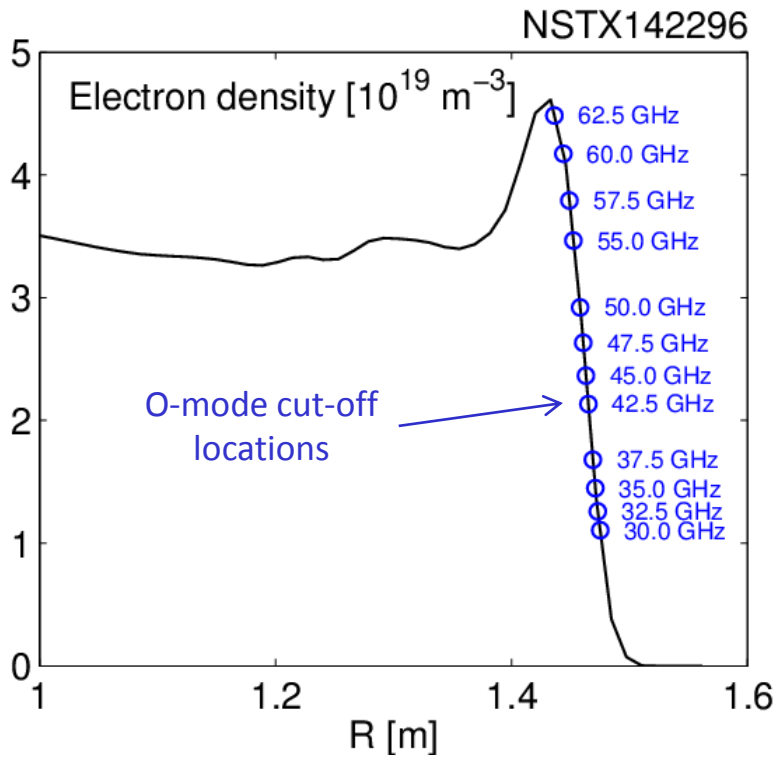
- Tangential SXR camera (20 chords, R_{tan} = 1.3-1.55 m, 50 µm Be)
- Evolution of line-integrated emissivity captures mode dynamics
- Periodic expansion-compression at 8 kHz for r/a>0.6

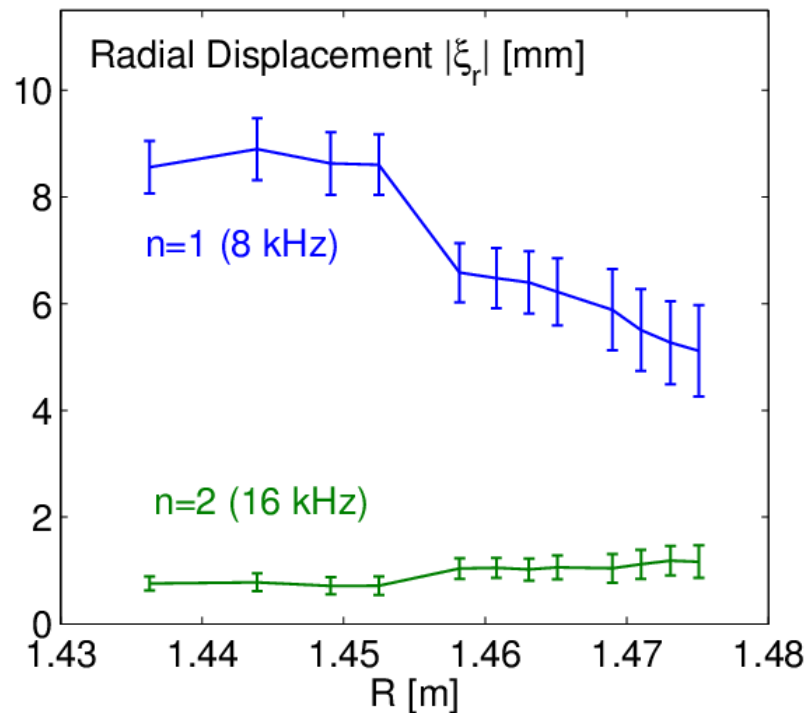




Reflectometer provides local measurement of radial displacement

- 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)

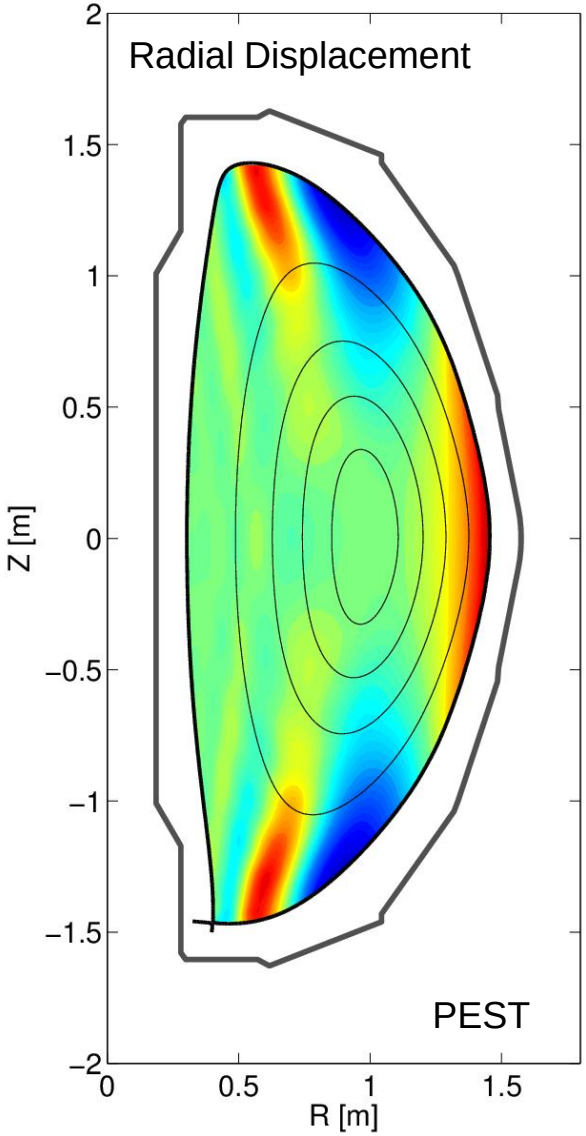




Free boundary PEST simulation predicts instability to n=1 kink

- 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:

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

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

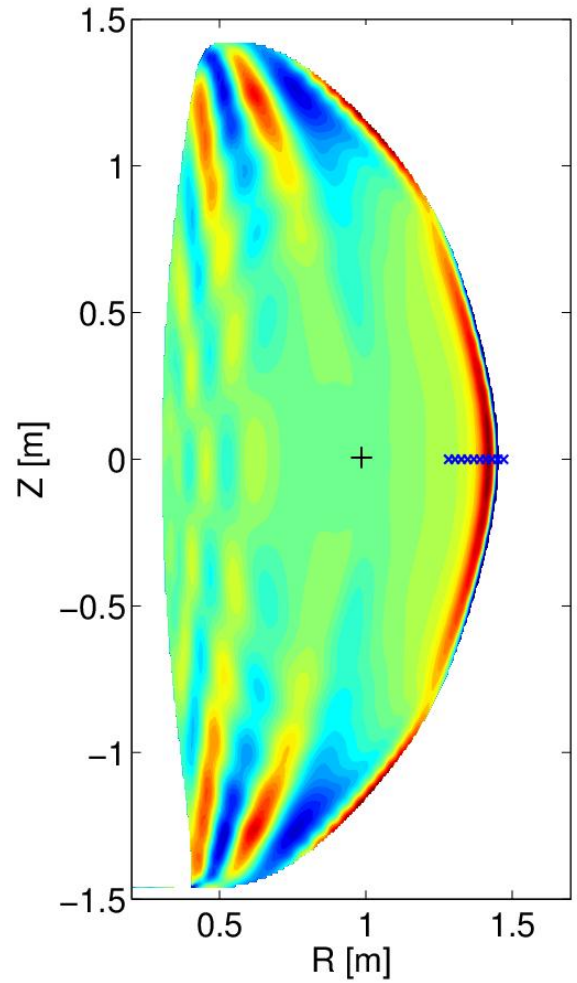
2. SXR emissivity assuming carbon impurity only:

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

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

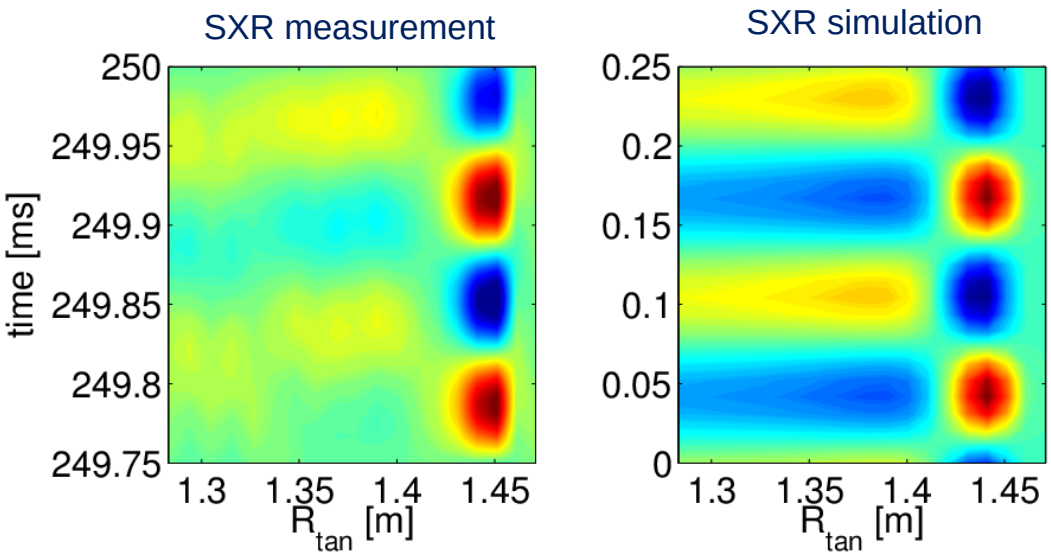
Assumption: structure to linear solution is preserved in the saturated phase

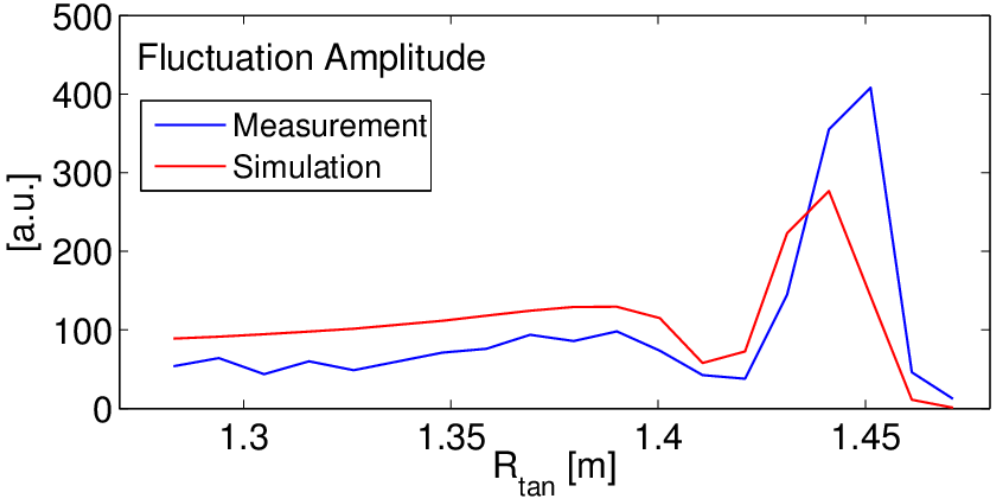
Simulated density perturbation



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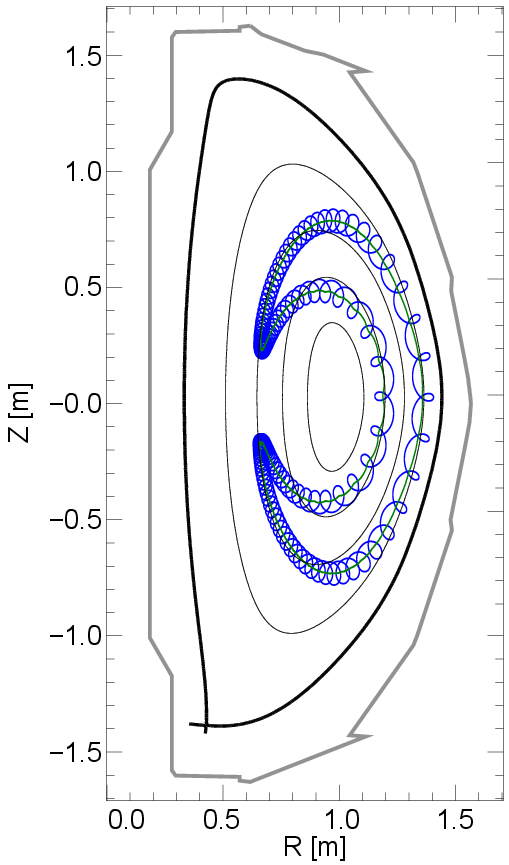
Full-orbit Monte-Carlo code SPIRAL predicts fast-ion redistribution and small particle losses

- 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)

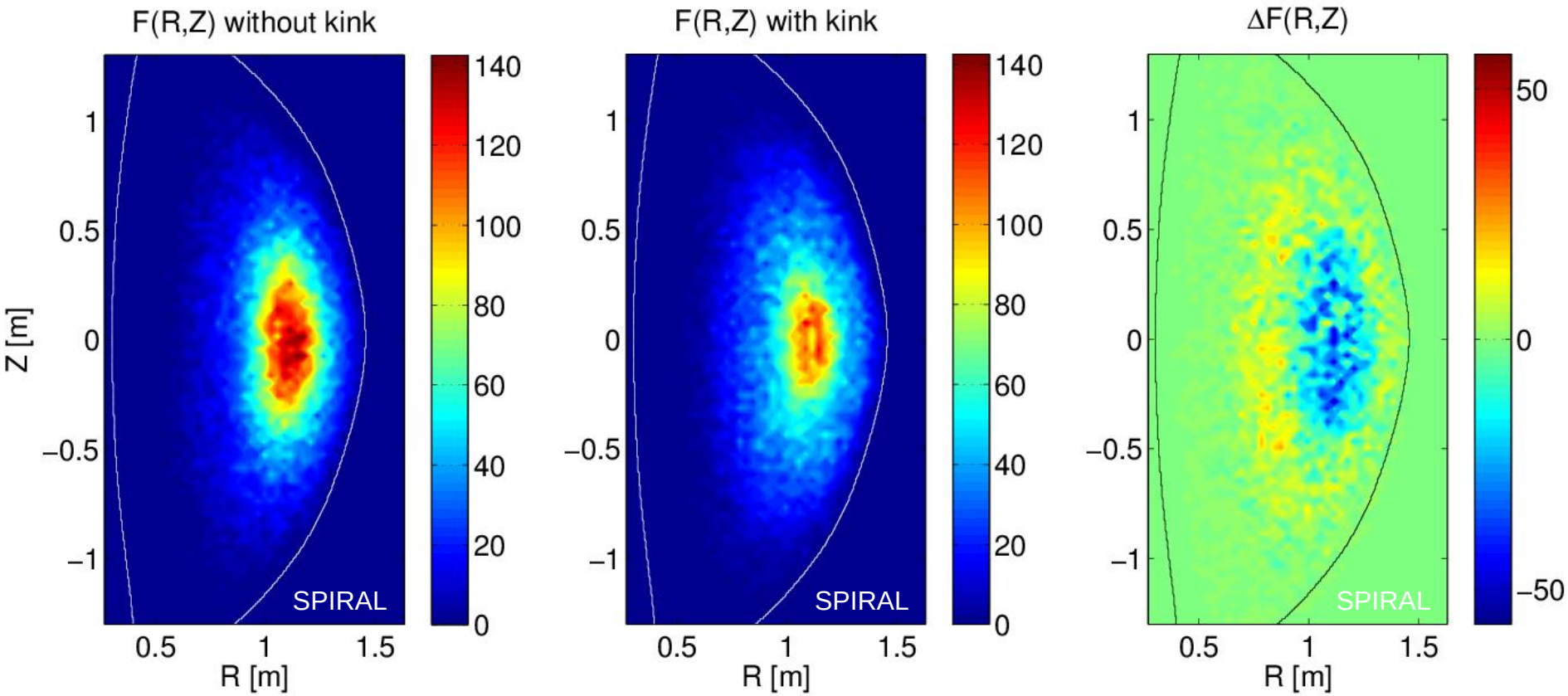


- Small increase of fast-ion losses (-3% confined particle)
- 8% decrease in neutron production rate

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

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

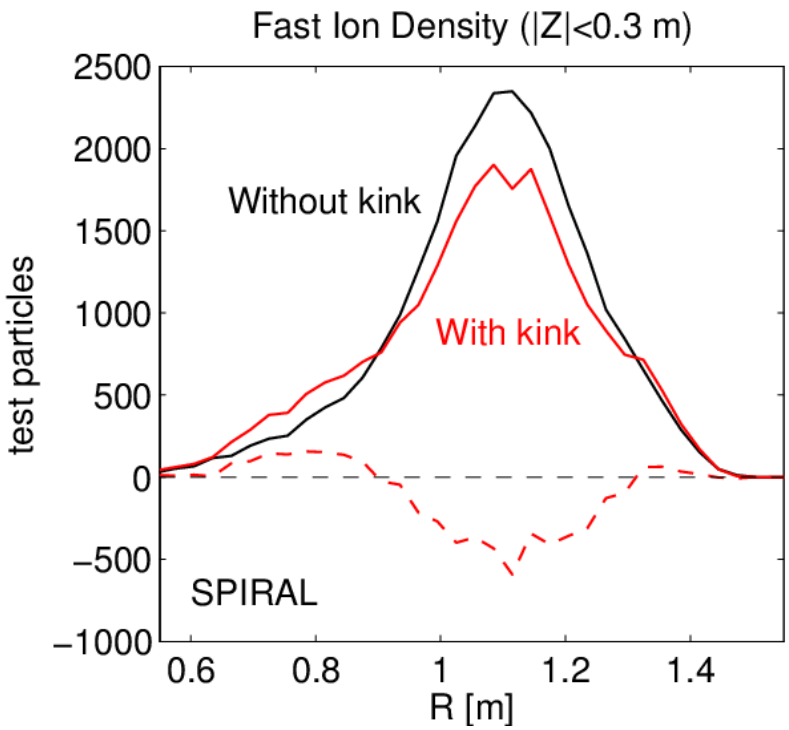
Integrated over velocity space

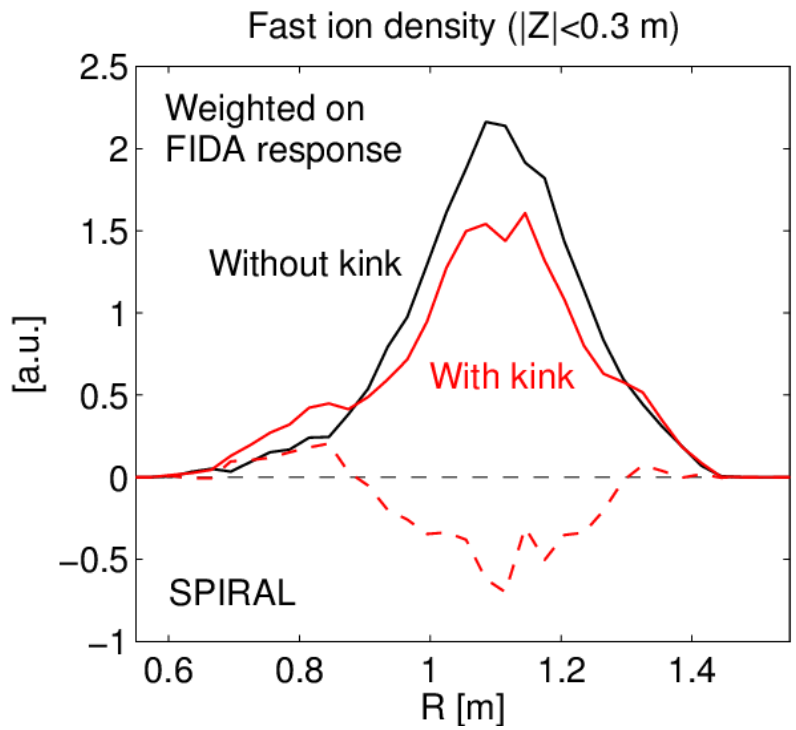


In presence of the kink:

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

Kink effect on radial profile of fast-ion density



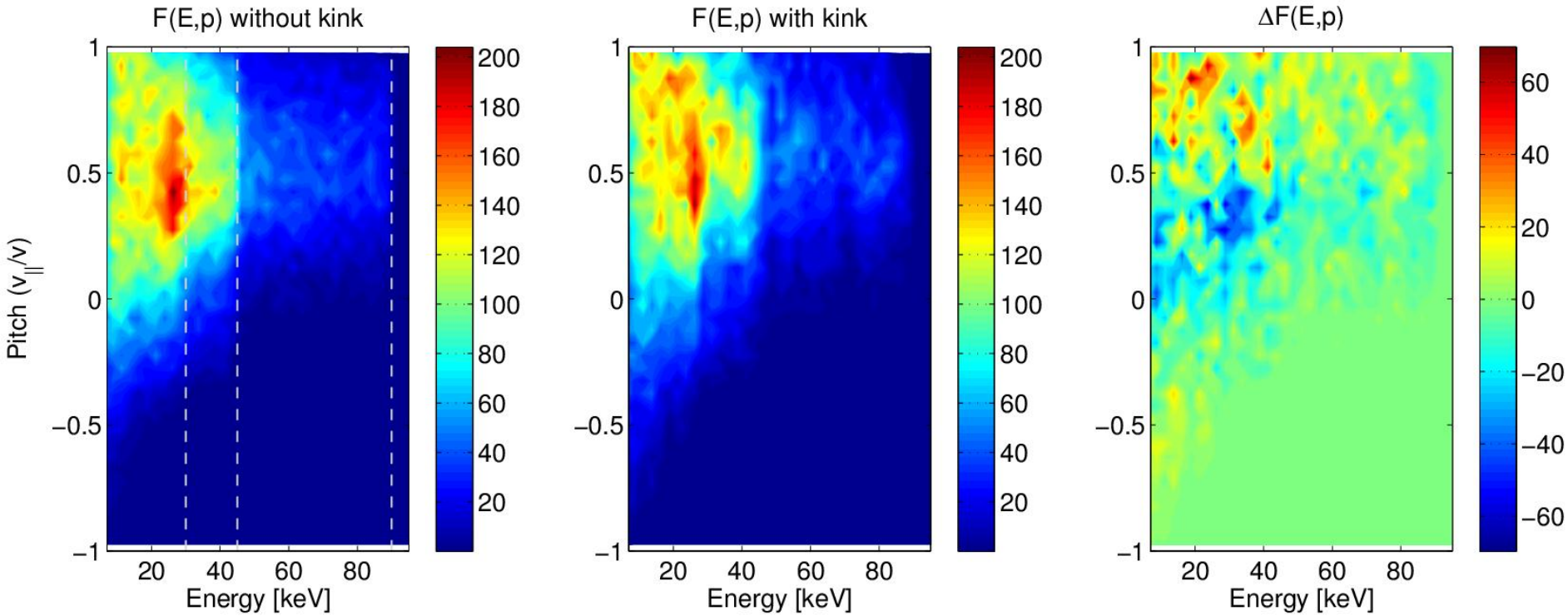


- Decrease of n_{fast} by ~20% in the core
- Increase of n_{fast} for R<0.9m (inboard) and R>1.3m (outboard)
- Accounting for the FIDA weight function (λ=653nm, R=1.2m) leads to an apparent collapse of -25% in the core

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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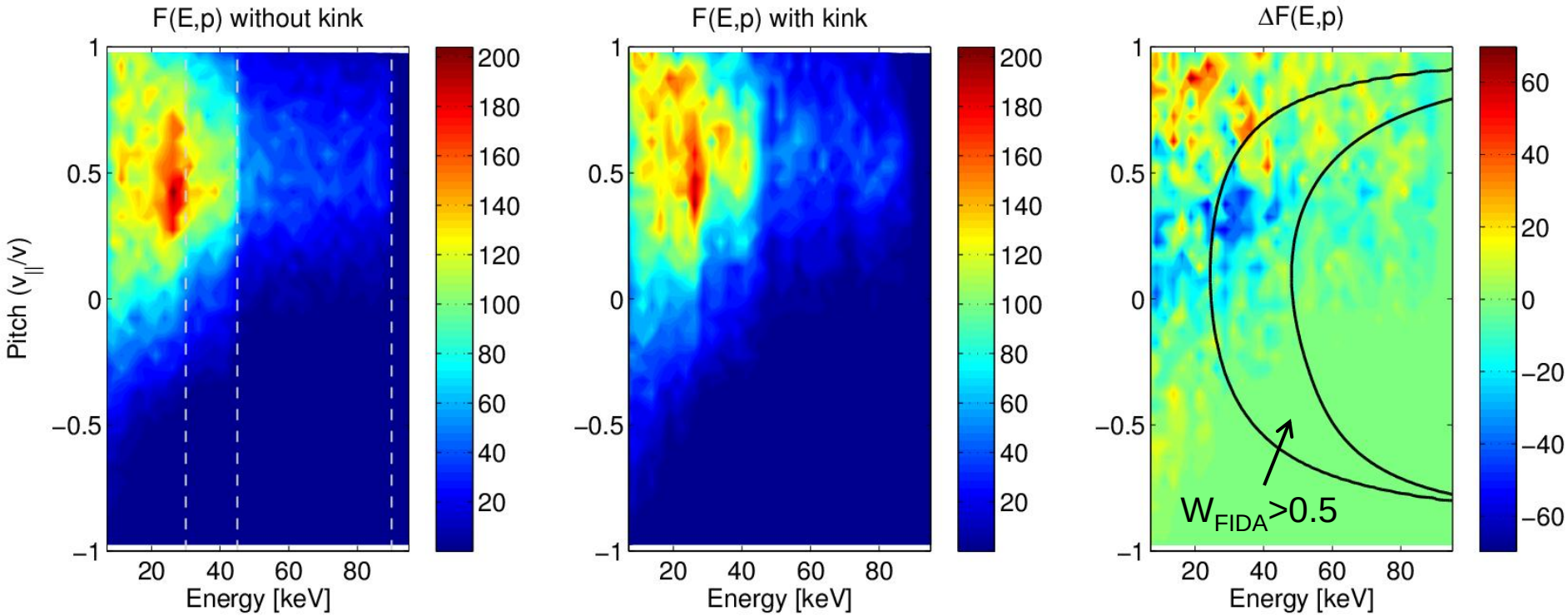

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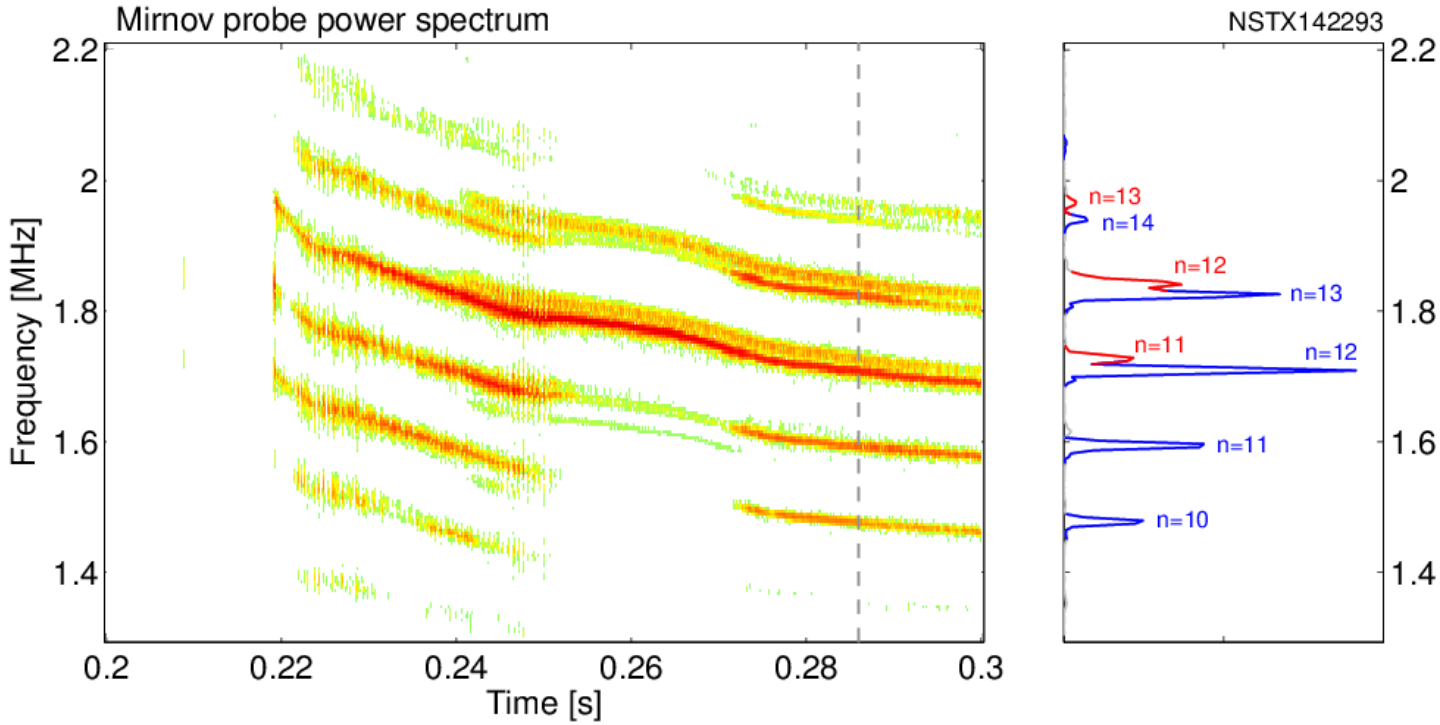
Mirnov array measurements show multiple sequences

- 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

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

Wave in a box form (Schroedinger-like)

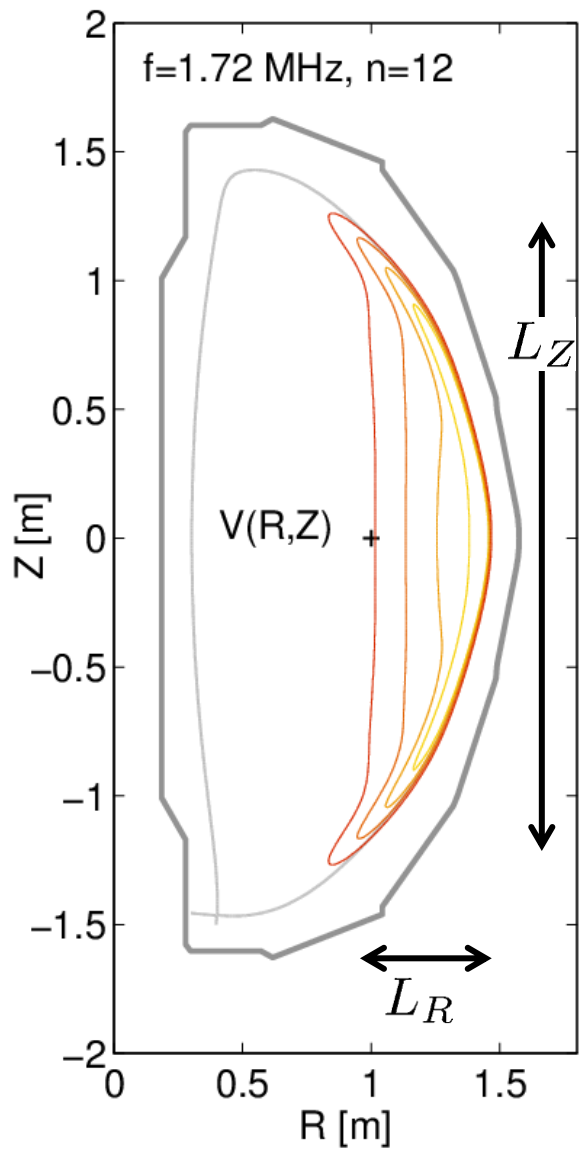
Effective Potential Well (equilibrium and toroidal structure)

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

- Eigenmodes can be classified according to effective quantum numbers:

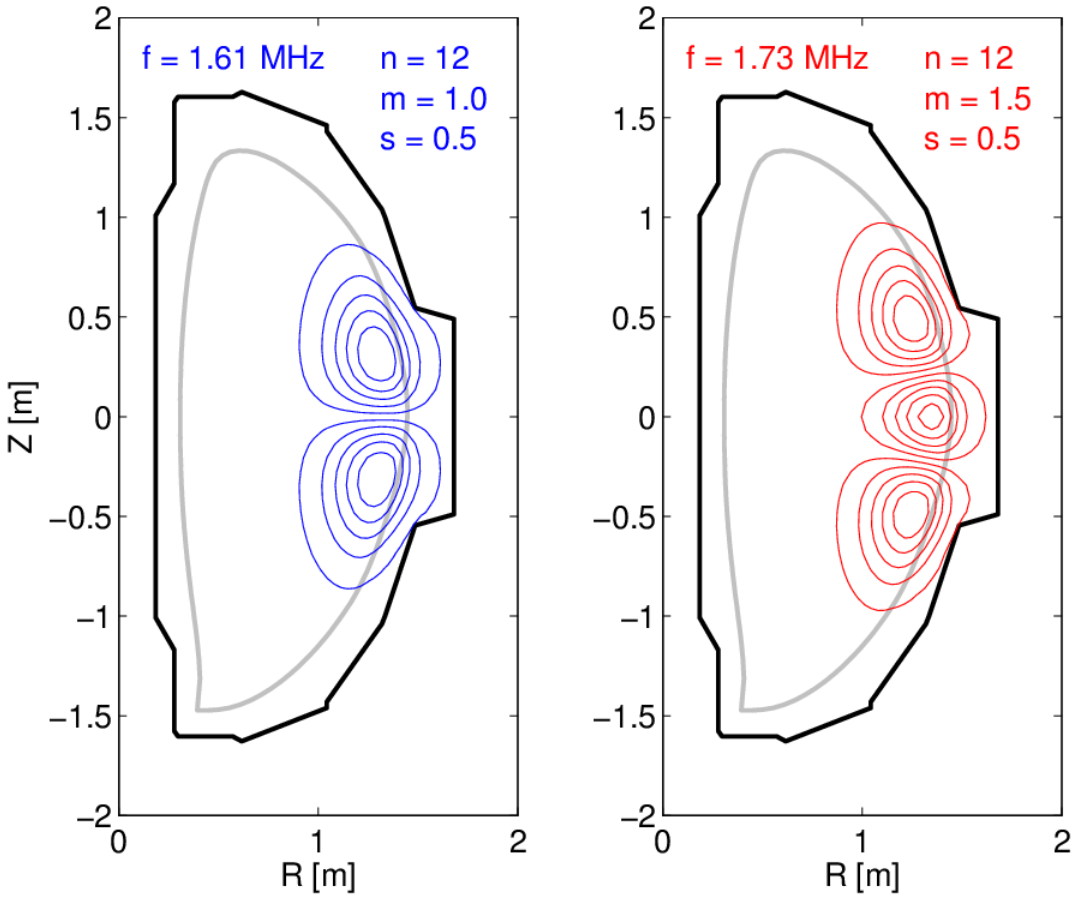
$$\vec{k} = \left(\frac{n}{R}, \frac{2\pi m}{L_Z}, \frac{2\pi s}{L_R}\right)$$

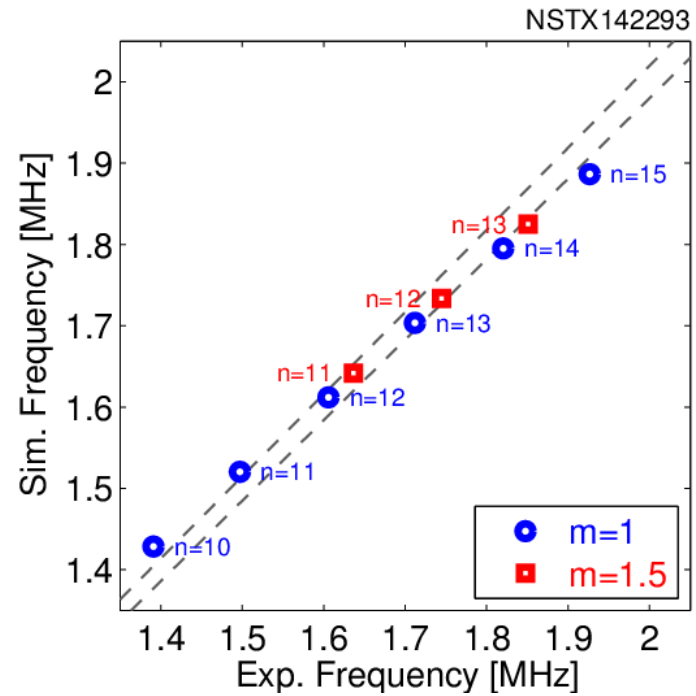
- n, m , s number of wavelengths in toroidal, vertical, radial direction



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)





Good agreement between experimental and simulated frequencies

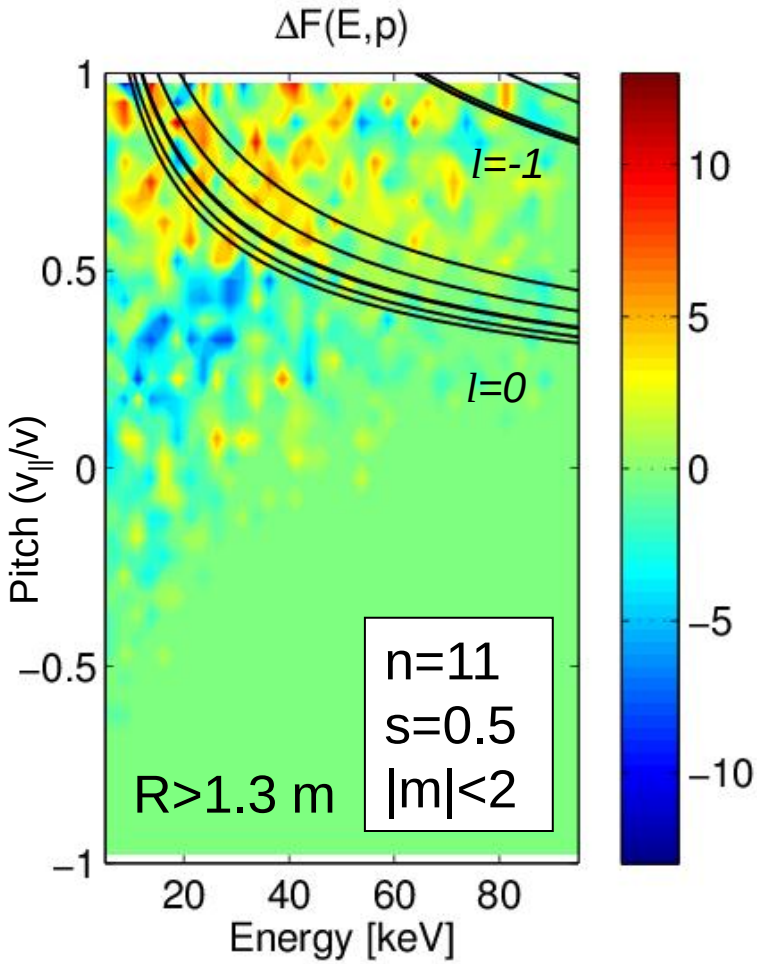
Fast-ion redistribution by kink populates CAE resonances

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

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

- 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



Conclusions and outlook

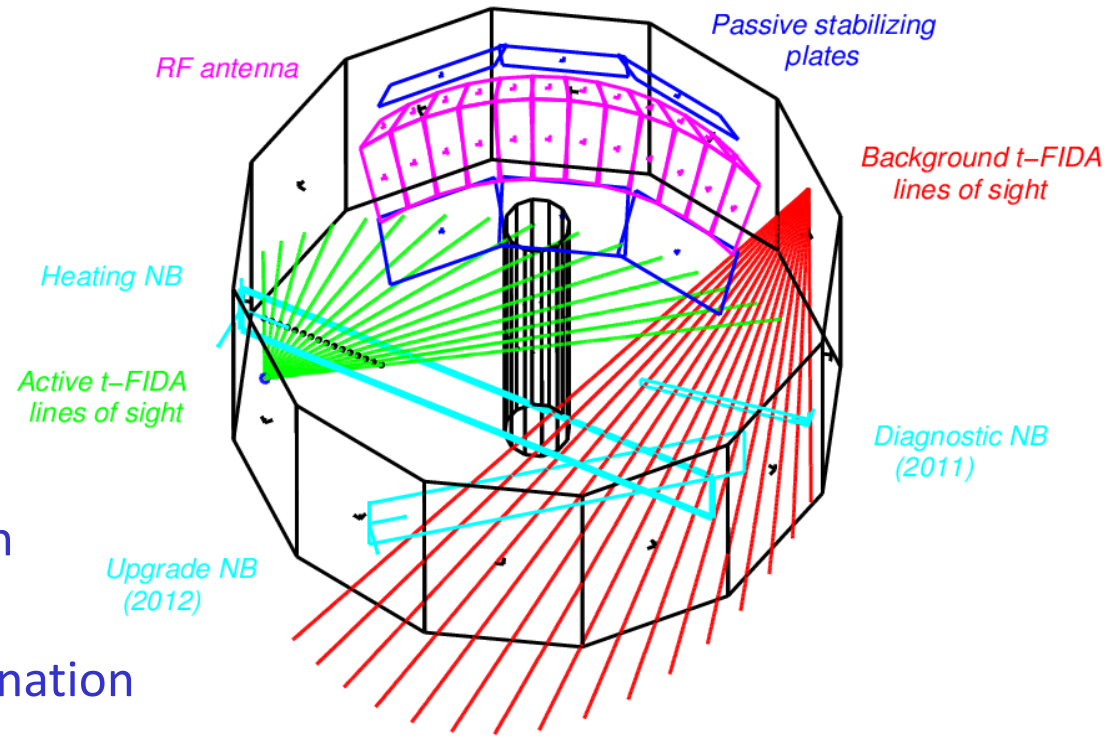
- Fast ions can mediate the interaction between instabilities that differ by localization, timescales and underlying physics
  - Complex integrated analysis is required to investigate these processes experimentally
- In NSTX H-modes, kHz-frequency ideal kinks can induce substantial fast ion redistribution 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
  - Modification of the AE activity by n=3 fields documented [***Lore PSI 2012***]
- Experimental data from different regions of velocity space required to confirm the result of the modeling
  - Tangential FIDA (installed in 2010-11) has the potential to fill this gap

Tangential FIDA for NSTX(-U)

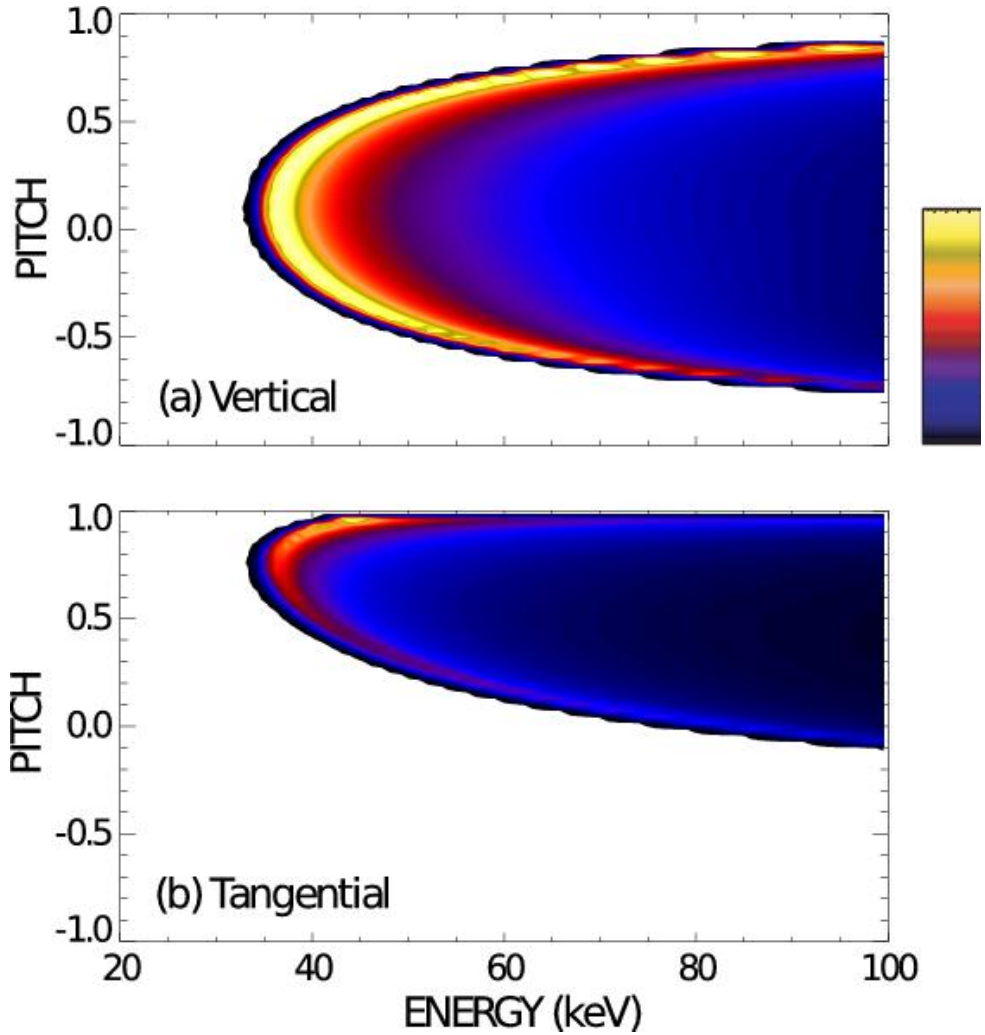
- During 2010-11, a new tangential FIDA diagnostic has been designed, installed and calibrated

- Provide data to study
  - Fast ion transport
  - NB induced current drive

- Optimized view
  1. Maximize the observation parallel to magnetic field
  2. Avoid sources of contamination (background light, beam)
  3. Compatibility with NSTX upgrade



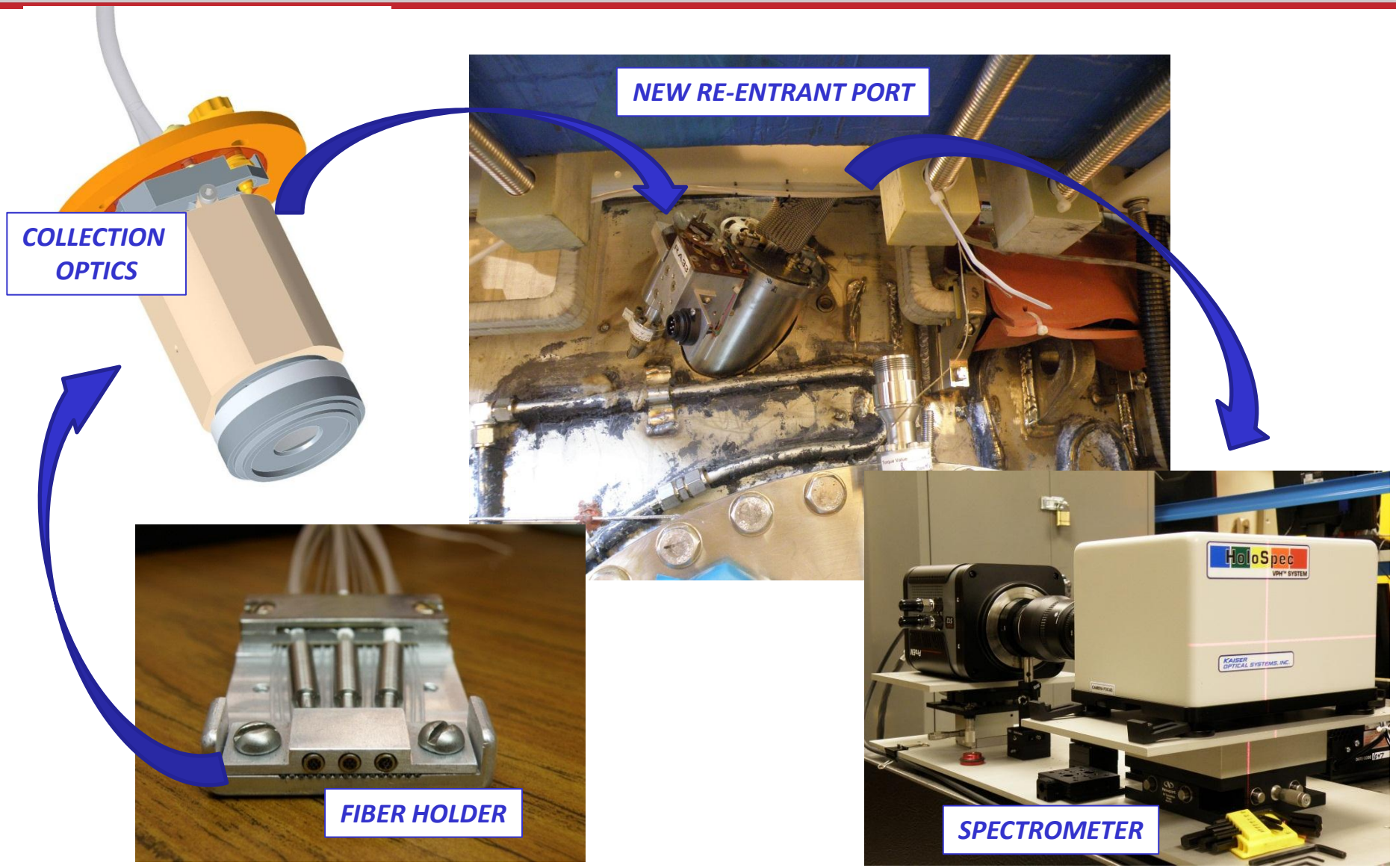
Velocity space weight function for NSTX FIDA systems



- $W_\lambda(E,p)$ evaluated at
  - R=1.2 m,
  - λ=652.1 nm (E=35 keV)
- Tangential view is sensitive to pitch $v_{||}/v>0.8$
- Contribution from small region of phase space

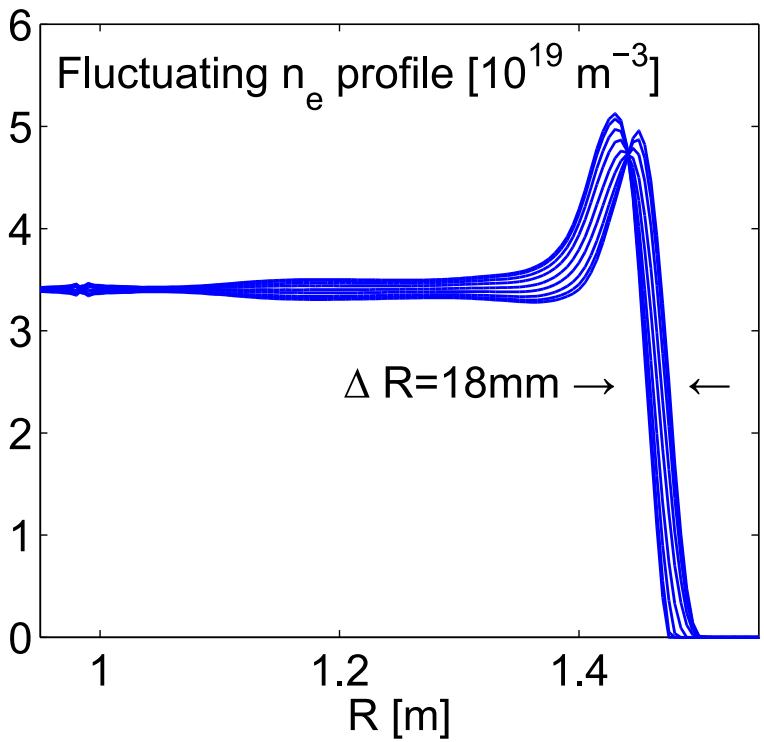
- Complementary sampling of velocity space
- Enhanced energy resolution

Tangential FIDA will support NSTX-U operations



Conclusions and outlook

- 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
  - Modification of the AE activity by n=3 fields documented [***Lore PSI 2012***]
- Experimental data from different regions of velocity space required to confirm the result of the modeling
  - Tangential FIDA (installed in 2010-11) has the potential to fill this gap



Simulated fluctuating density profile (midplane)

Resonance conditions for co-propagating CAE

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

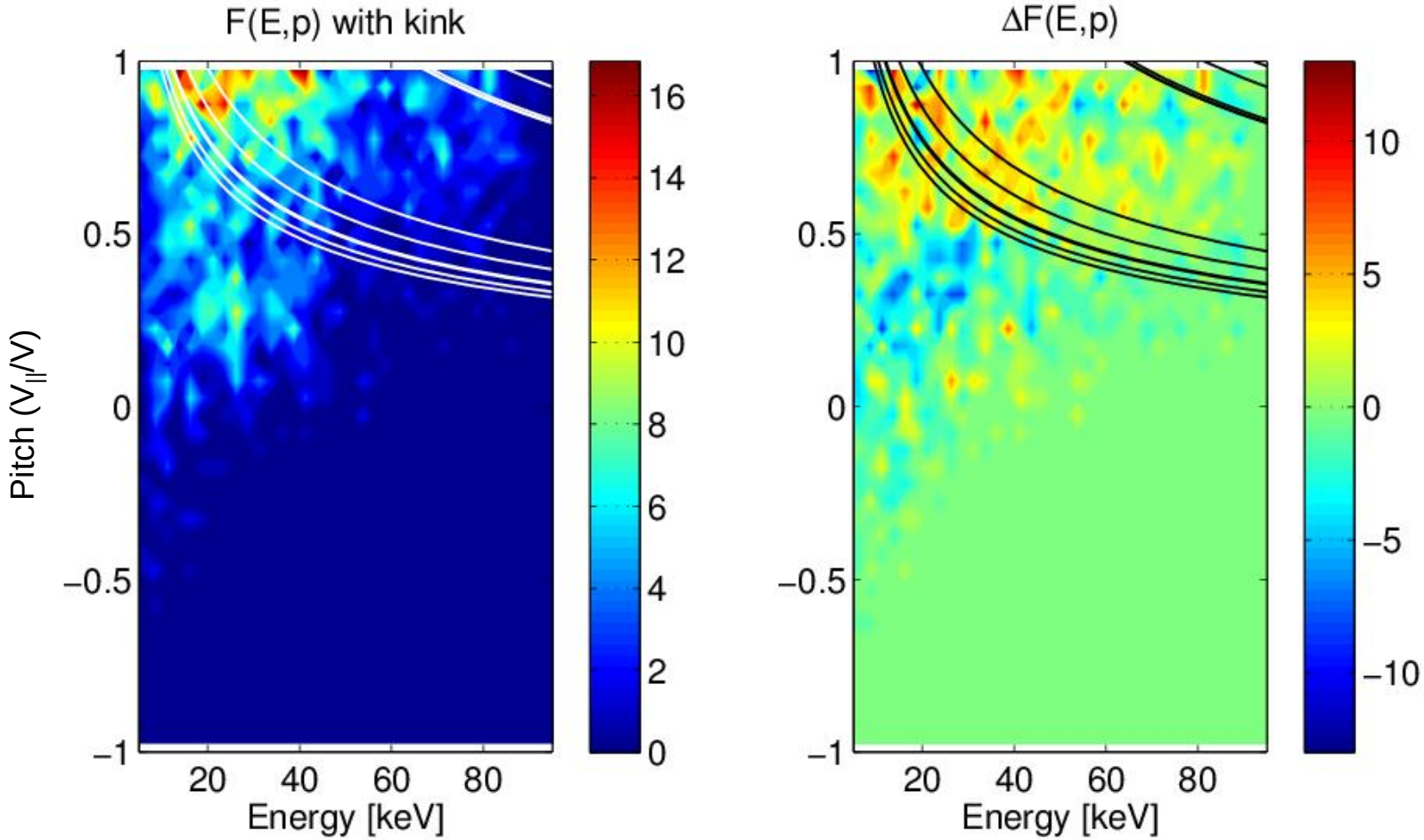
1-3.5x10^6 m/s **15 MHz**

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

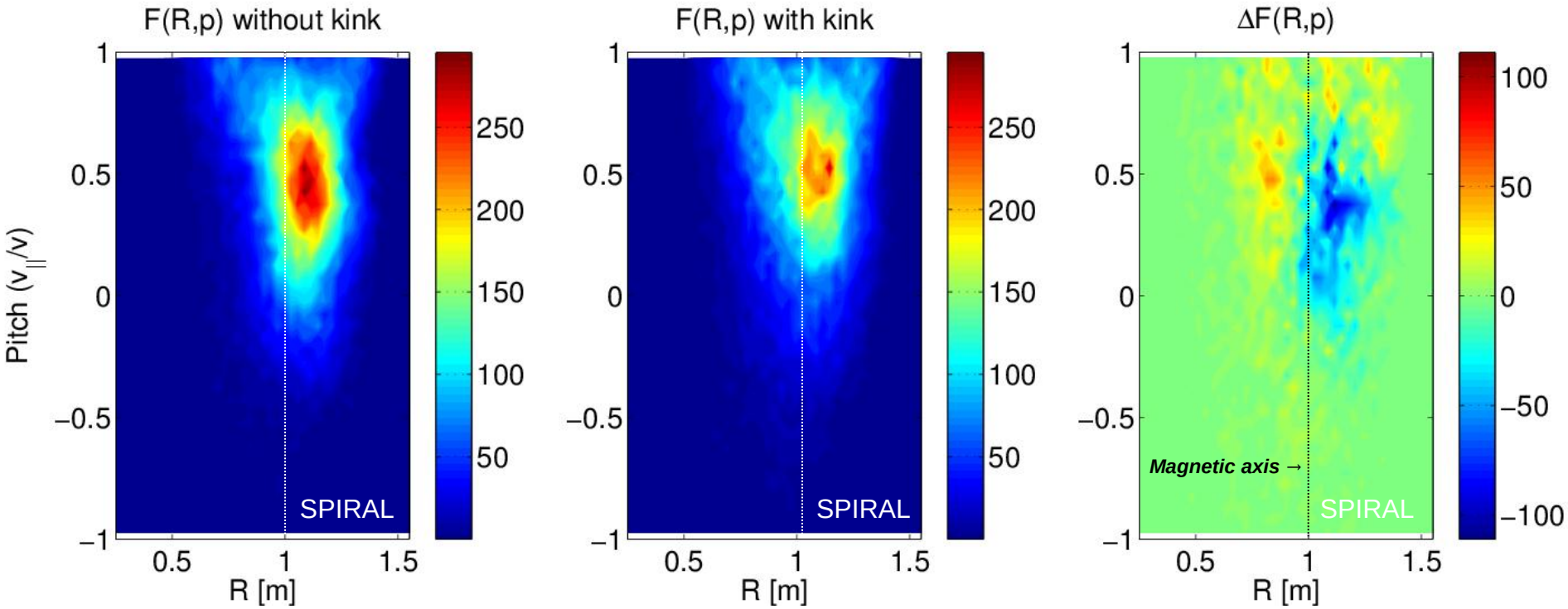
$k_{\|} \approx 8 - 10 > 0 \Leftarrow \begin{cases} k_\varphi = n/R, & n = 9 - 13 \\ k_\vartheta \approx \frac{2\pi M}{L_\vartheta}, & |M| \leq 2 \end{cases}$

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

Distribution function at CAE location (R>1.3)



Radial Profile of Pitch Angle Distribution

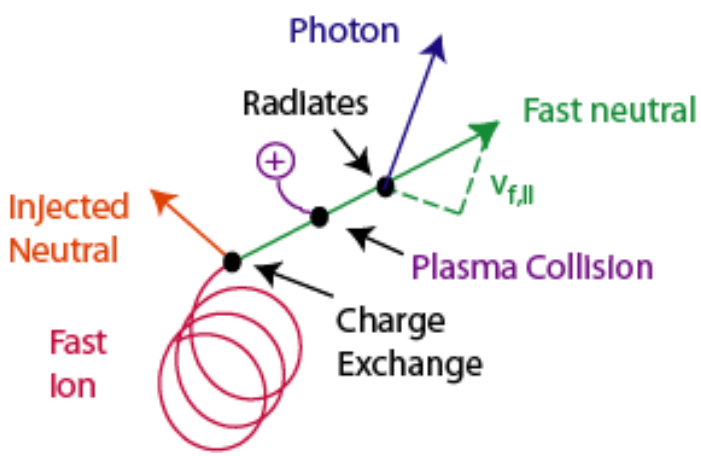


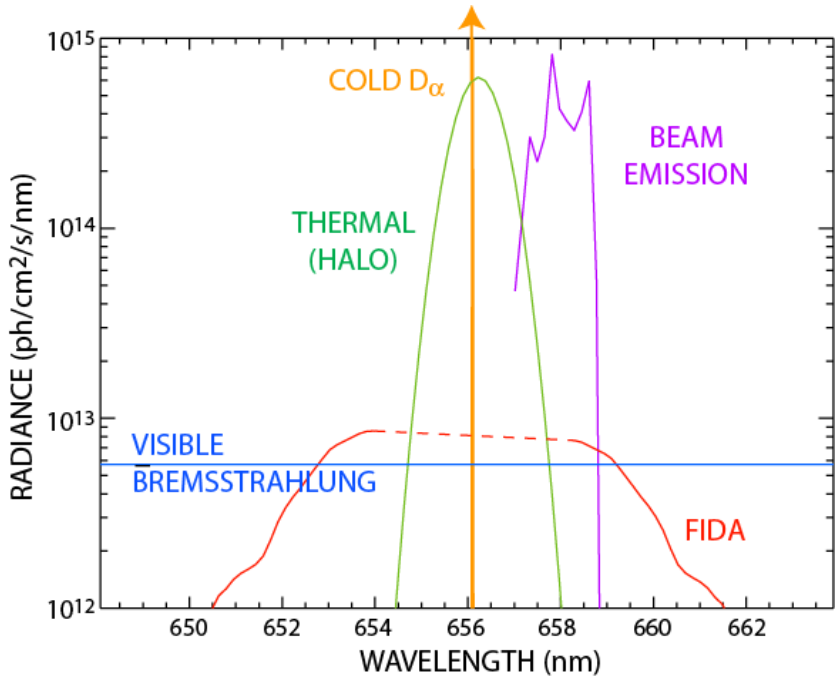
LFS ⇒ ***increase of ions with $v_{||}/v$ >0.5 (more parallel)***

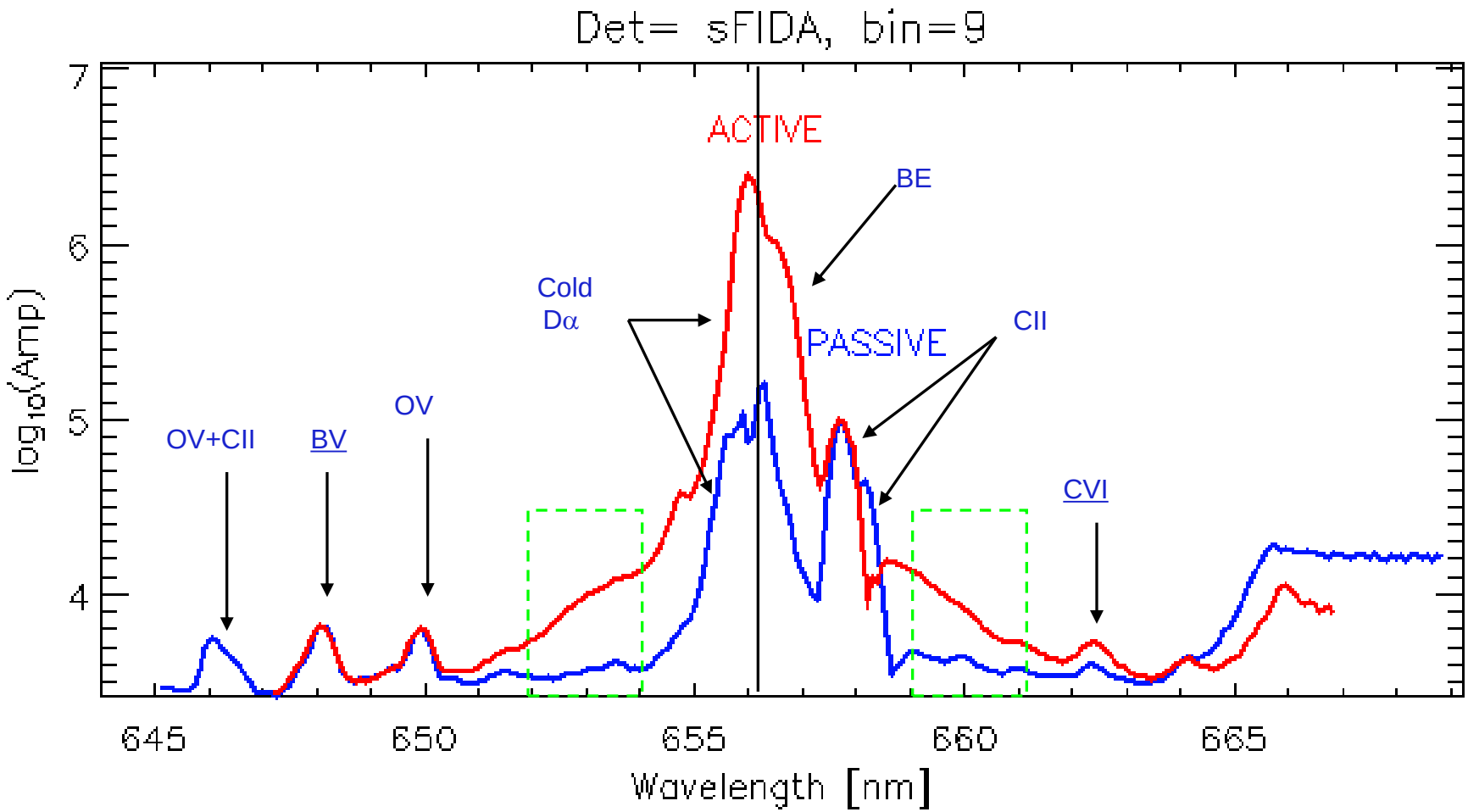
HFS ⇒ ***increase of ions with $v_{||}/v$ <0.5 (more perpendicular)***

A recent paper* reviews the FIDA spectroscopy technique

- Photons emitted by re-neutralizing fast ions have Doppler shifted wavelengths
  - Key is distinguishing fast-ion features from the dominant cold D_a emission
- Active views intersect neutral beam
- Passive views miss the neutral beam - used for background subtraction





*Heidbrink, Rev. Sci. Instrum. 81 (2010) 10D727

Example of FIDA spectrum (NSTX vertical view)