NSTX

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Effect of Low Frequency MHD on the Fast Ion Population in NSTX Plasmas based on FIDA Observations

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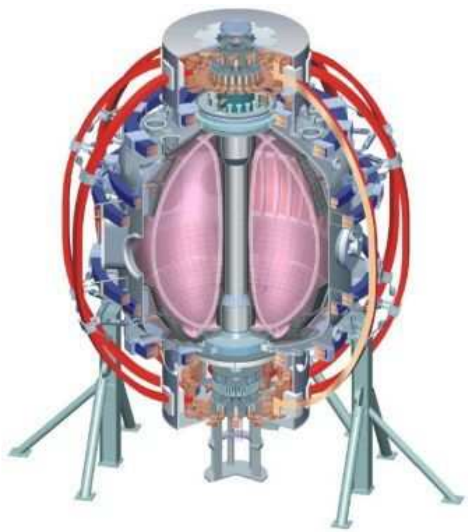

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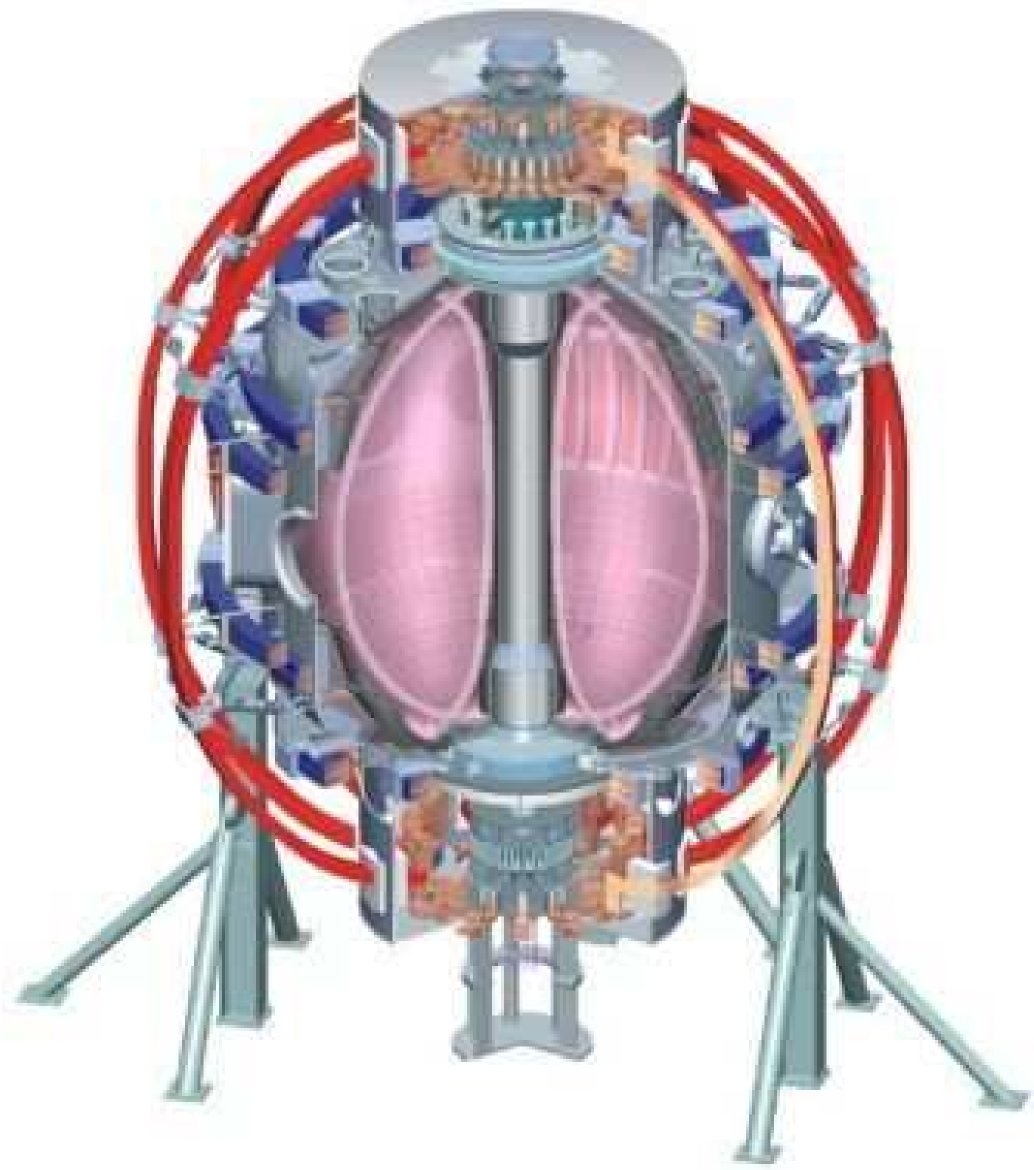
Introduction and motivation

- Energetic particle confinement in tokamak plasmas deteriorates in the presence of low frequency, low wavelength MHD instabilities. This work addresses the effect of the low frequency MHD on the fast ion population in NSTX, NBI heated discharges.
- On NSTX, a Fast Ion D_α (FIDA) diagnostic routinely provides 16 local measurements of the fast ion D_α emission with 5 cm radial resolution and 10 keV energy resolution, providing information on the Fast Ion distribution function.
- The study focuses on plasmas where a **dominant mode develops after a quiescent phase**, in presence of little Alfvénic activity. After the mode onset, a **collapse of FIDA density** profile is observed, with central values reduced by as much as 30%.
- The mode is though to be of tearing nature (n=1, m=3-5), with the resonant surface is often located close to the pedestal region.
- By means of a FIDA synthetic diagnostic, the **observations are compared with the predictions of the full orbit code SPIRAL**, used to simulate the effect of a given magnetic field perturbation on fast ion orbits and predict the distortion in the fast ion distribution function.

NSTX parameters

Major radius	0.85 m
Aspect ratio	1.3
Elongation	2.7
Triangularity	0.8
Plasma current	~1 MA
Toroidal field	<0.6 T
Pulse length	<2 s



Fast Ions from NBI

3 Neutral Beam sources

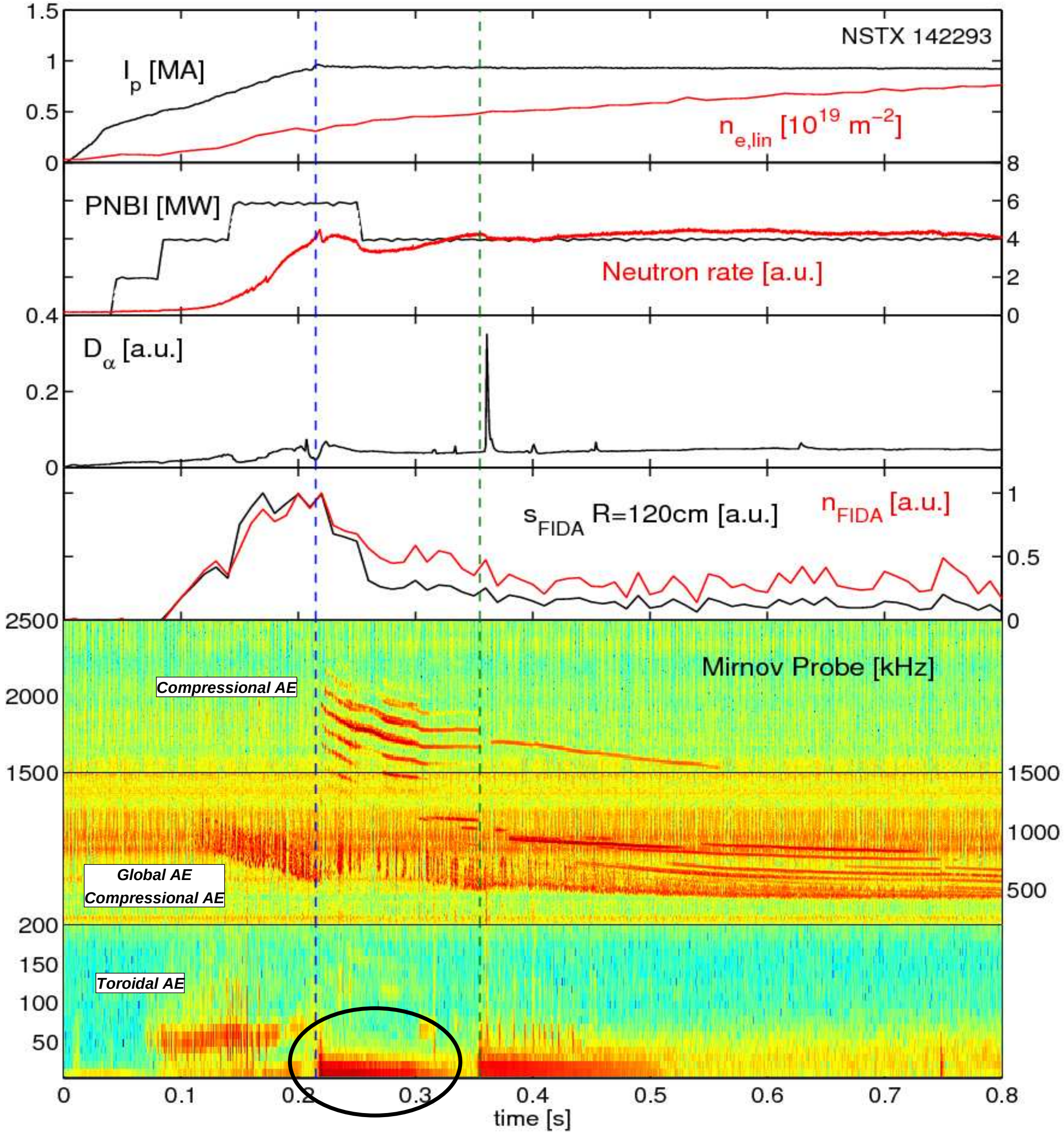
$P_{NBI} \leq 6$ MW

$E_{injection} \leq 90$ keV (45, 30)

$1 < v_{fast}/v_{Alfven} < 5$

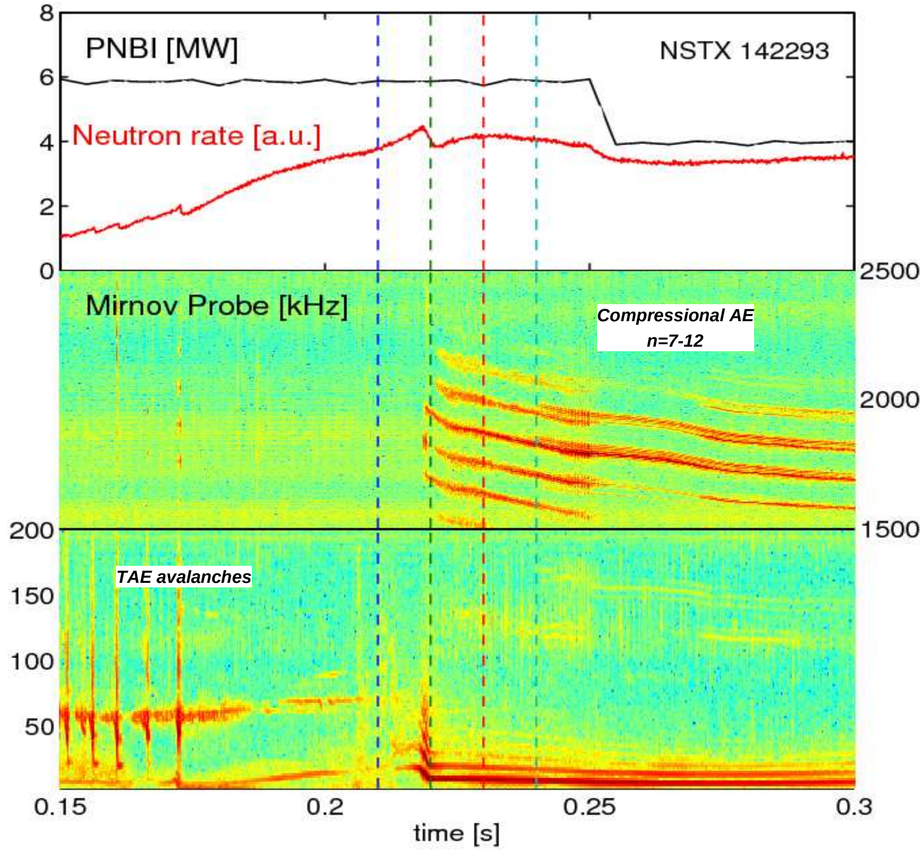
Fast Ion Larmor radius <20 cm

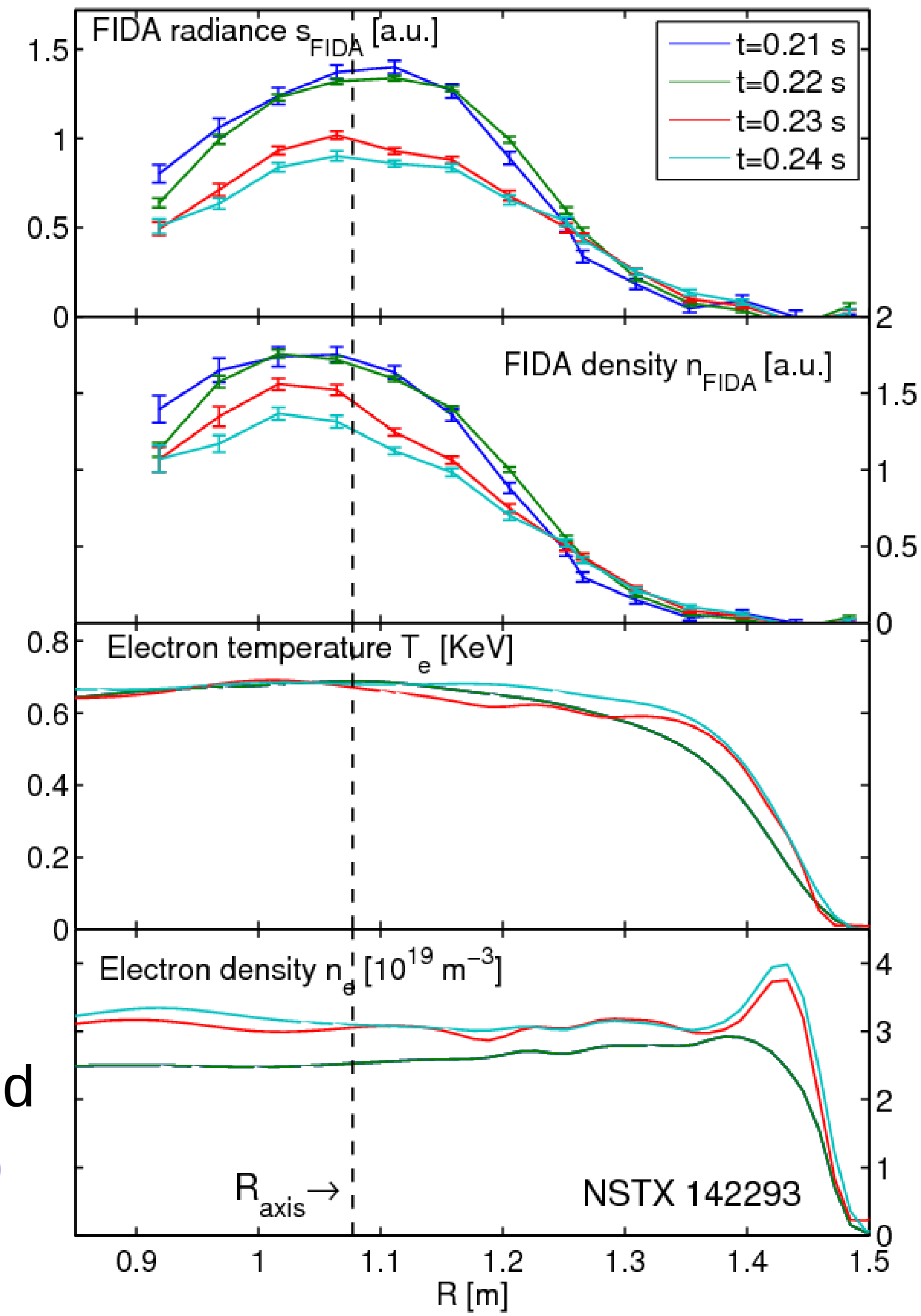
Low Frequency MHD Example of time traces



- NSTX H-mode scenario
- MHD activity at different frequencies:
  - Toroidal AE (bursting)
  - Global/Compressional AE (bursting/continous)
- Fast ions determine stability of different AE modes
- Low frequency MHD affect the fast ion content (n_{FIDA})
- ***High frequency modes (CAE) appear in combination with LF MHD***
- CAE are destabilized after the LF onset

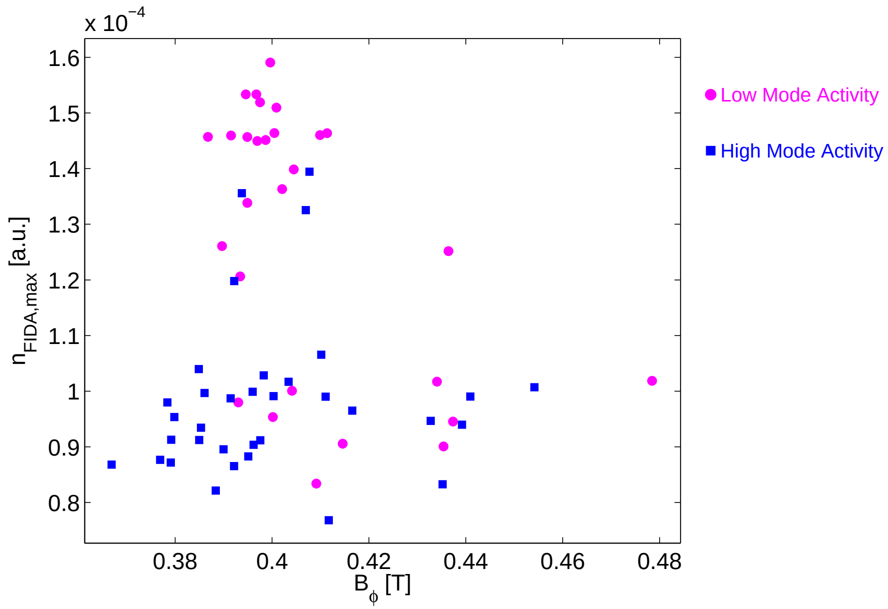
Low Frequency MHD FIDA density evolution



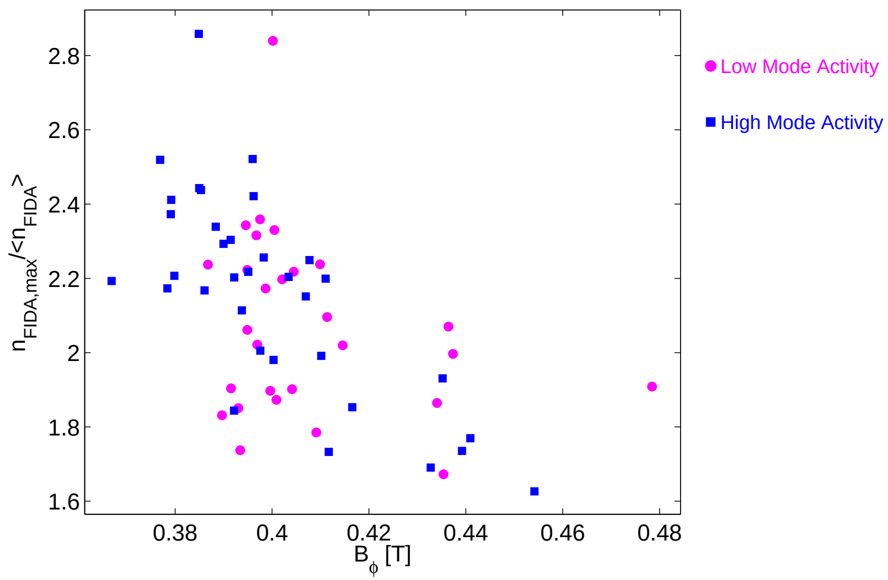


- Chirping at onset (follows rotation)
- n_{FIDA} depletion on 10 ms timescale
- Fast ion confinement remains deteriorated
  - **n_{FIDA} does not recover (cst. NB source)**
  - **lower neutron emission rate**

Low Frequency MHD vs Fast Ion content



- Statistical approach: consider a set of n_{FIDA} profiles from multiple discharges and multiple times
- Select two classes of n_{FIDA} profiles characterized by ***strong*** or ***weak*** LF mode activity (freq. < 20 kHz)
- Restricting to profiles with high FIDA radiance

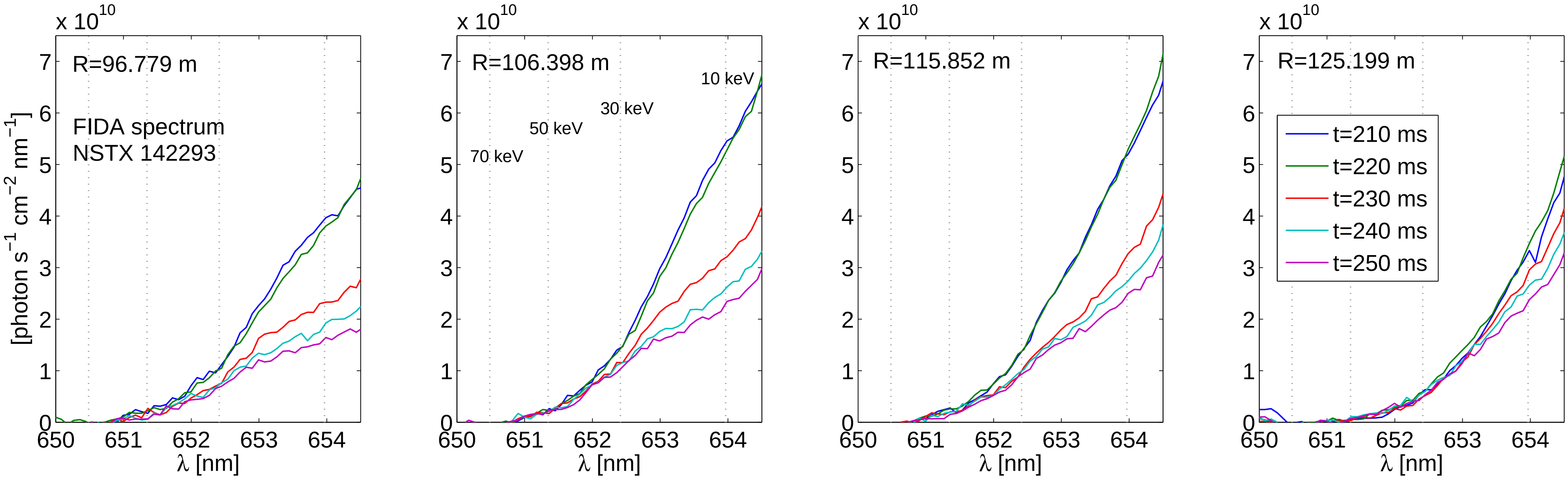


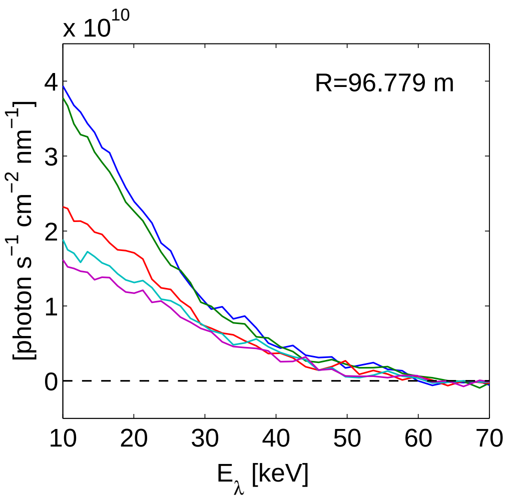
Reduced FIDA density in presence of mode activity

No clear distinction on n_{FIDA} peaking dependence on B_{tor}

FIDA spectra across LF mode onset

- Background contribution from a passive view is subtracted
- Spectral signal decrease in a broad band on wavelength/energies

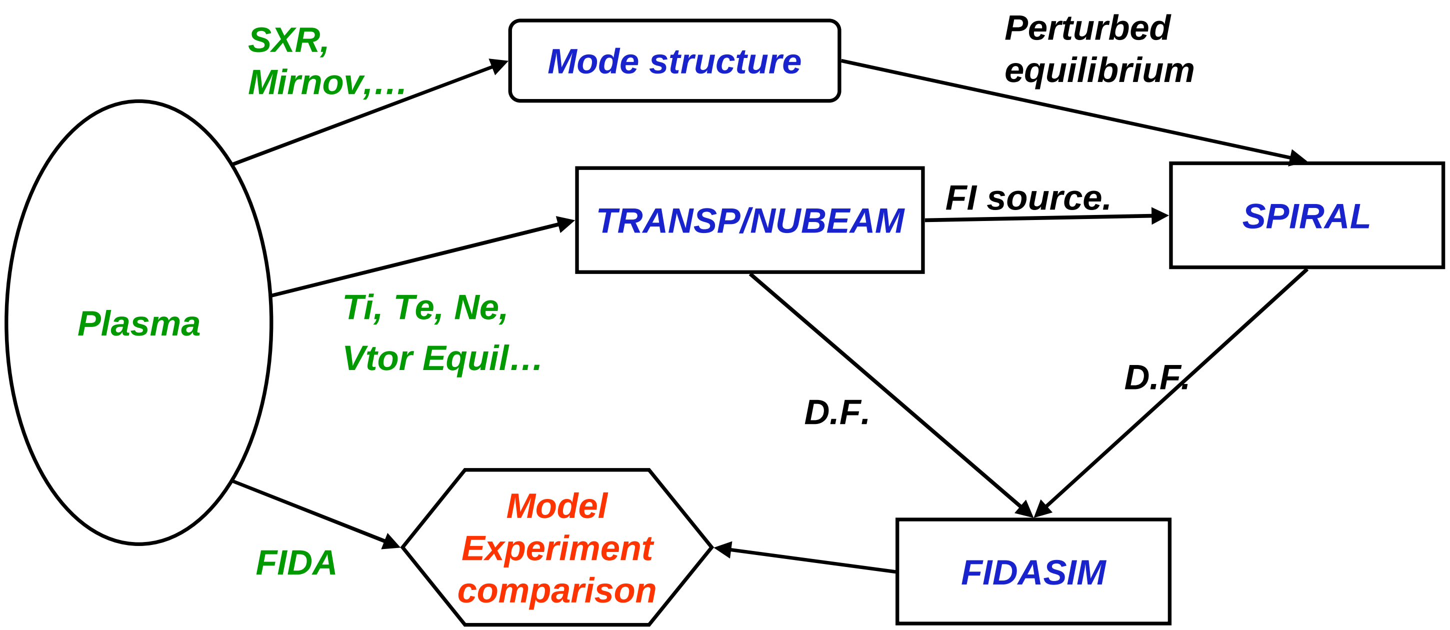




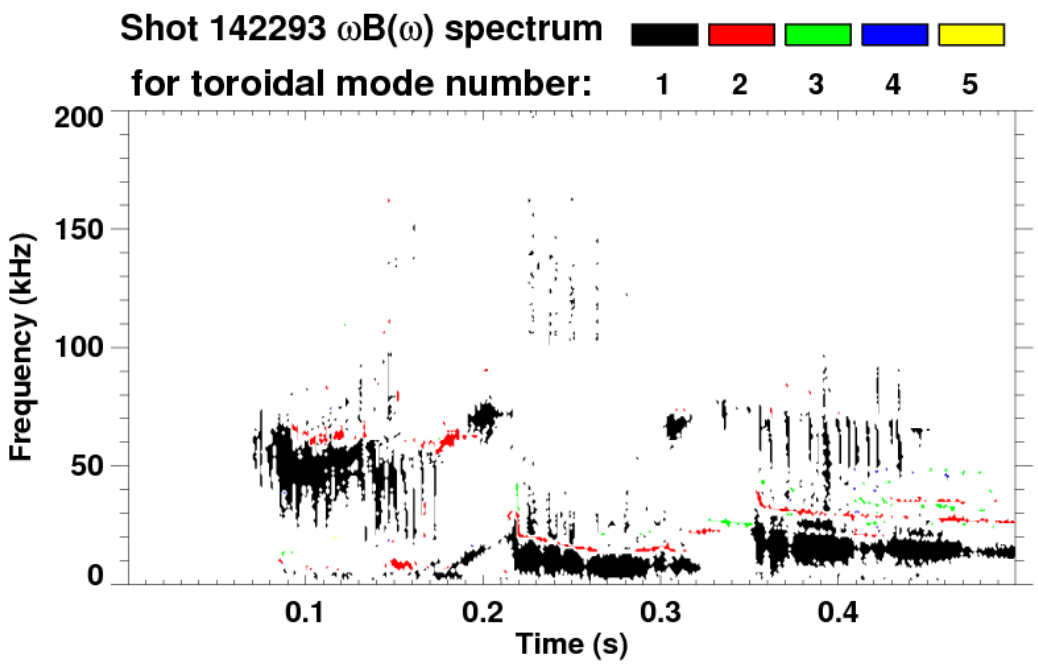
- The vertical view is sensitive to low pitch angles ($p=v_{||}/v$ <0.6, E~30-60 keV)
- Conjecture: does Low Frequency MHD activity affect mostly trapped population?

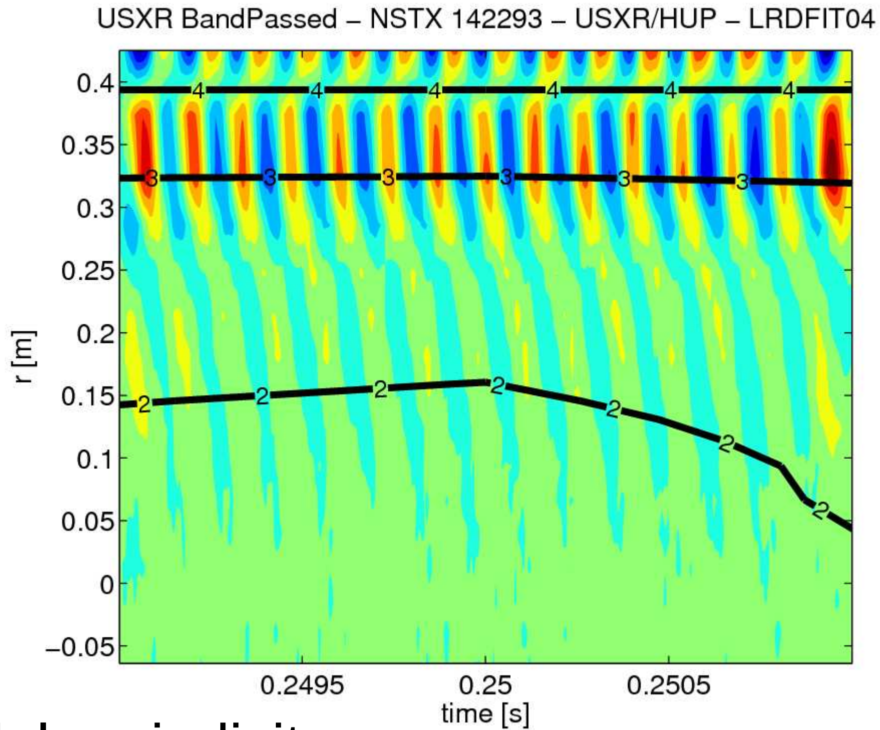
Analysis approach

- Understand the effect of the LF MHD using FIDA simulation with an integrated analysis approach:
  - Mode characterization to obtain perturbed magnetic equilibrium
  - Use full orbit code to predict the perturbed distribution function
  - Produce synthetic diagnostic data to compare with experimental data (spectra and profiles)
- Assumes Fast Ions see passively the saturated magnetic perturbation
- Needs a plasma scenario where LF mode is dominant



Low frequency mode in NSTX 142293

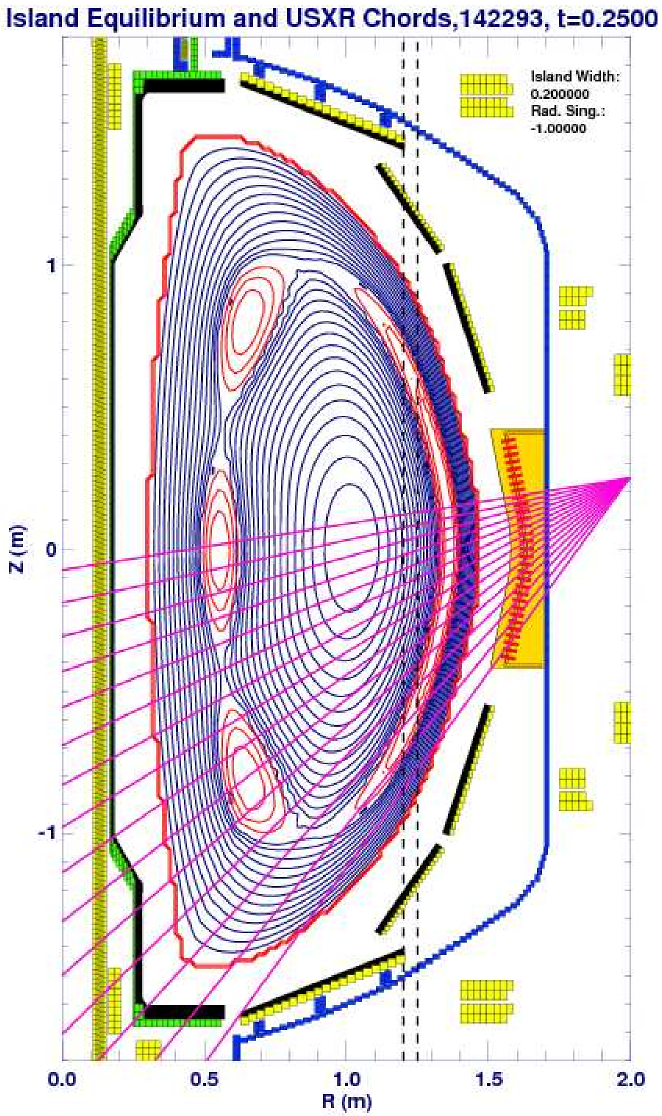




- ❑ Mirnov coils indicate dominant n=1 toroidal periodicity
- ❑ Phase inversion in USXR data at q=4, ρ_{pol}=0.8 resonant surface, suggesting n=1, m=4 magnetic island
- ❑ Nature of the mode difficult to determine
  - Hollow SXR emission profile
  - No core coverage from fluctuation diagnostics (e.g. reflectometer)
- ❑ Mode is expected to be more complex
  - Kink modes may be destabilized and coupled with tearing [6]

Perturbed magnetic equilibrium

- As a first attempt we **assume** tearing mode n=1, m=4
- Working hypothesis to test the sensitivity of the method



- Perturbed magnetic equilibrium from model [6,7] of single helicity magnetic island resonant at $q_s=m/n=4$, $\rho_s=0.8$
- Perturbation expressed as function of helical flux

$$\delta\psi_h = A(\psi)\cos(n\alpha)$$

$$A(\psi) \propto \rho^m (1-\rho)^{m(1-\rho_s)/\rho_s}$$

- Amplitude of radial component determines the island width

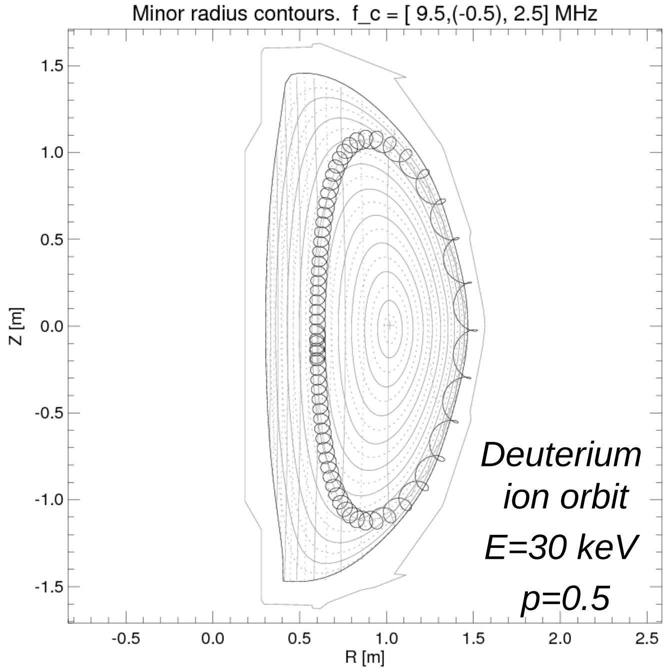
Island width assumed 20% edge poloidal flux

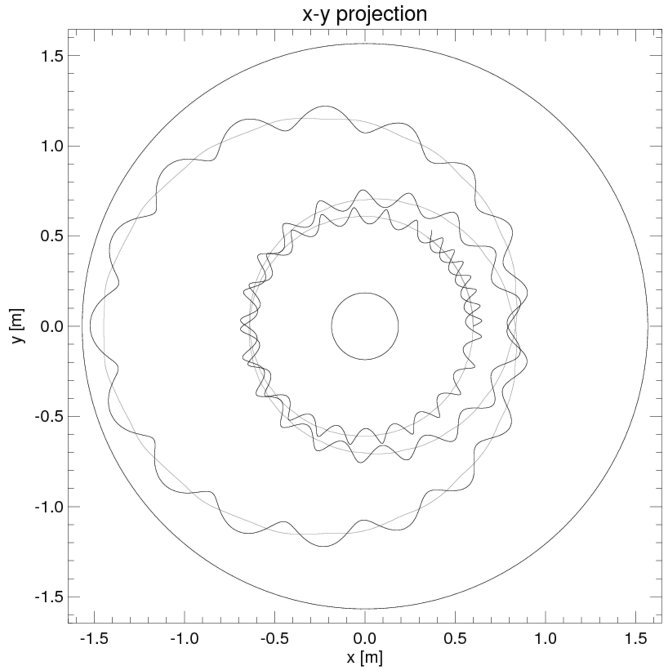
The full orbit following code SPIRAL (by G. J. Kramer)

- The SPIRAL code follows the particle orbits by solving the Lorentz equations:

$$\vec{v} = \frac{d\vec{r}}{dt} \qquad \frac{d\vec{v}}{dt} = \frac{q}{m}(\vec{v} \times \vec{B} + \vec{E})$$

- The magnetic field B and electrical field E are usually given on an (unstructured) mesh
- A robust interpolation procedure, based on Chebyshev polynomials, is used so that Maxwell's equations are satisfied for all interpolated points
- Ripple fields, slowing-down, and pitch angle scattering can be included together with MHD modes and RF fields
- Realistic walls are included to calculate heat loads
- Particle deposition profiles from, amongst others, TRANSP can be used

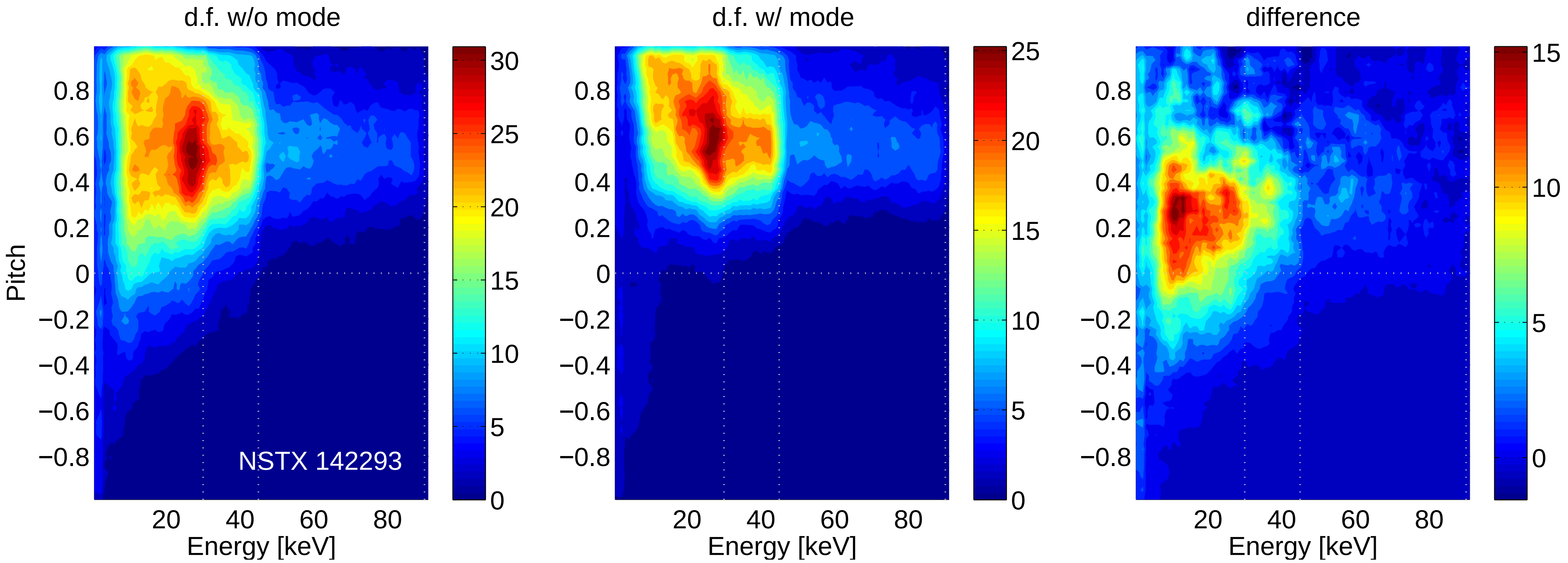




SPIRAL simulation strategy

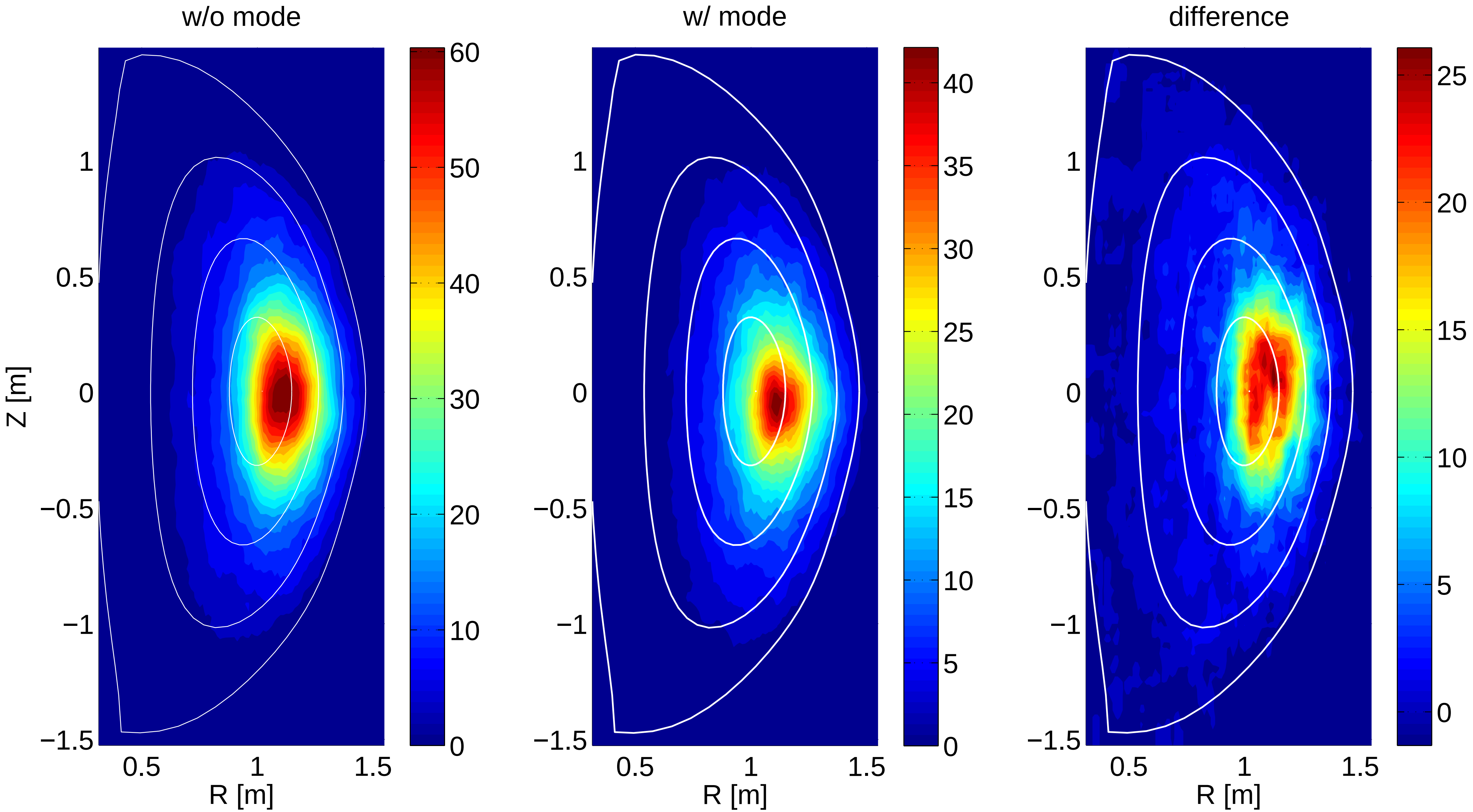
- The objective is to obtained steady state fast ion distribution function with and without mode
  - Fast ion birth profile from TRANSP/NUBEAM (10^5 particles launched along 25000 tracks, including 3 NB sources and 3 energy fractions - 90,45,30 keV)
  - Random selection of 75000 ionizing neutrals introduced at **uniform rate** along **25 ms simulated time window**
  - Since energy slowing down time for 90 keV ion is ~15 ms, the **final distribution assumed to be representative of the steady state**
- SPIRAL's output is the collection of particles each defined by (R,φ,Z,E,p)
- Present simulations also include effect of:
  - Radial electric field E_r from plasma rotation
  - Magnetic ripple

SPIRAL results: phase space distribution function



- ❑ Unperturbed d.f. is a *slowing-down* distribution
- ❑ Mode presence causes depletion for pitch $p = v_{||}/v < 0.4$
- ❑ Strong reduction of $p\sim 0$ and counter going ions ($p<0$)
- ❑ Particle loss affect the trapped part of d.f.

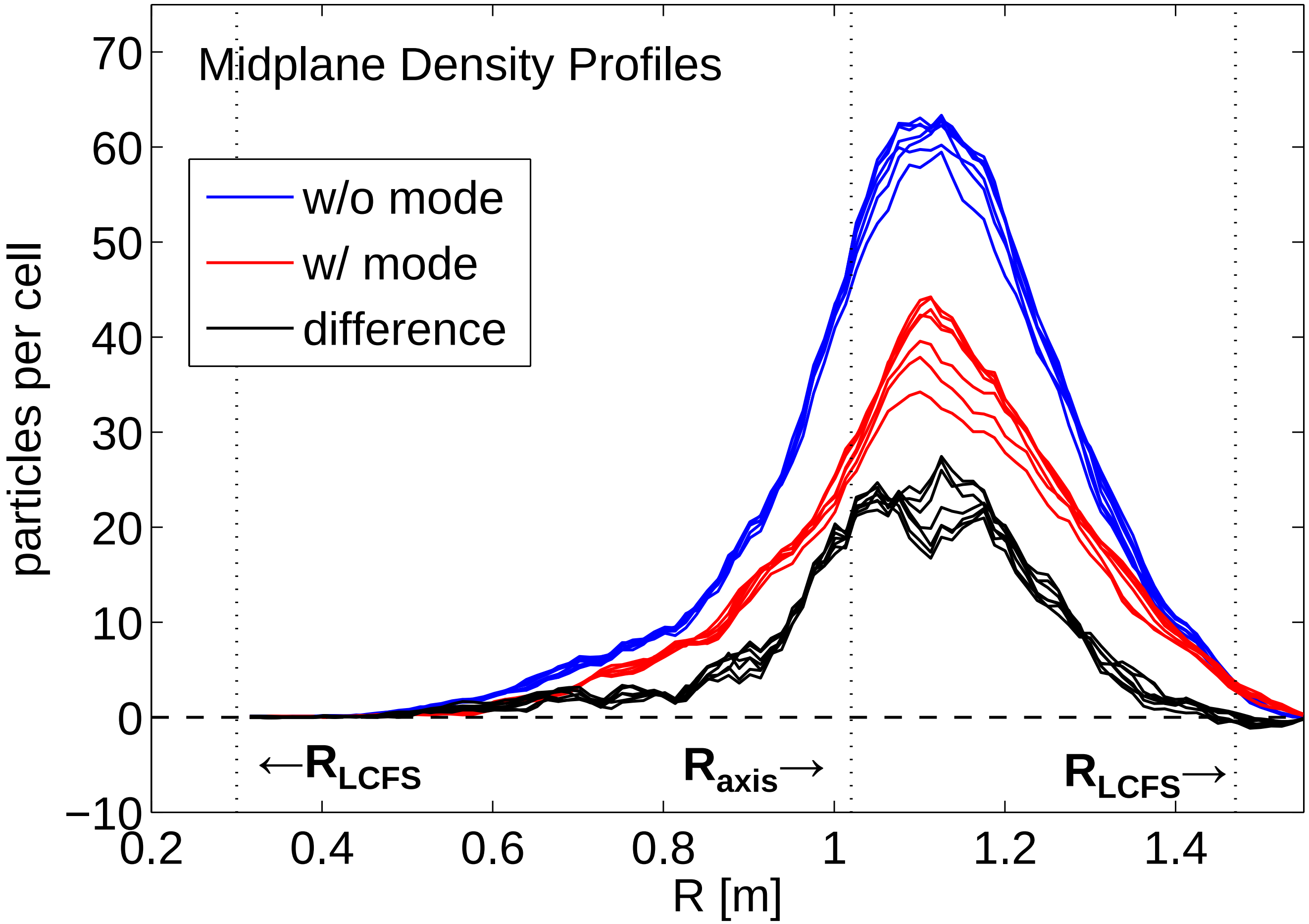
SPIRAL results: real space distribution functions



- ❑ Predicted Fast Ion population peaks off axis (R_{mag}= 1 m)
- ❑ Fast ion losses affect a wide core region

Fast Ion population in the mid plane region

- Region of FIDA measurement -10 < Z< 10 cm (NB footprint)
- Fast Ion profile peaks off axis R_{max}~1.11m R_{mag} ~1.0m



- Fast Ion density reduced over a wide core region
- 30% peak reduction
- No core/edge redistribution

FIDASIM synthetic diagnostic

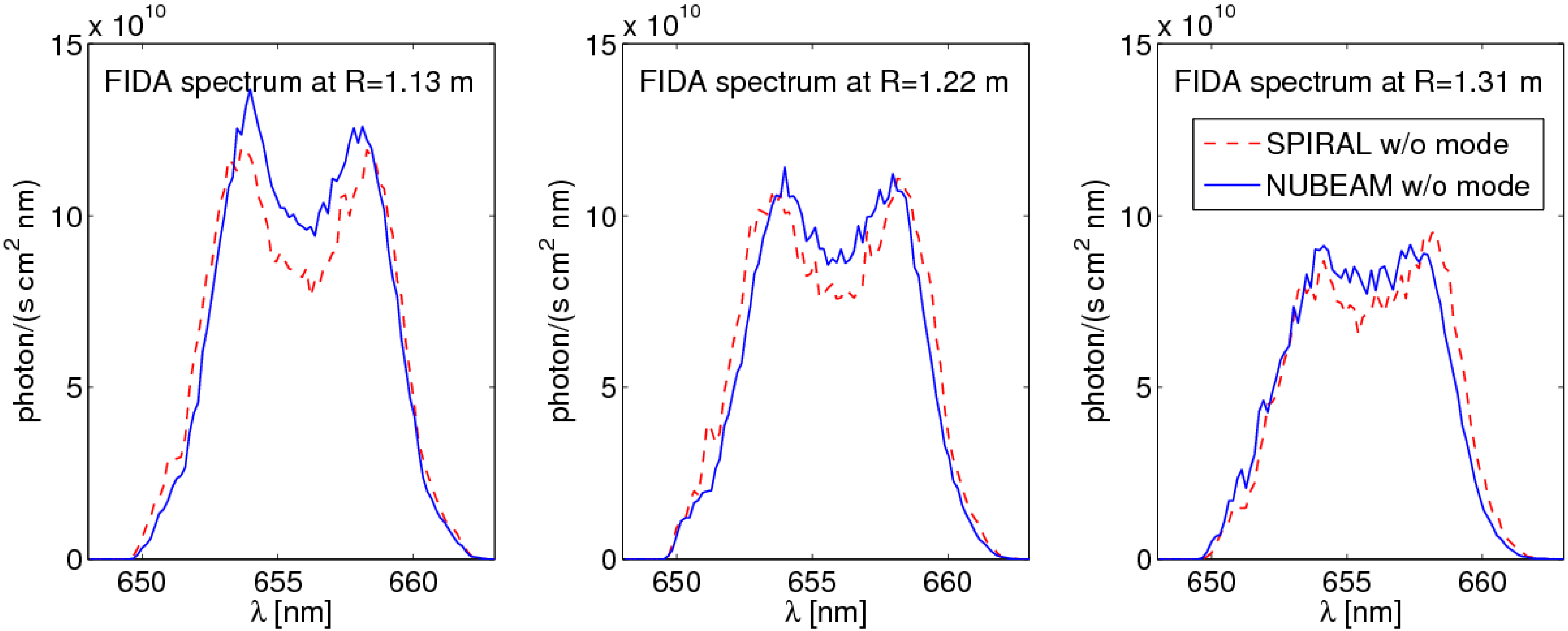
- FIDASIM is a 3D Montecarlo code that reproduces the FIDA spectra measured by a given FIDA diagnostic
- Accounts for the diagnostic response function
- The fast ion distribution function *f(E,p,R,Z)* is provided as input
- Includes contribution of **Neutral Beam** and **Halo** Neutrals
- Solves for the (time dependent) occupation of excited levels of recombined fast neutrals

For the runs in this work:

- SPIRAL confined particles are sorted to obtain *f(E,p)* on regular 2D spatial grid
- Cells of ΔR=10cm, ΔZ=20cm to improve statistics
- *f* normalized so that $\int f(E,p)\, dEdp\, dV = N_{dep}$, where N_{dep} ~2×10^{20} s^{-1} is the total particle deposition rate calculated by NUBEAM
- 5×10^{6} MC particles used

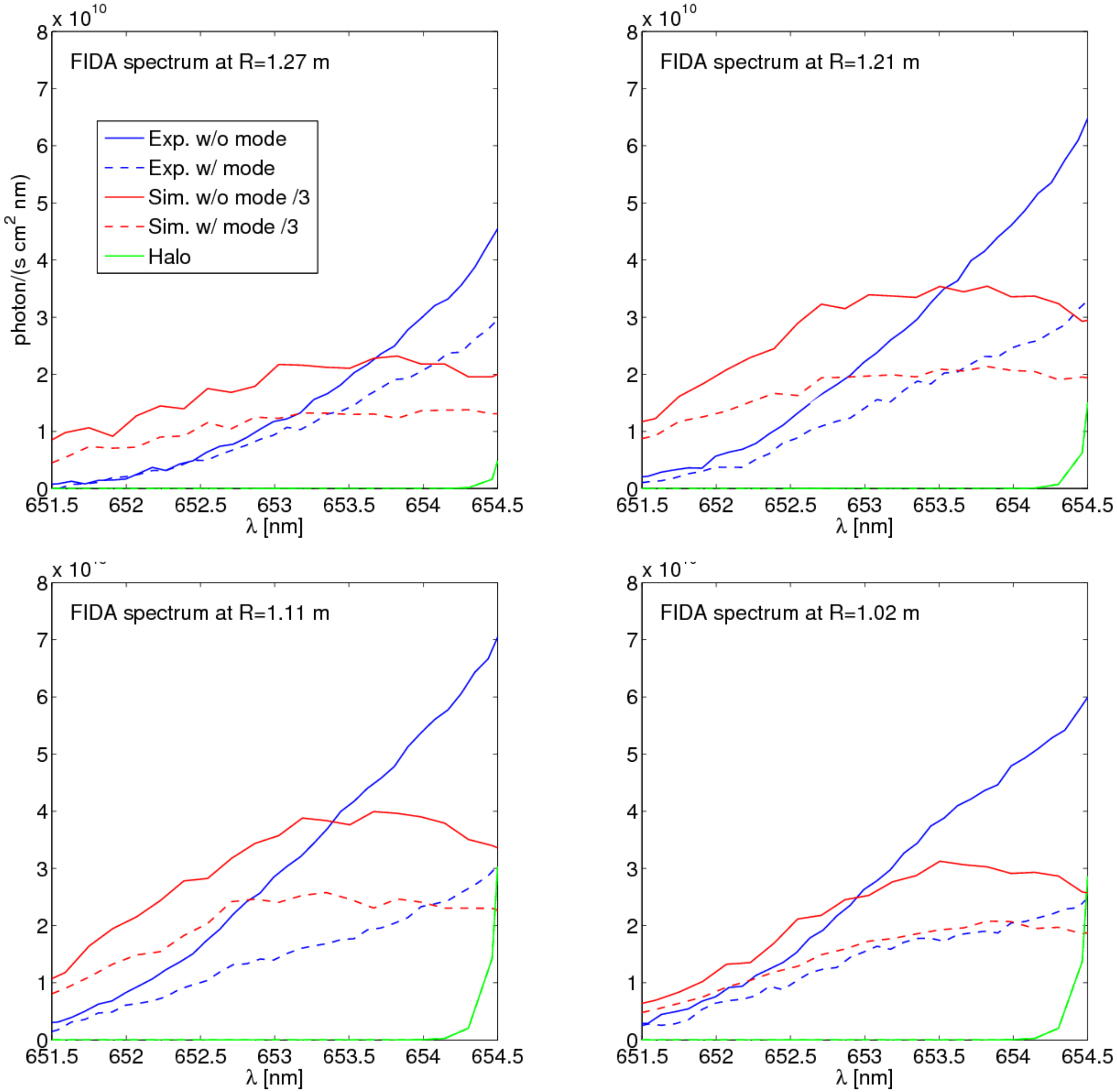
Simulated FIDA spectra for unperturbed equilibrium

- FIDA emission spectra predicted by FIDASIM at different locations using:
  - NUBEAM distribution function (guiding center, includes CX losses)
  - SPIRAL stationary distribution function for unperturbed equilibrium



- Reasonable agreement between the two predictions
- SPIRAL spectra are slightly broader: effect of larger cells

FIDASIM results: spectra comparison

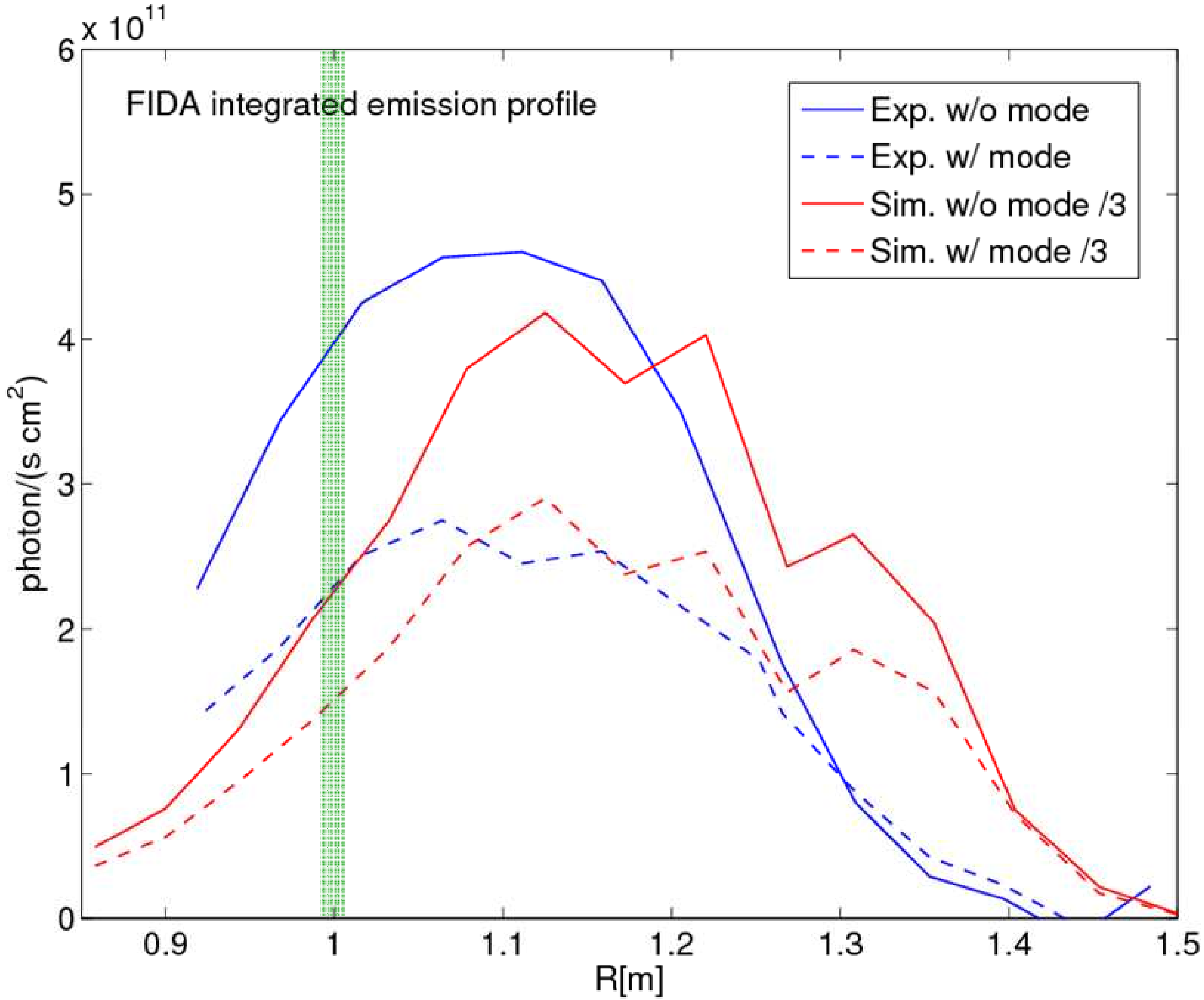


<u>Disagreement</u>
between model and measurements

For both **<u>perturbed</u>** and **<u>unperturbed</u>** cases

- ❑ Prediction of FIDA yield in excess of factor of 3
- ❑ Broader predicted spectrum
- ❑ Extends to high Doppler shift

FIDASIM results: integrated emission profile



FIDA spectra integrated over

650.7< λ <653.5 nm

15< E_λ <65 keV

- ❑ All profiles peak off-axis: effect of NB attenuation
- ❑ Predicted profile of FIDA yield is shifted outward by ~10 cm!

Conclusions

- Low frequency MHD is observed to affect the fast ion population on FIDA measurements
  - Fast Ion population reduced by as much as 30%
- An integrated analysis approach has been carried out on a specific case
  - Reconstruction of perturbed equilibrium (resonant magnetic island assumed)
  - Prediction of the perturbed fast ion distribution function (full orbit simulation)
  - comparison with experimental data (synthetic FIDA spectrum with FIDASIM)
- Results or… lessons learned
  - Need for more detailed information on the mode structure
    - Seek to exploit core diagnostic BES, interferometer
  - "**Encouraging disagreement**" is found between synthetic diagnostic predictions for the unperturbed case:
    - Passive background subtraction issue?
    - Incomplete physics in the model? (e.g. no Alfvénic modes included)
    - Inaccurate NB source information? (e.g. n=2 neutral fraction)
    - Implementation error?
- In next experiments t-FIDA will provide extended phase space insight

References

1. *W. W. Heidbrink, RSI 81 (2010) – Review of FIDA diagnostics*
2. *M. Podestà RSI 79 (2008) – NSTX vertical FIDA*
3. *A. Bortolon RSI (2010) – Design of NSTX tangential FIDA*
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5. *accepted for publication in Comm. Comp. Physics. - FIDASIM*

6. *S.P. Gerhardt NF 51 (2011) - Reconstruction of perturbed SXR emission*
7. *J.E. Menard NF 45 (2005) - Modeling of magnetic island structure*

8. *E.D. Fredrickson PoP 13 (2006) – Overview of Fast Ion losses, AE and energetic particles modes in NSTX*
9. *N.N. Gorelenkov PoP 9 (2002) – Compressional Alfvén Eigenmode*

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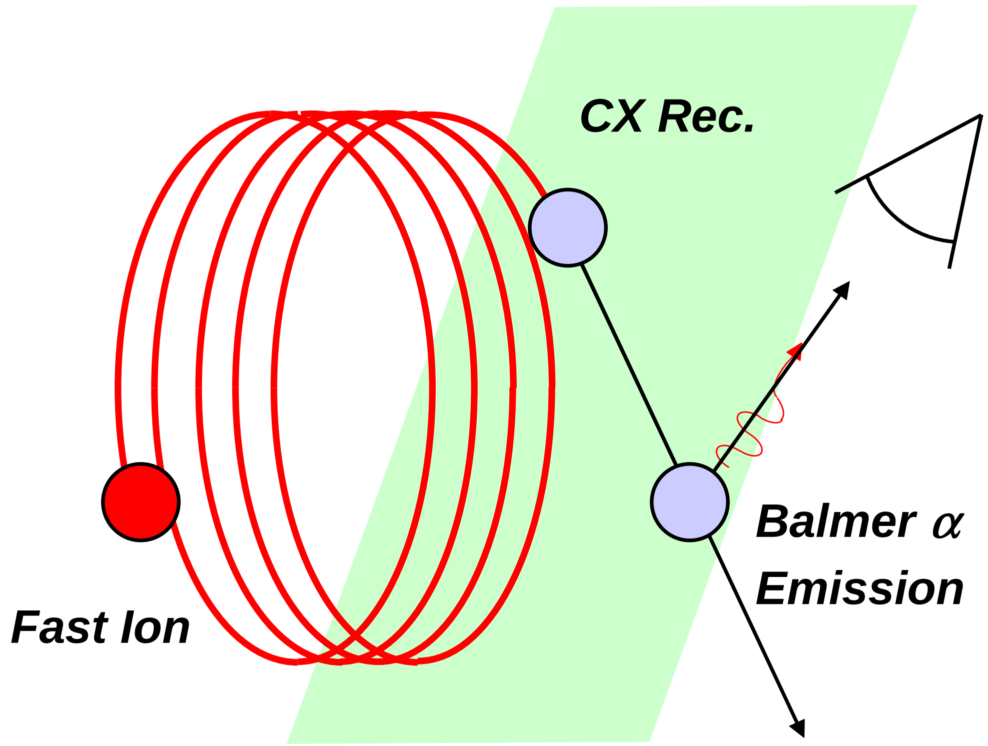
FIDA measurement concept



- 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 $p=v_{||}/v$)

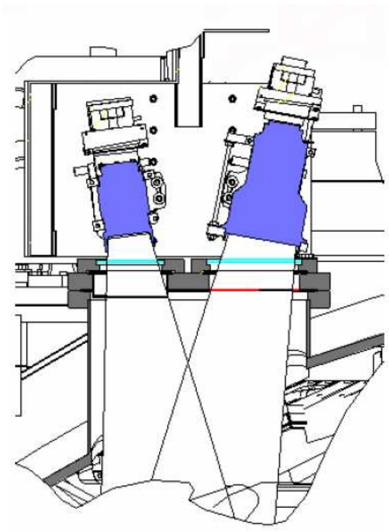
An approximate Fast Ions Density n_{FIDA} can be obtained from

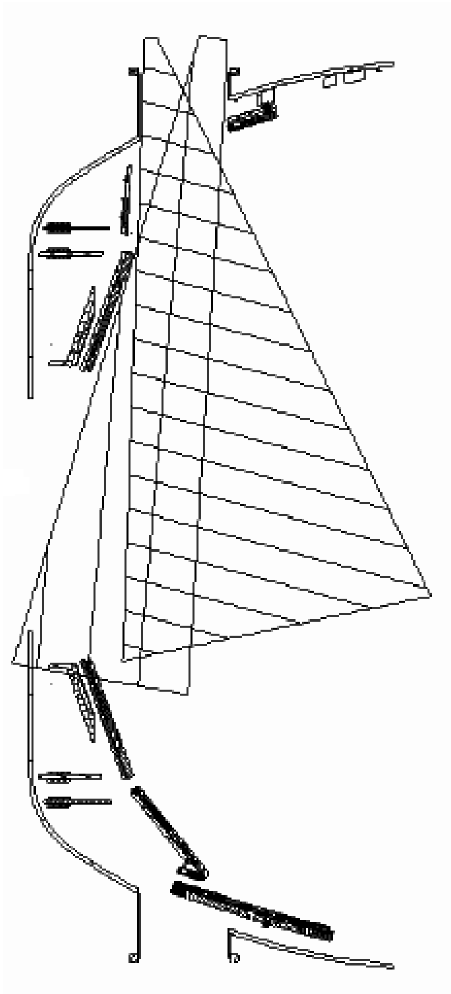
$$\mathbf{n_{FIDA}}=\int_{\Delta\lambda} s_f d\lambda \propto n_f n_b \langle \sigma_{cx}\bar{v}\rangle$$

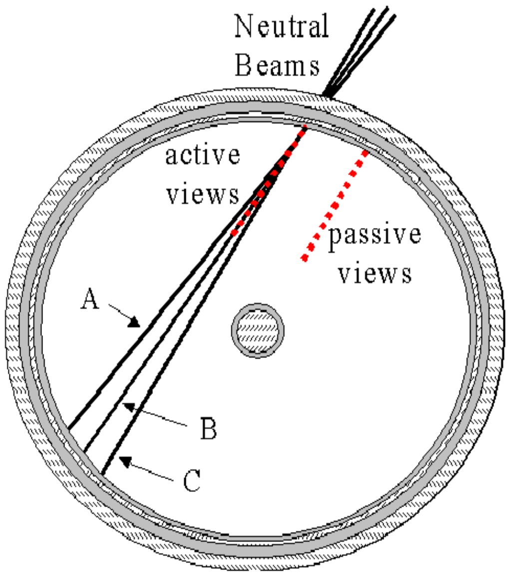
FIDA spectrum — Weight function — FI distribution function

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

NSTX Vertical FIDA diagnostic





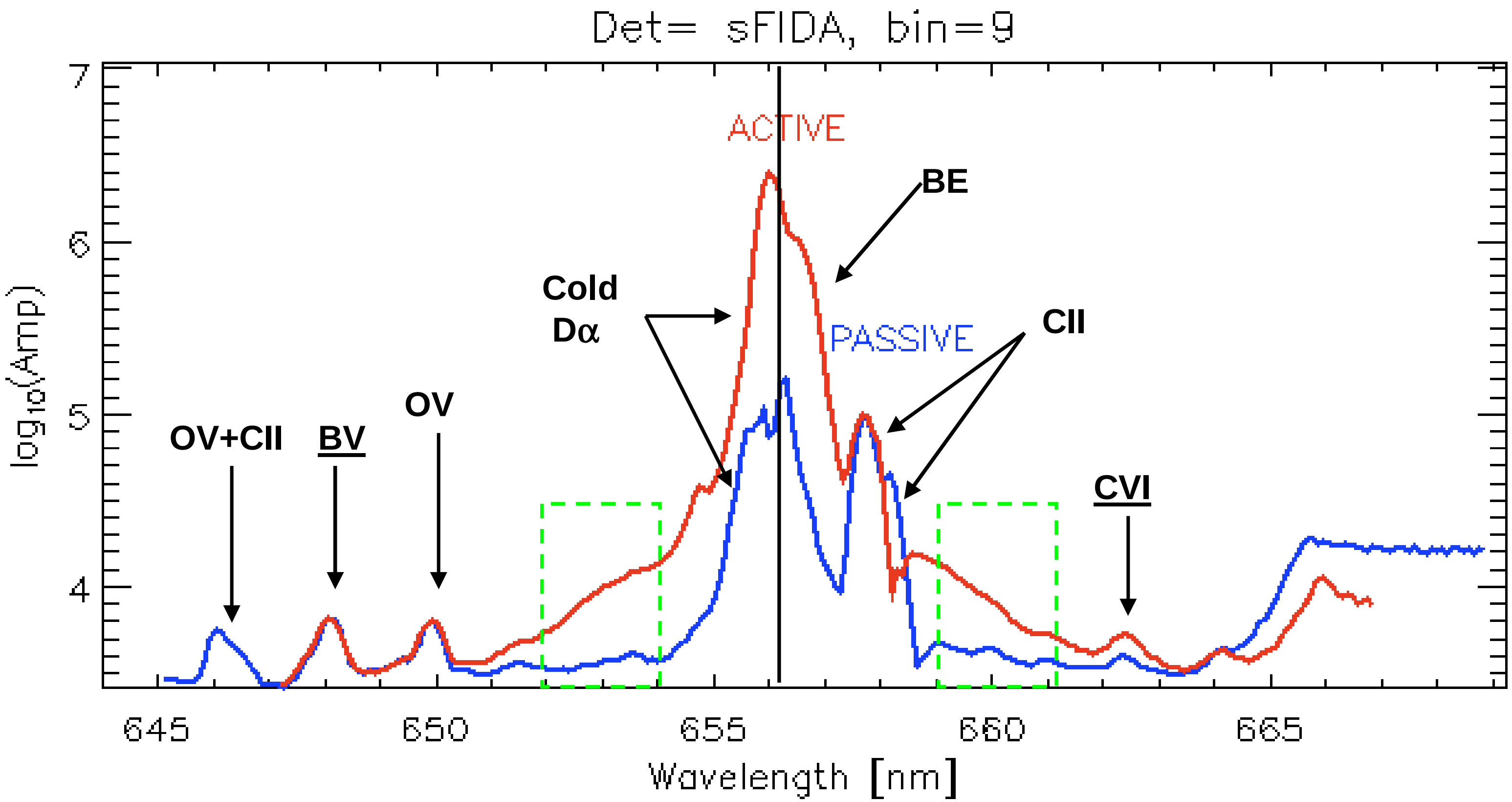


- Two systems
  - Spectroscopic (s-FIDA) top view
  - Filter (f-FIDA) bottom view

- Duplicate view to evaluate background emission
  - Faster than beam modulation
  - Toroidal symmetry hypothesis

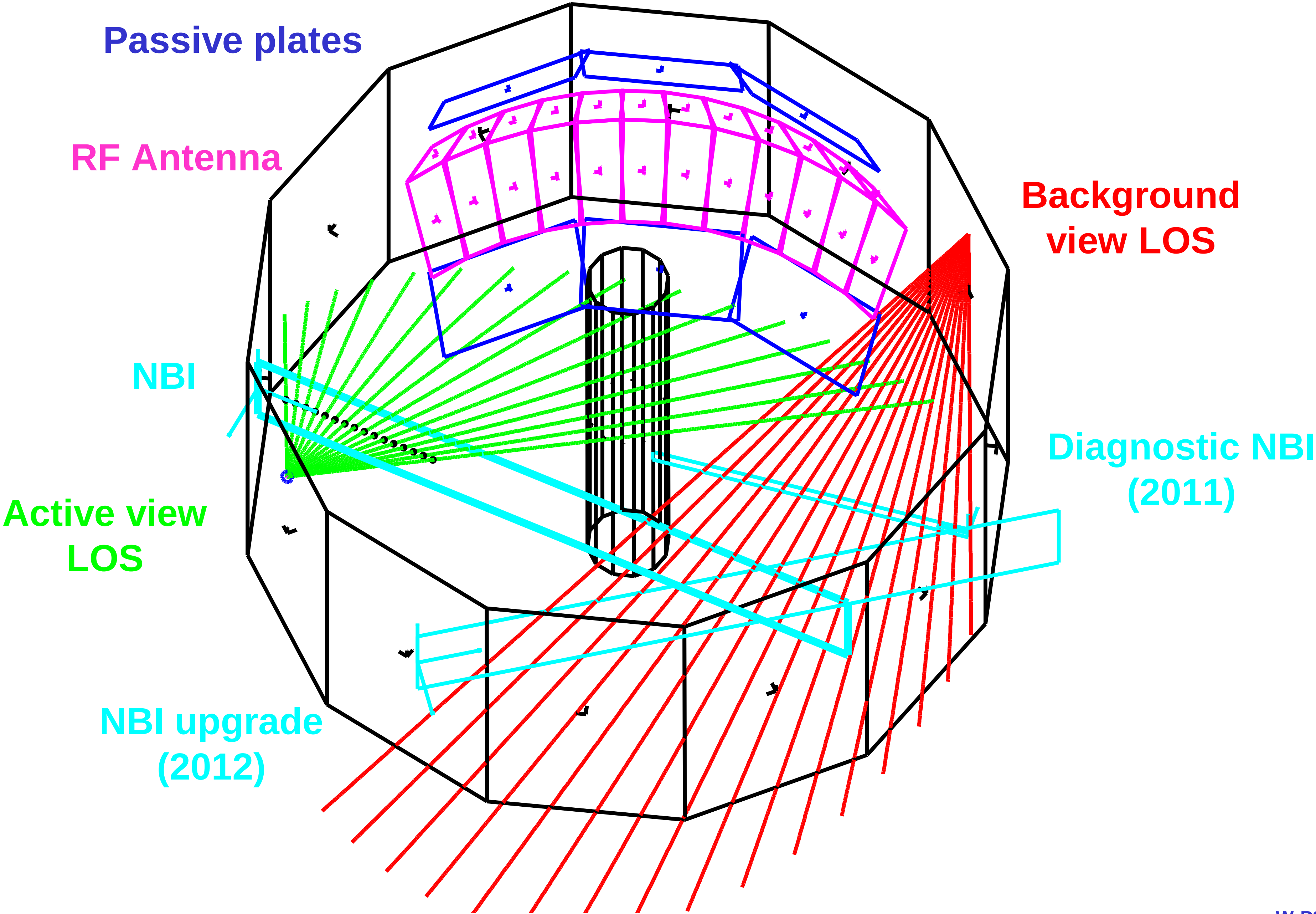
- Vertical view
  - signal from fast ions with large perpendicular velocity
  - sensitive to high pich angle region of velocity space

Example of Vertical s-FIDA spectra

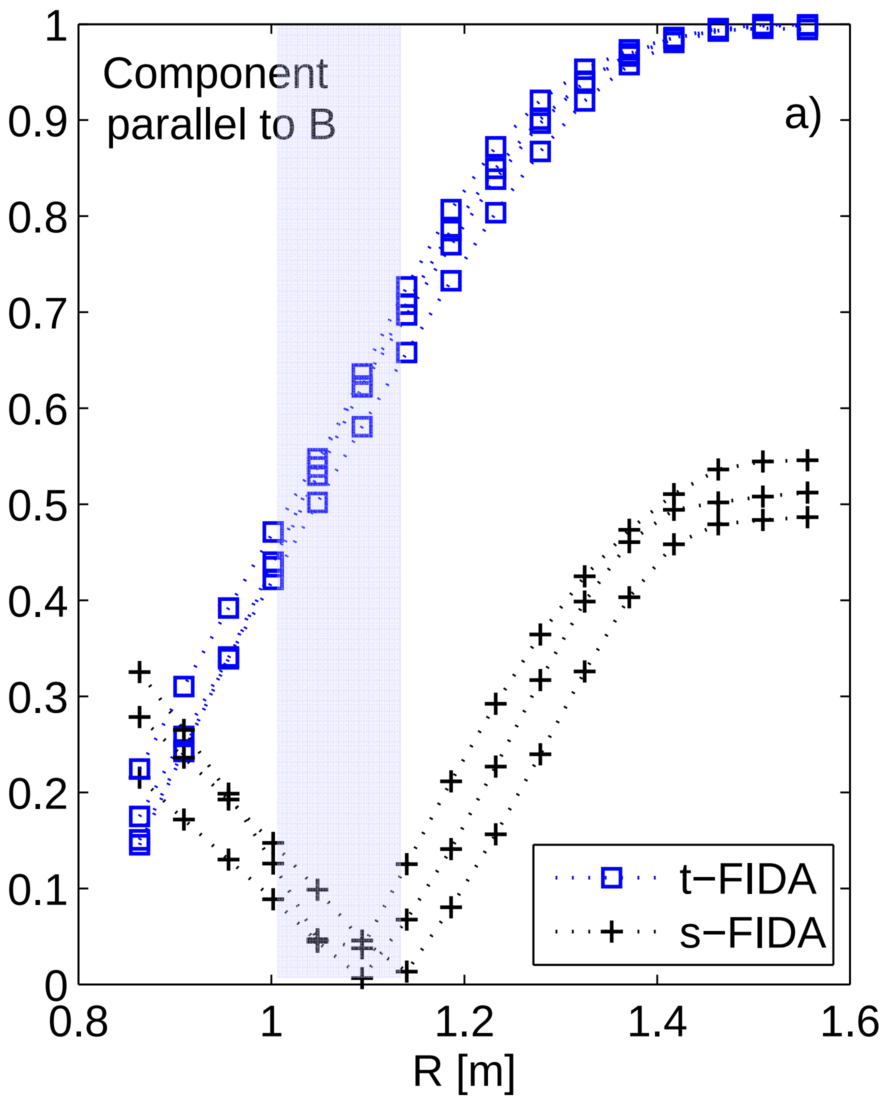


- ❑ Dα cold peak recovered from neutral filter transmission function
- ❑ Impurity lines from Oxygen and Carbon
- ❑ Beam emission on red side
- ❑ Exploitable range on blue side 652-654 nm (E_{λ}~10-40 keV)

New! Tangential FIDA is being installed

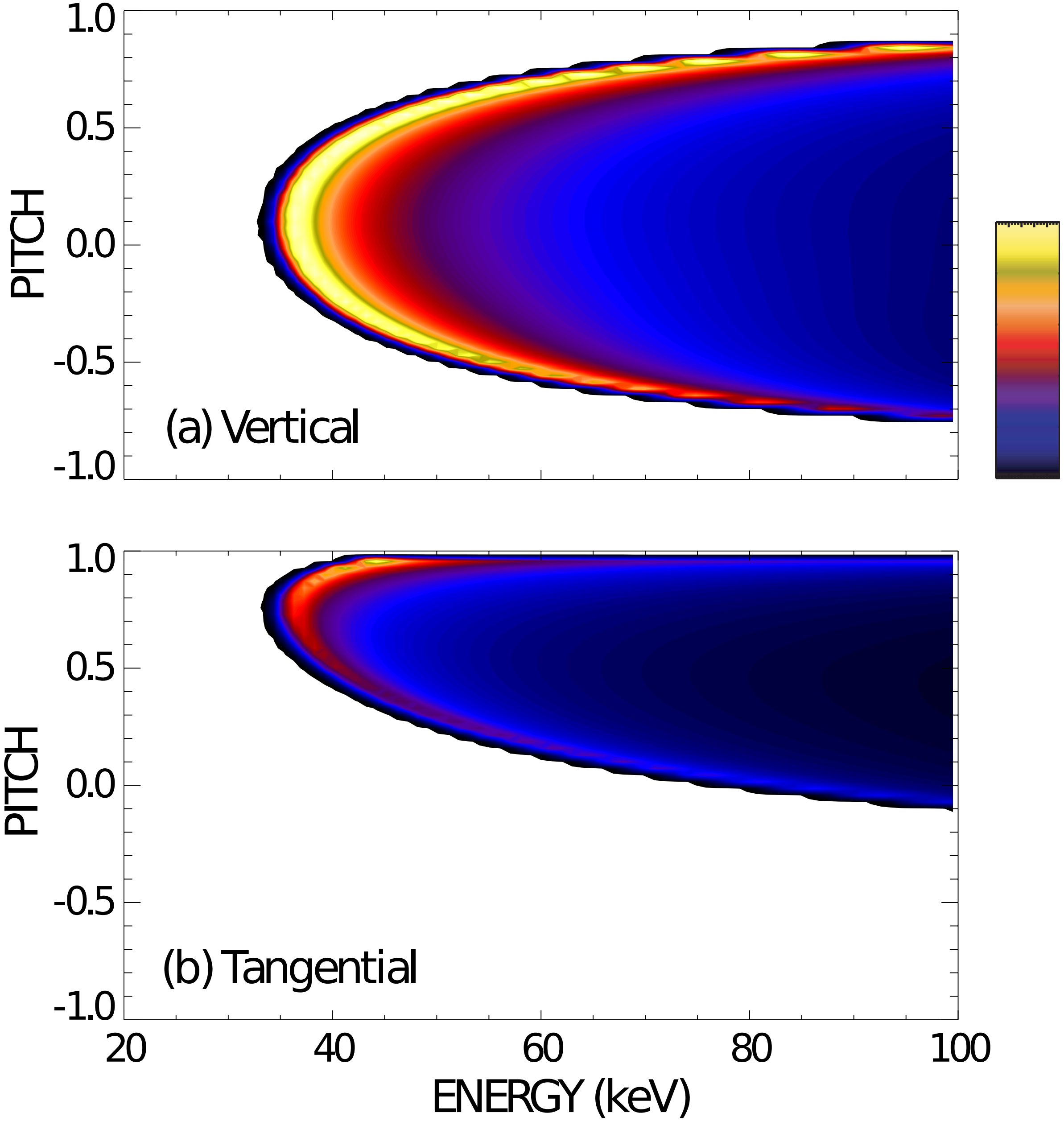


Parallel component



- Component of the LOS unit vector parallel to B field at measurement location
- Representative set of NSTX plasma discharges: max pitch angle 35-42º
- Large parallel component along LFS minor radius
- Consistent difference with present s-FIDA in the maximum Fast Ion density region
- Innermost channel almost perpendicular: cross validation of s-FIDA and t-FIDA

Response function of t-FIDA



- W_λ (E,p) evaluated at
  - R=1.2 m,
  - E_λ=35 keV (652.1 nm)
- Tangential view is sensitive to p>0.8
- Contribution from small region of phase space

- Enhanced energy resolution
- Enhanced source of FIDA signal

Complementary sampling of velocity space