Fast ion losses and redistribution induced by low frequency MHD in NSTX plasmas

A. Bortolon

G.J. Kramer, J. Manickam, E. Fredrickson, M.Podestà, W.W. Heidbrink and the NSTX Research Team

Columbia U
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Johns Hopkins U
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LLNL
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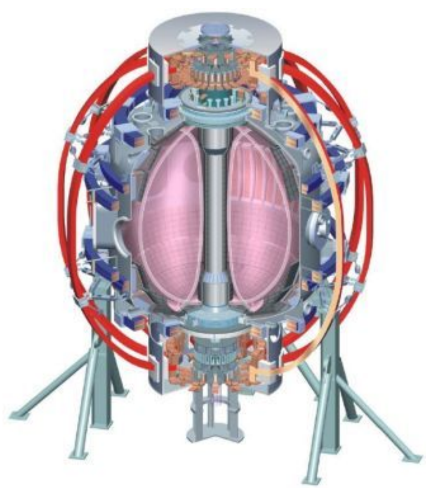

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Introduction and motivation

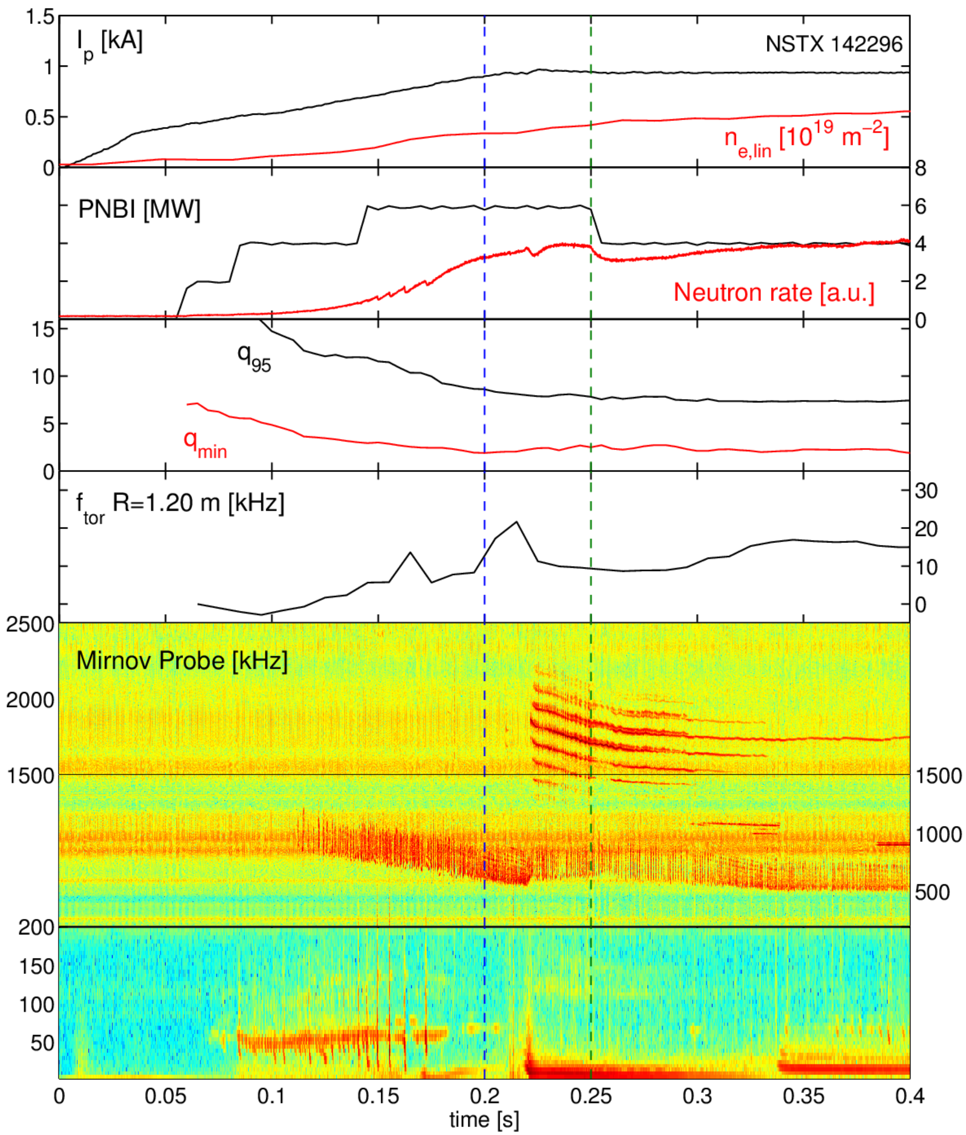
- Fast particle transport and losses in presence of Low Frequency MHD modes has been studied in different devices (TFTR, DIII-D, ASDEX, NSTX, ...)
- Often core modes have been addressed described by single helicity radial perturbation (NTM, tearing mode, core kink)
- Former studies on NSTX focused on (m=2,n=1) core kink
  - Depletion at particle energies below the injection energy (NPA)
  - Passing particles ($E<E_{inj}$) are preferencially affected
- Here we address early low frequency MHD activity on NSTX
  - Strongly affects fast ion population (FIDA)
  - Appears to be an important element for the destabilization of high frequency CAE modes

Outline

- Experimental scenario
  - Typical discharge evolution, MHD activity
  - FIDA observations
  -
- Mode characterization
  - Experimental observations
  - Mode structure from ideal stability computations

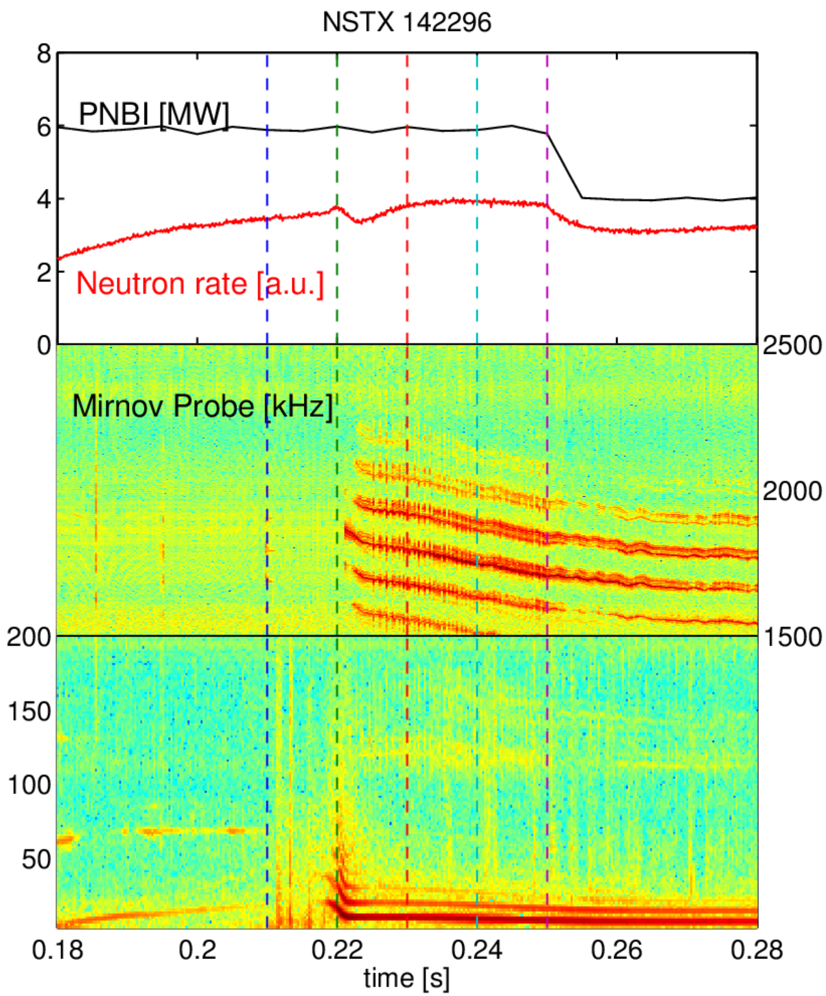
- Losses and redistribution of beam ions
  - Full orbit simulations results

Experimental Scenario



- H-mode plasma (t<300 ms)
  - B_t=0.4T I_p=900kA
  - P_{NBI}=4-6 MW
- MHD activity at different frequencies:
  - Toroidal AE (bursting)
  - Global/Compressional AE (bursting/continous)
- 8kHz mode destabilized at 0.22s (beginning I_p flat top)
- Mode onset induces plasma braking
- Mode vanishes after 100 ms, as density increases

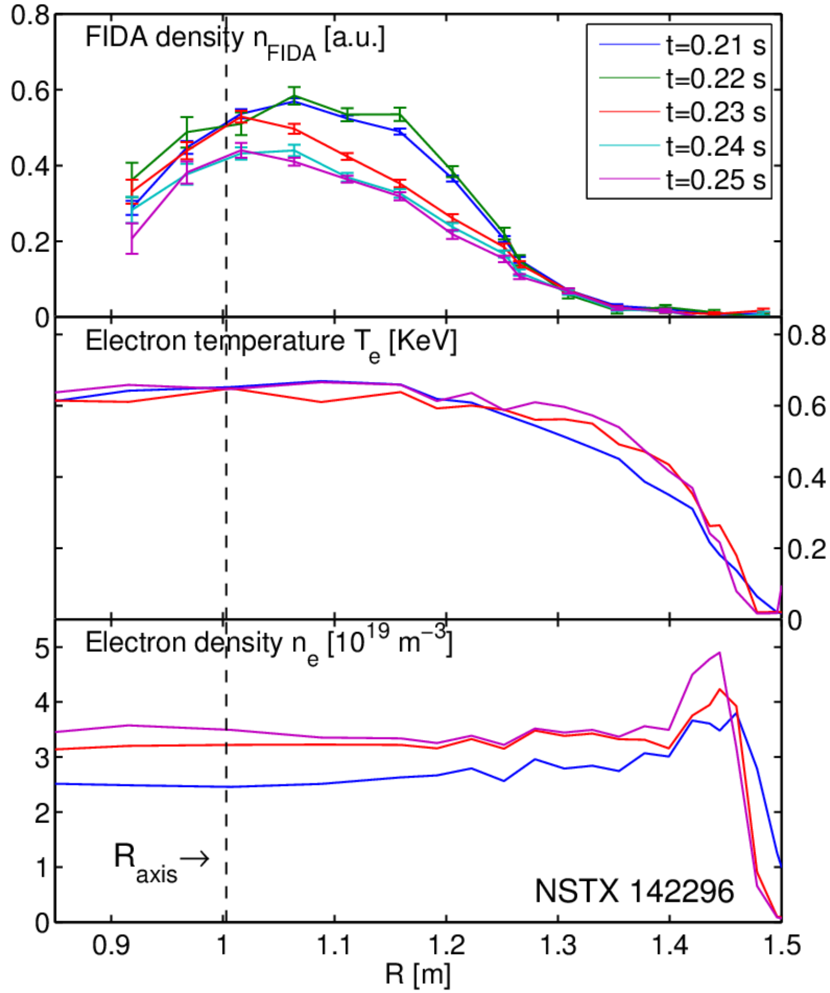
MHD dynamic at mode onset



- Low frequency mode appears with multiple toroidal harmonics
- Initial chirp follows the toroidal rotation drop (-15kHz)
- Persisting n=1 and n=2 components

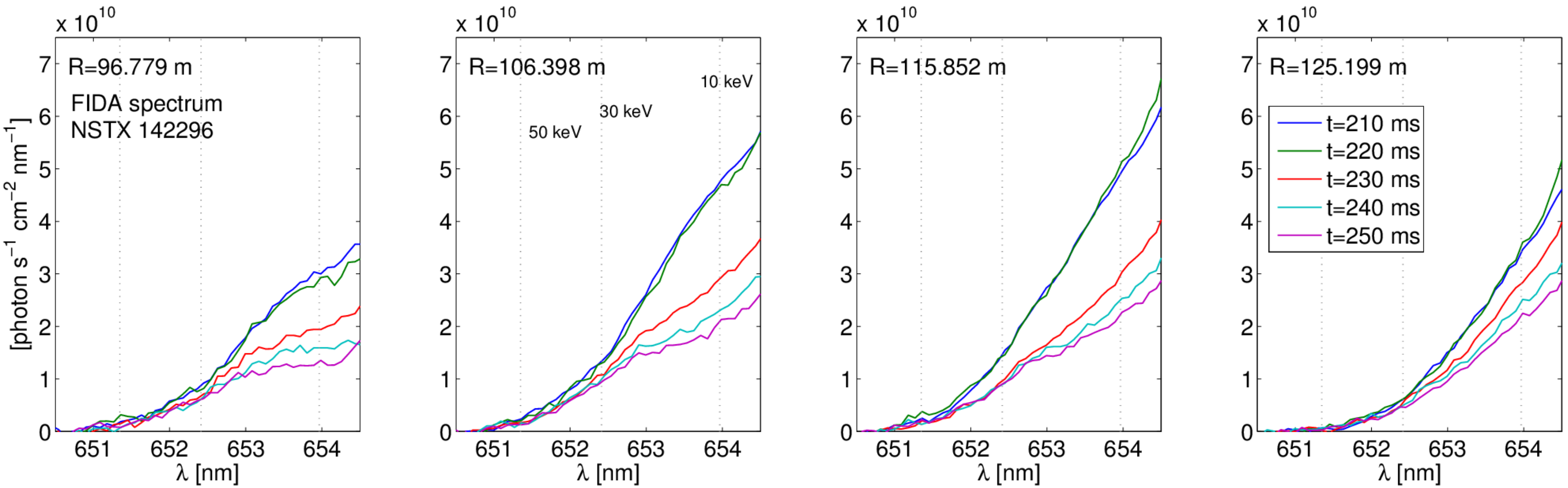
- Compressional AE cluster
- Co-propagating, n=9-13
- Resonate with co-moving ions
- Appear ***after*** onset of LF MHD

Depletion of FIDA density at mode onset



- Vertical FIDA diagnostic provide local information on fast ion density
- n_{FIDA} depletion observed after mode onset:
  - up to 30% reduction
  - LFS affected first and more
  - 10 ms time scale
- Fast Ion confinement remains deteriorated during the mode activity

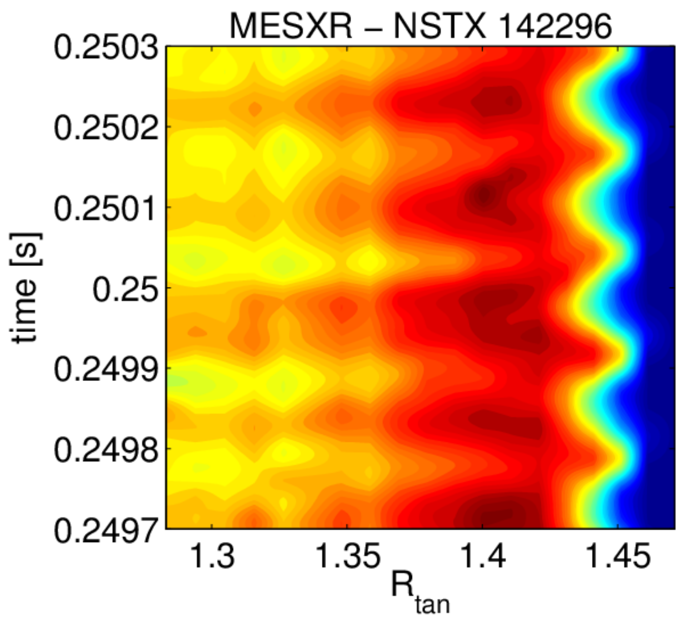
FIDA spectra evolution across mode onset

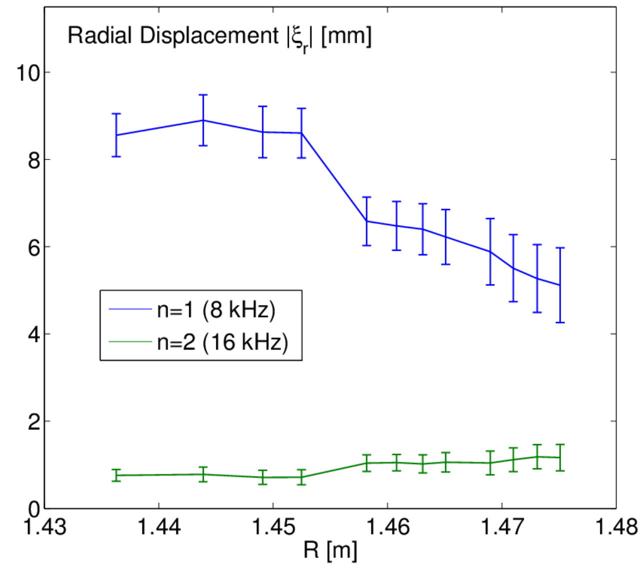


- Spectral signal decrease in a broad band of wavelength/energies
- Reduction of signal from $\Delta\lambda_{Doppler}$<2.5 nm (E_λ< 30 keV)
- Vertical FIDA is sensitive to low pitch angles ($p=v_{||}/v$ <0.6, E~30-60 keV)
- Low Frequency MHD activity affects mostly trapped population
- Fast Ion Losses vs Redistribution in phase space?

Low Frequency Mode Characteristics

- Mirnov array indicates n=1 (15 Gauss at plasma boundary), weaker n=2
- No clear evidence of magnetic island (e.g. Te)

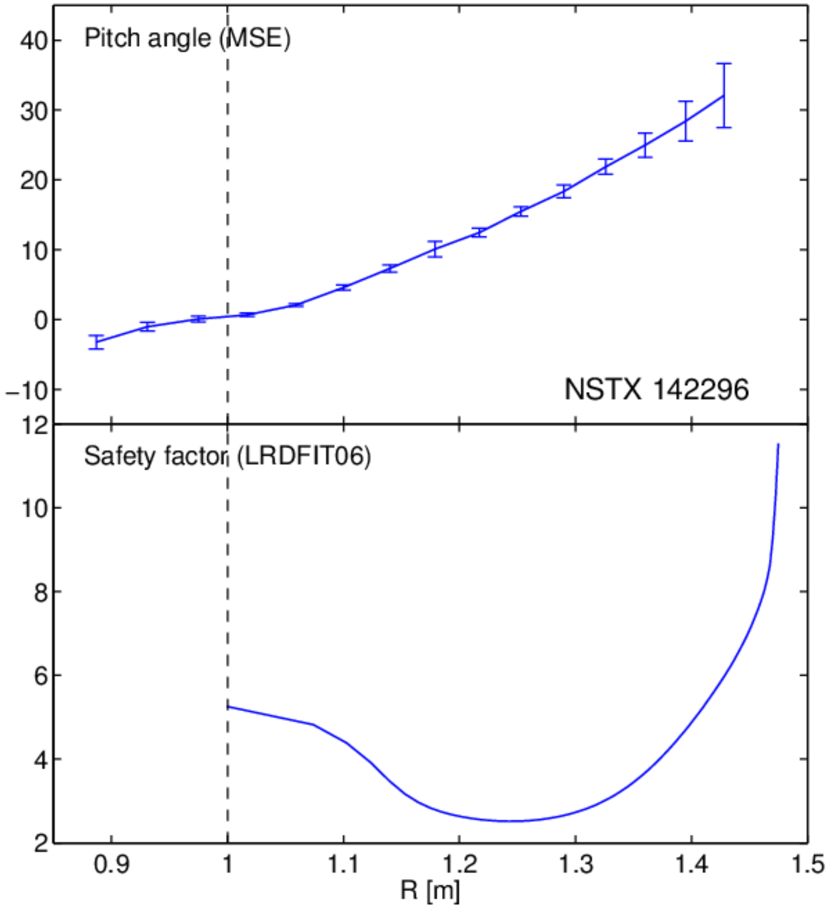




- Edge Toroidal SXR array (MESXR) captures peripheral dynamic:
  - expansion-compression
  - 8 kHz, r/a>0.6

- Radial displacement of plasma pedestal measured by reflectometer
- Difficult to determine internal mode structure (bat ear cut-off)

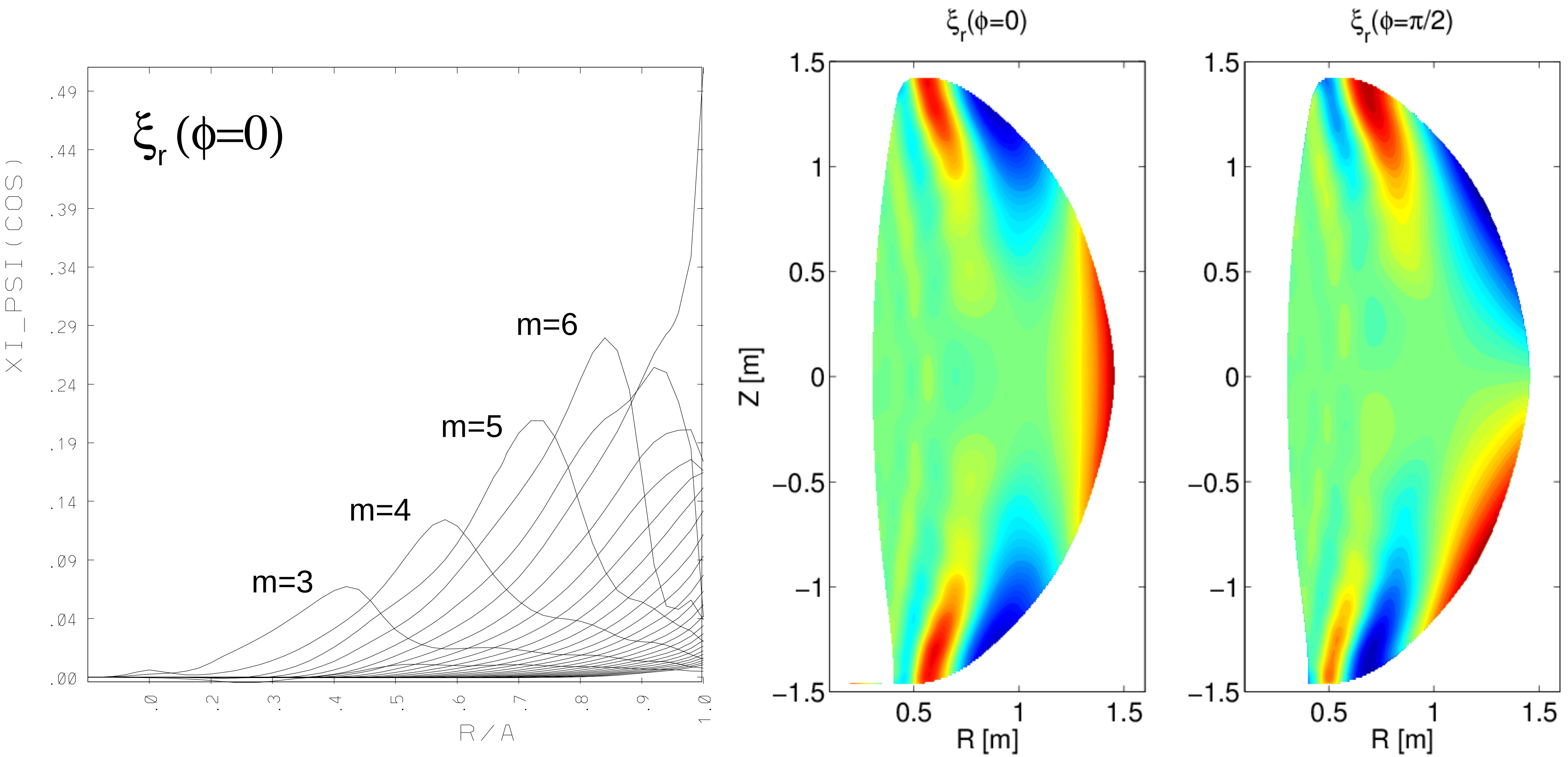
PEST code used to predict the mode structure



- Consider t=250ms, saturated phase, 30 ms after onset
- Input equilibrium from LRDFIT code with constraints on kinetic pressure and MSE
- Only n=1 component considered
- |m|<40 poloidal harmonics included
- Computation up to 99.98% of ψ_e

- Equilibrium results linearly unstable only under these conditions:
  - Reversed shear in plasma core
  - High pressure gradient at pedestal
  - Free boundary

Kink n=1 mode structure (PEST)



- High order poloidal harmonics contribute in the peripheral region
- Finite amplitude at the plasma boundary
- Mode amplitude is larger in the LFS (m=3-4 overall structure)

Kink structure validation and normalization (1)

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

- 3D n_e and T_e perturbation from radial displacement:

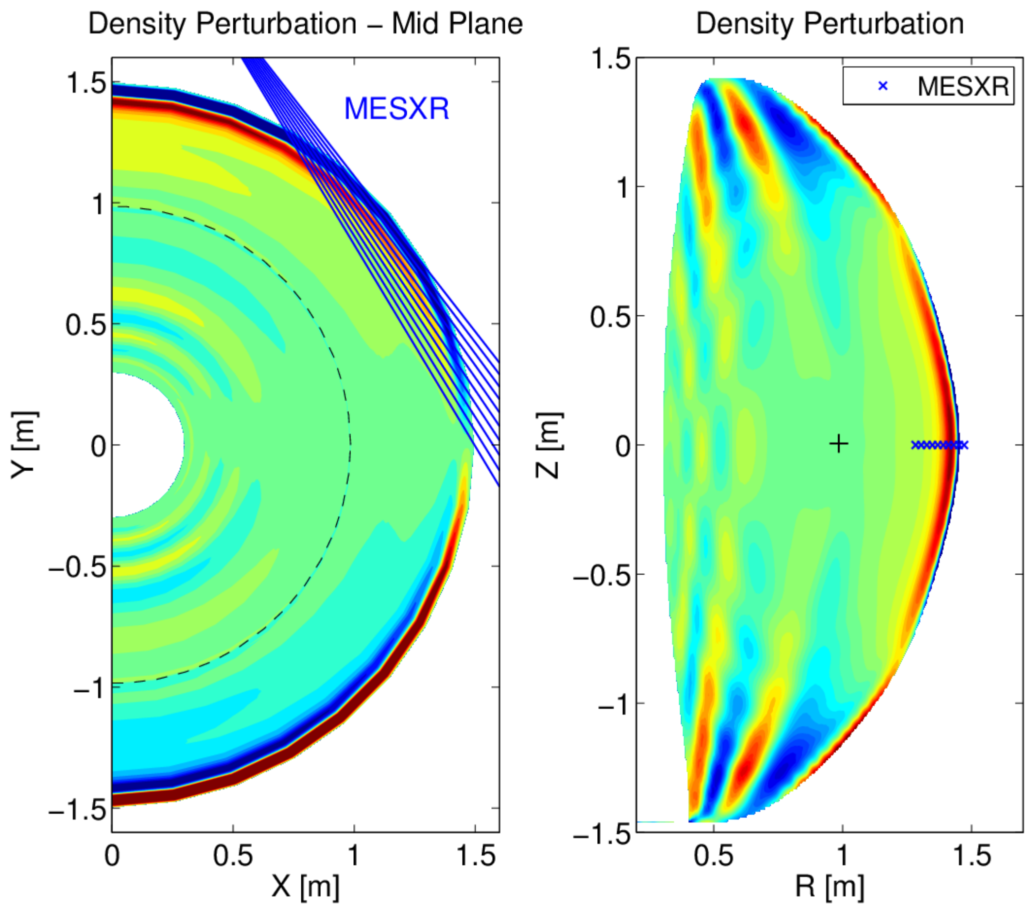
$$\delta n_e = -n_e \nabla \cdot \xi_r - \nabla n_e \cdot \xi_r$$

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

- SXR emissivity assuming carbon impurity only:

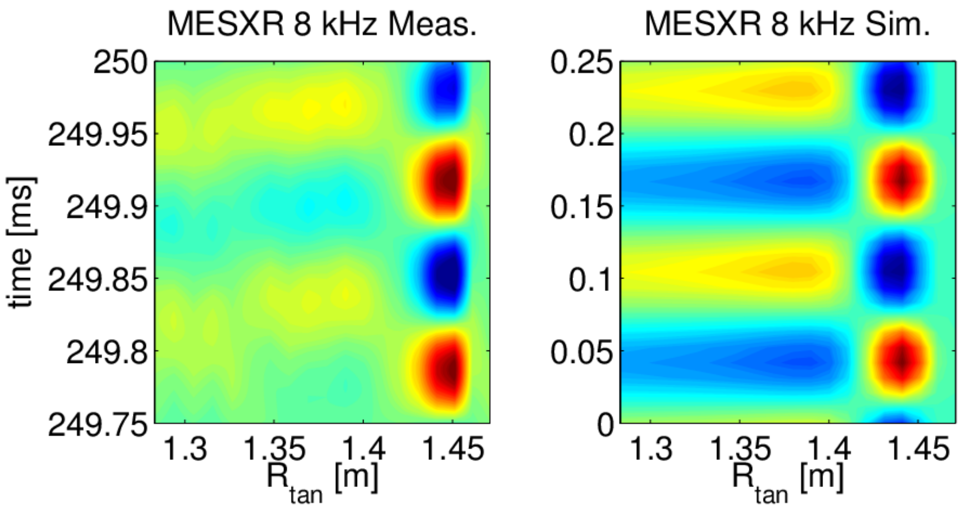
$$E_{SXR} = n_e^2 R_C(T_e)$$

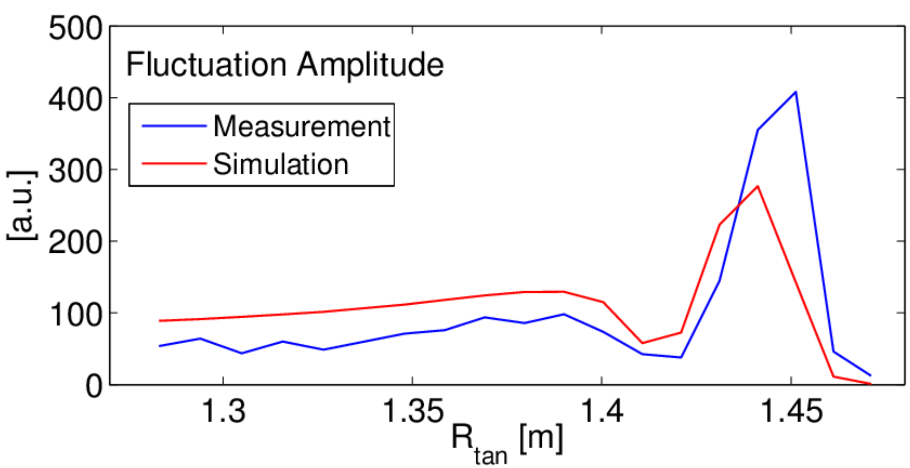
- Rigid toroidal rotation at mode frequency (8 kHz)



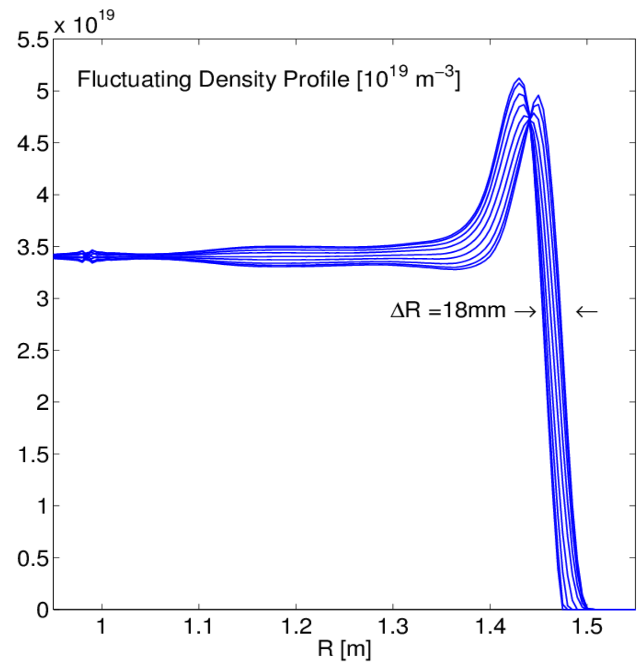
Kink structure validation and normalization (2)

Reasonable agreement with data if ξ scaled to 2% of PEST output





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



Predicting fast ion distribution function with SPIRAL

- The full-orbit MC code SPIRAL has been used to calculate the **fast ion losses** and **distribution function** in presence of the kink mode
- SPIRAL follows beam ions orbiting in the perturbed magnetic field according to PEST prediction (scaled)
- Simulation approach:
  - 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 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**
- Simulations also include effect of plasma rotation and magnetic ripple

SPIRAL results

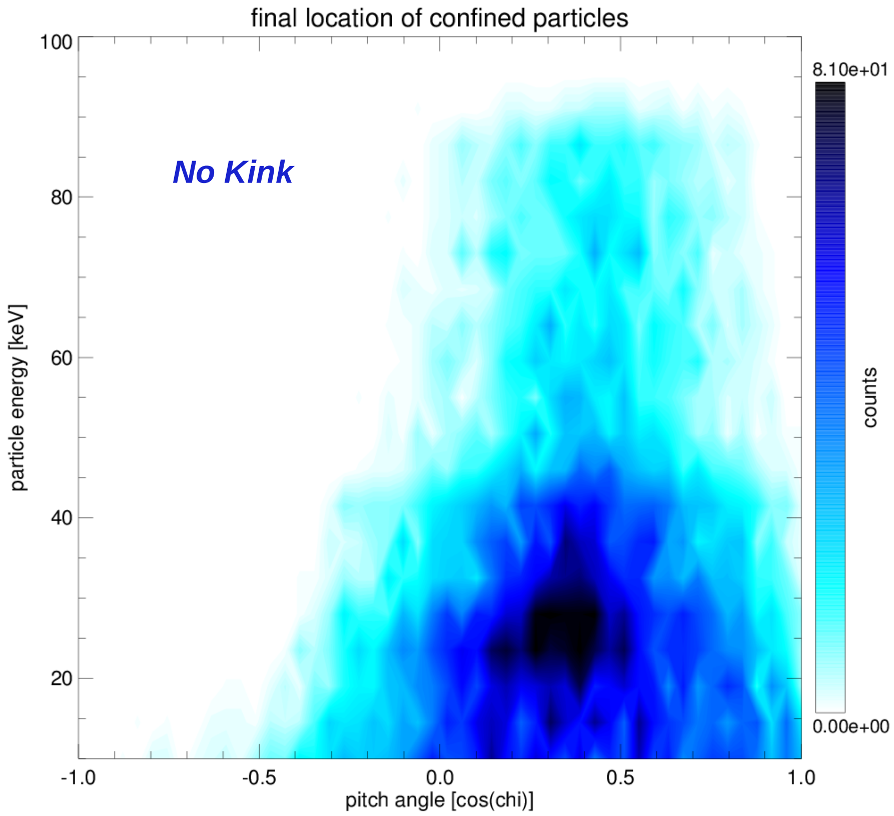
- Simulations have been conducted for 3 NSTX beams separately
- Reference case with equilibrium field only ran for comparison
- So far, ensembles of 2000 particles per beam have been processed
- Low statistics:
  - adequate to evaluate total losses
  - insufficient to address redistribution in phase space

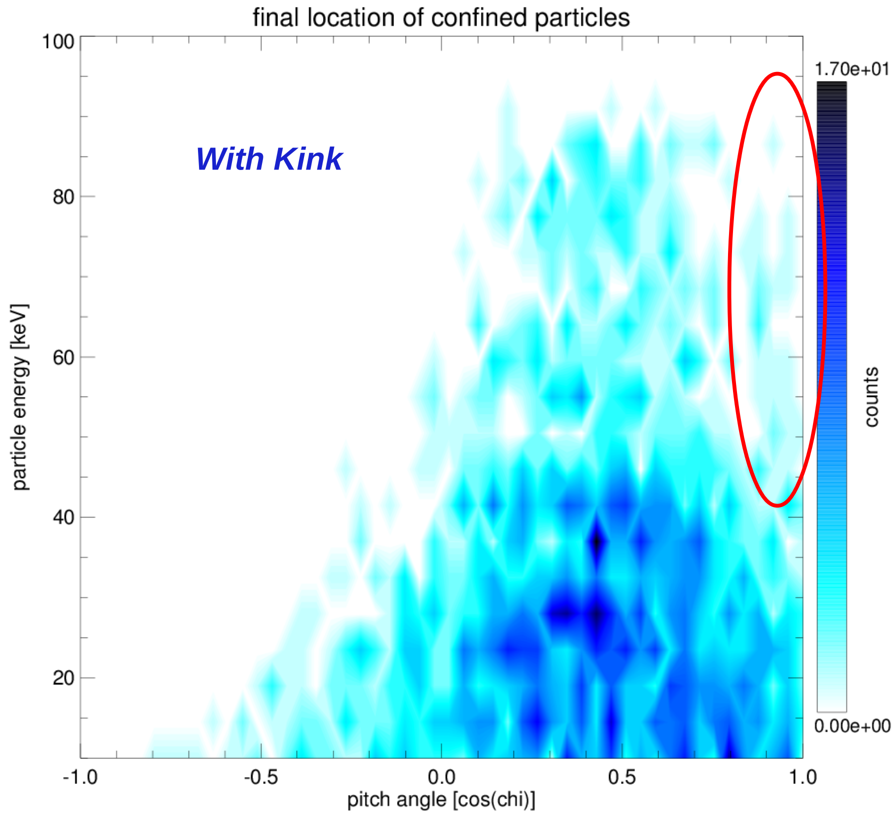
Total Beam Ion Losses			
	Without kink	With kink	Difference
Beam A	9.2 %	12.3 %	+ 3.1 %
Beam B	17.9 %	21.2 %	+ 3.3 %
Beam C	25.1 %	28.2 %	+ 3.1 %

Incremental effect on fast particle losses

SPIRAL: effect on distribution functions

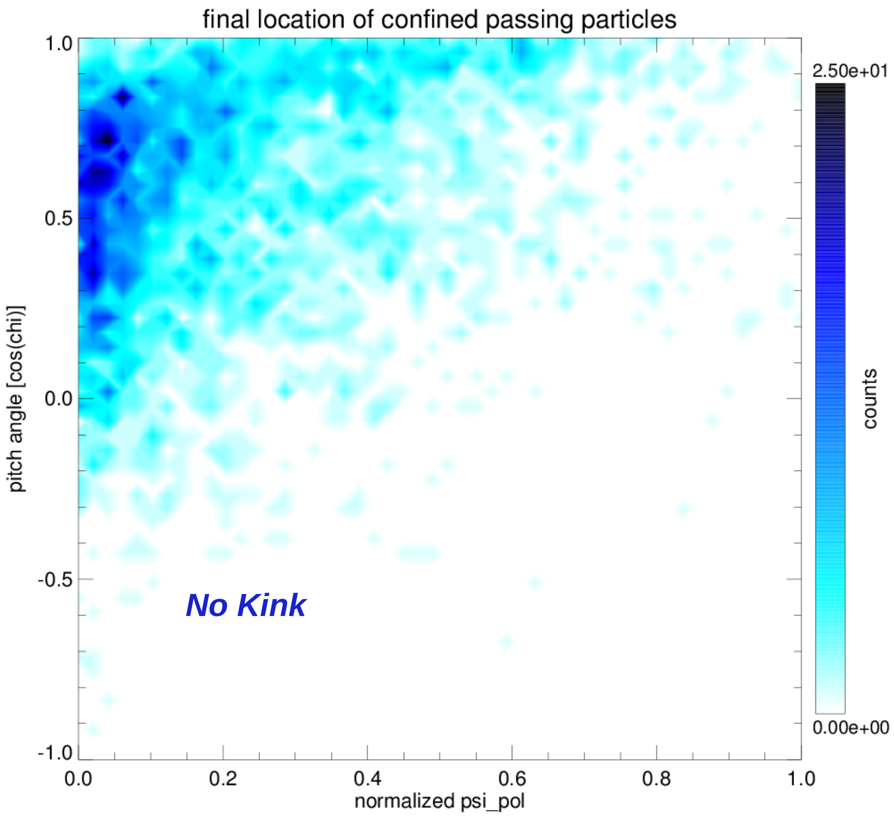
- Low statistics: insufficient to address redistribution in phase space
- Possible indication of increase of pitch~1 population

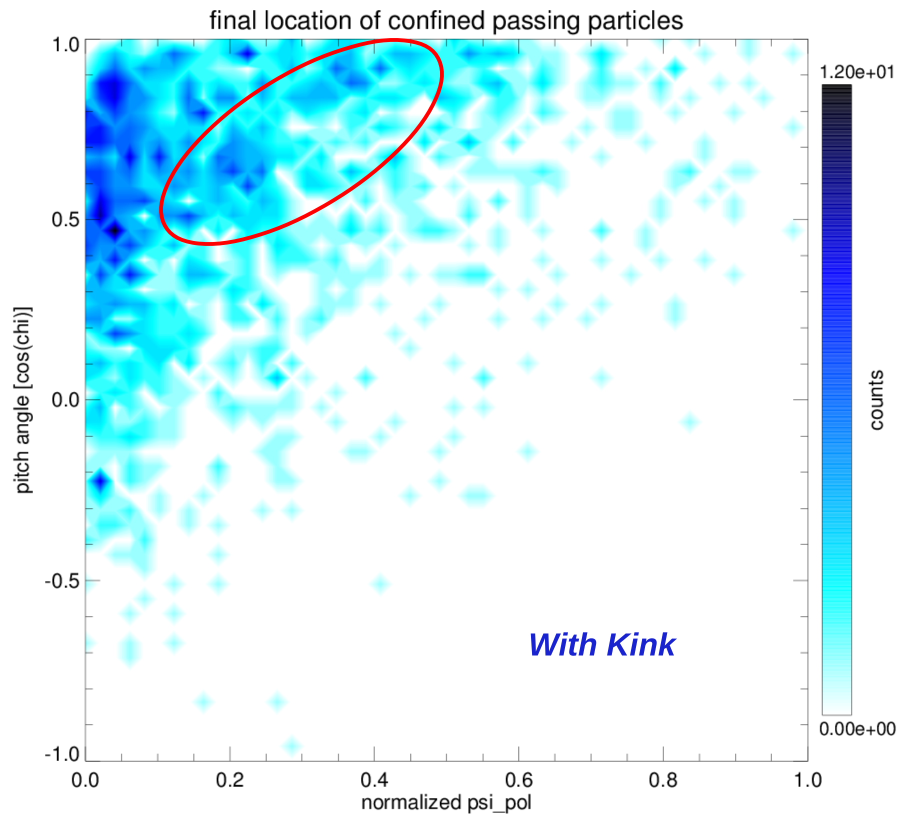




SPIRAL: radial distribution of particle pitch (Beam C)

- Radial variation of distribution function can be considered
- Possible indication of off-axis increase of pitch>0.5 population





Conclusions

- Early LF MHD is observed to affect strongly the fast ion population on FIDA measurements
  - Fast Ion polulation reduced as much as 30%
  - Fast ion redistribution may be responsible for the high frequency CAE associated with the LF MHD
- Mode nature and structure studied with ideal MHD stability
  - global kink nature, finite edge amplitude, associated to a residual reversed shear
  - a kink perturbed equilibrium has been constructed consistent with experimental observations
- Full-Orbit simulations with SPIRAL used to study the effect on fast ion confinement
  - Fast ion losses increase by 3%, suggesing redistribution can play a role
  - At present the MC statistics is insufficient to draw conclusions on redistribution
  - Possible indications of redistribution of fast passing ions need confirmation