Characterization of fast ion confinement in the NSTX based on FIDA diagnostic measurements

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NSTX

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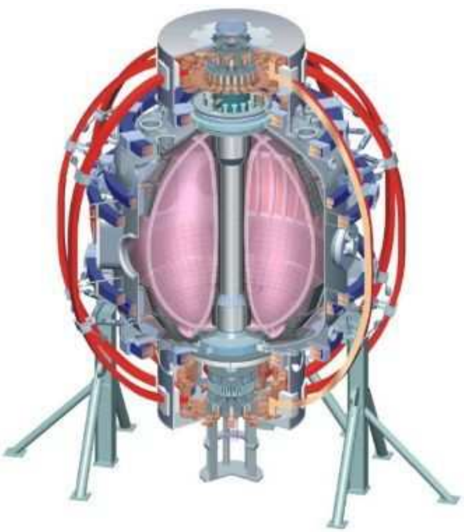

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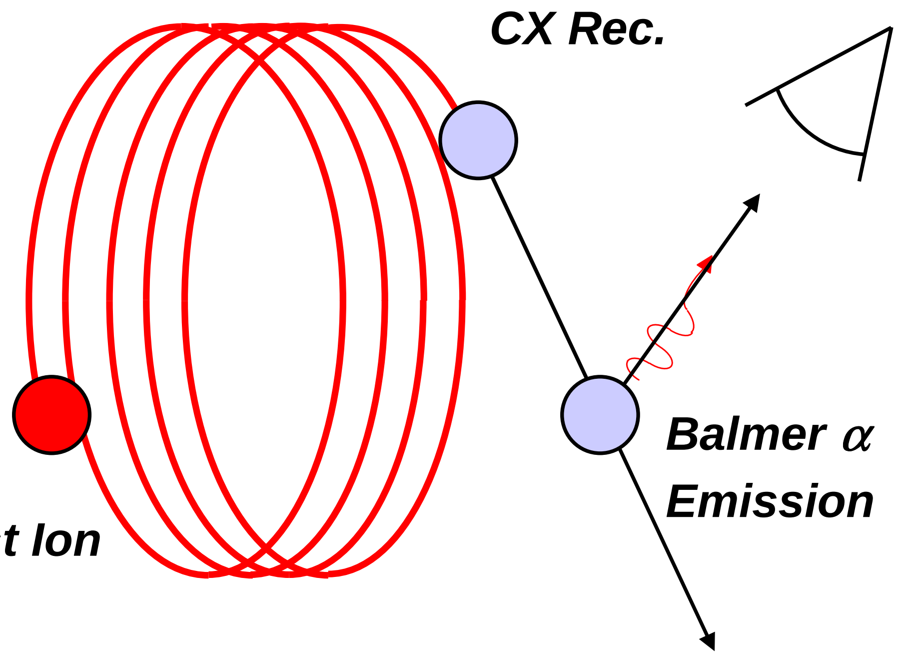
Motivation

- Strong interest on fast ion transport: responsible for fusion yield, drive for several type of instabilities
- In NSTX Fast Ion density profile is routinely measured by FIDA diagnostic
- FIDA density profiles are observed with different degrees of peaking in different plasma conditions
- The objective of the work is to assess the fast ion density profile on an extended set of NSTX discharges
- Identify dependences on main plasma parameters, regimes with specific features in the fast ion profile

FIDA measurement concept



- Active Charge eXchange
  - Measures hot tails of Balmer alpha line
  - 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 $p=v_{||}/v$)

W(E,p) accounts for:

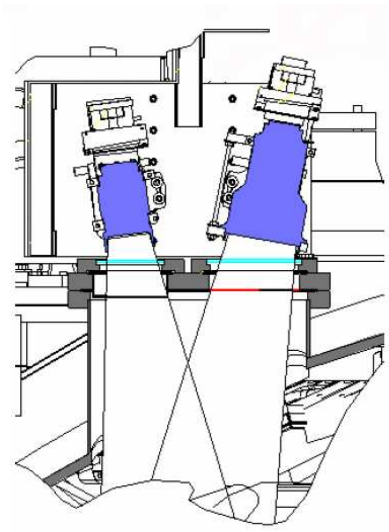
1. ***Viewing geometry (Minimal Energy)***
2. ***Gyro angle average***
3. ***CX cross sections and radiative rates***

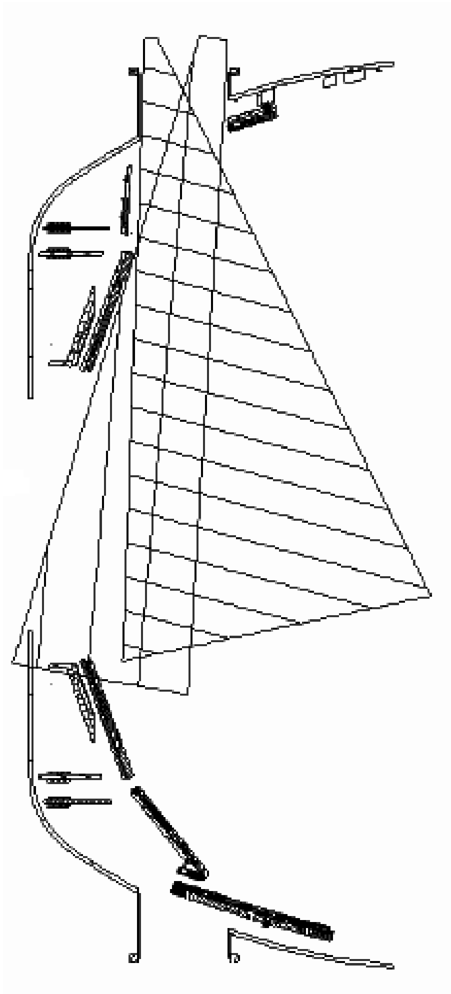
FIDA spectrum — ***Weight function*** — ***FI distribution function***

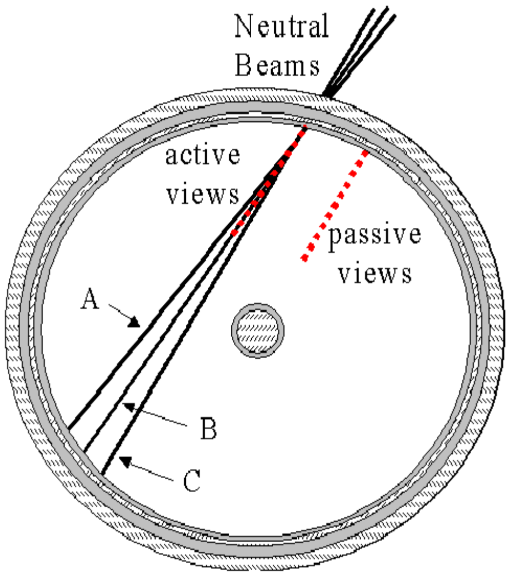
$$s_f(\lambda) = \int W_\lambda(E,p) F_f(E,p) dEdp$$

[W. W. Heidbrink RSI 81 (2010)]

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 pitch angle region of velocity space
  - Important contribution from trapped fast ions

[M. Podestà RSI 79 (2008)]

FIDA density definition

- An approximate Fast Ions density may be calculated from the experimental radiance over a wavelength interval

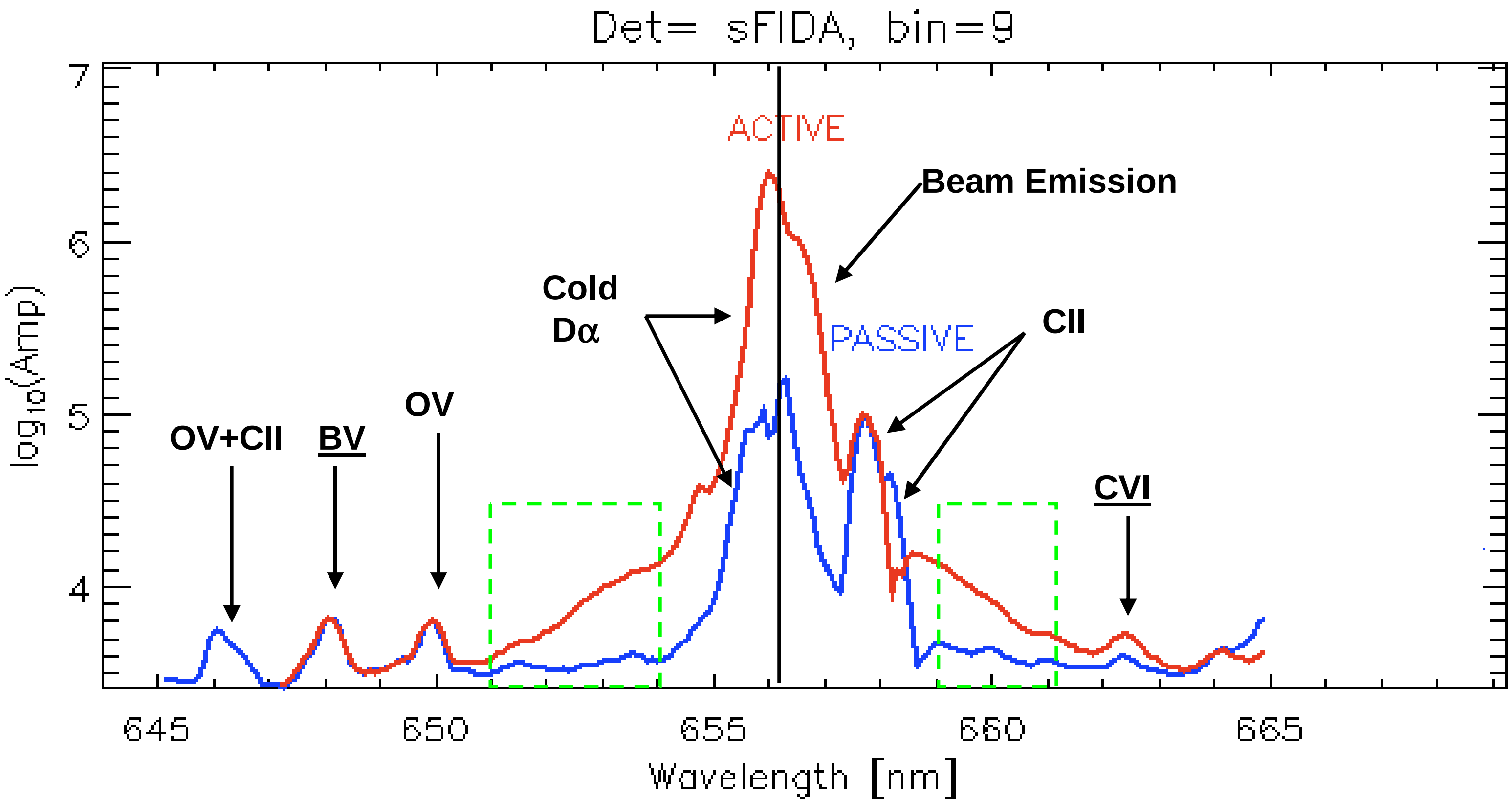
$$I_{\Delta\lambda} = \int_{\Delta\lambda} s_f \, d\lambda \propto \int n_f n_b \langle \sigma v \rangle dl \approx n_f \langle \sigma v \rangle \int n_b \, dl$$

- The average is taken over the fast ion distribution function. To obtain n_f one should already know F(E,p)
- Full treatment requires accounting for W(E,p) (FIDASIM code [Ref.6])
- In this work we calculate n_{FIDA} as:

$$n_{FIDA} = \frac{I_{\Delta\lambda}}{\int n_b \, dl} = n_f \langle \sigma_{CX} v \rangle$$

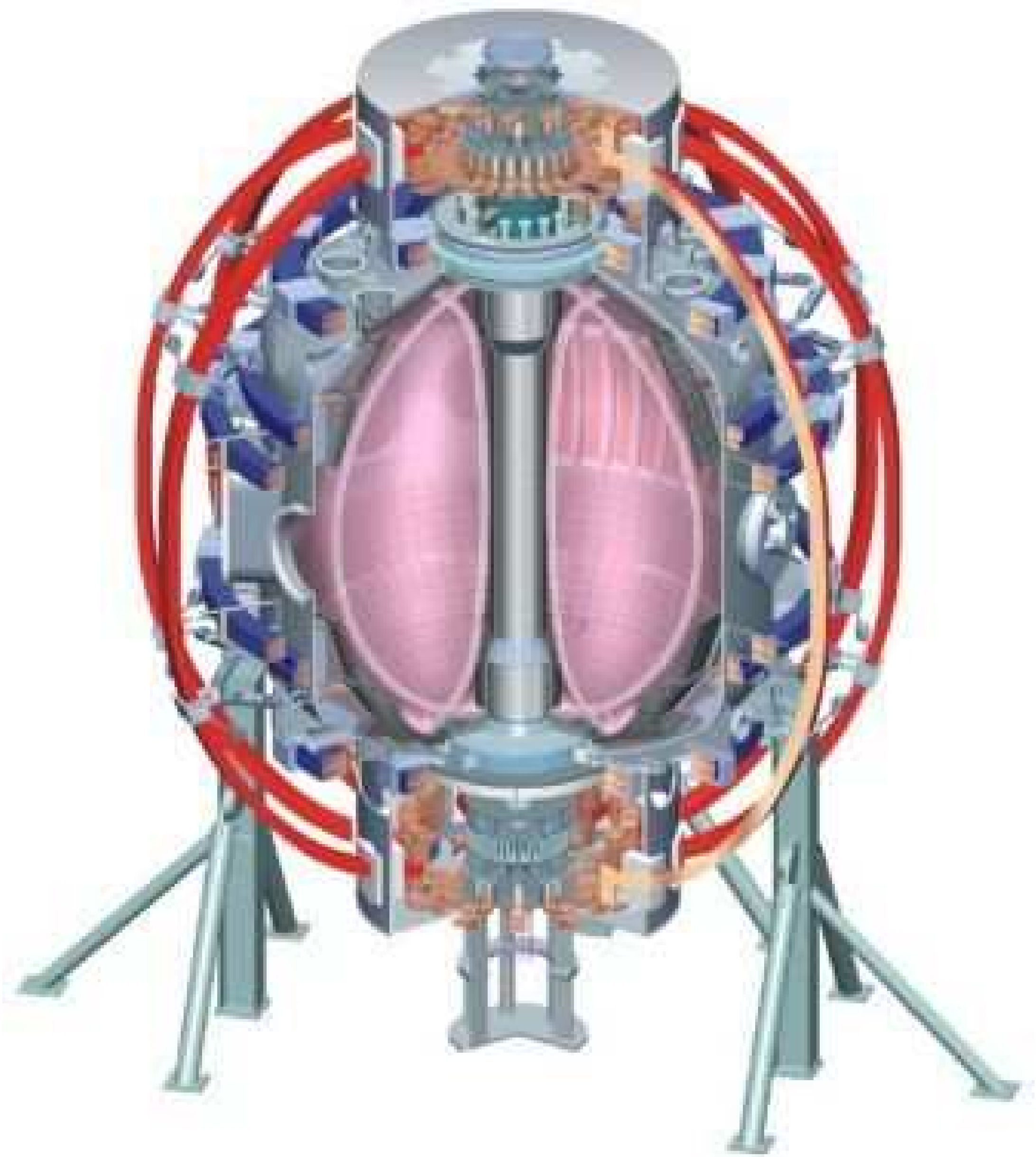
- Neutral density calculated using a pencil beam attenuation code [Ref. 7]
- Halo neutrals are not taken into account!

Example of s-FIDA spectrum



- D_α cold peak recovered from neutral filter transmission function
- Impurity lines from Oxygen and Carbon (some are CX)
- Beam emission on mostly on red side
- Exploitable range on blue side 651-654 nm (E_λ~10-60 keV)

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

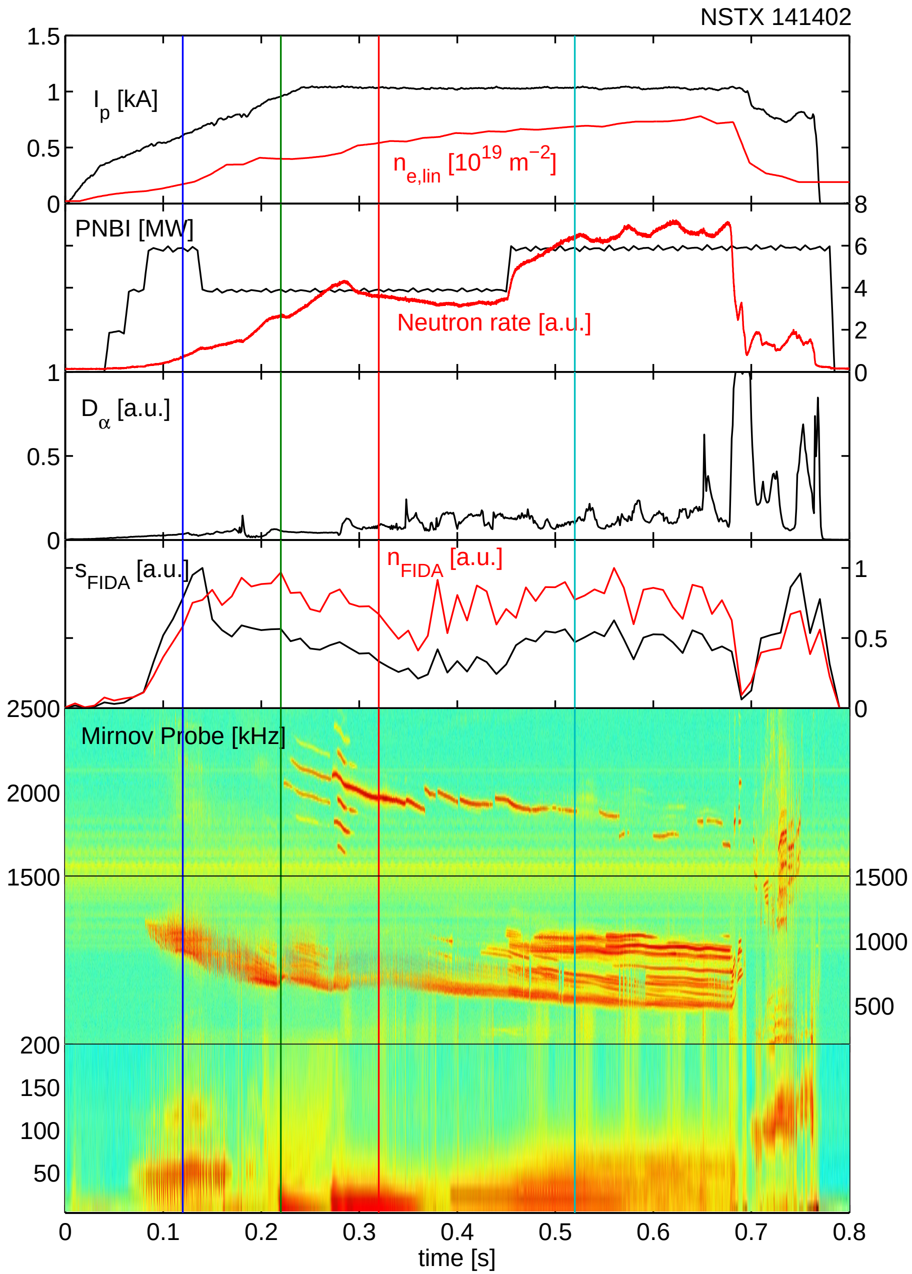
3 Neutral Beam sources

$P_{NBI} \leq 6$ MW

$E_{injection} \leq 95$ keV

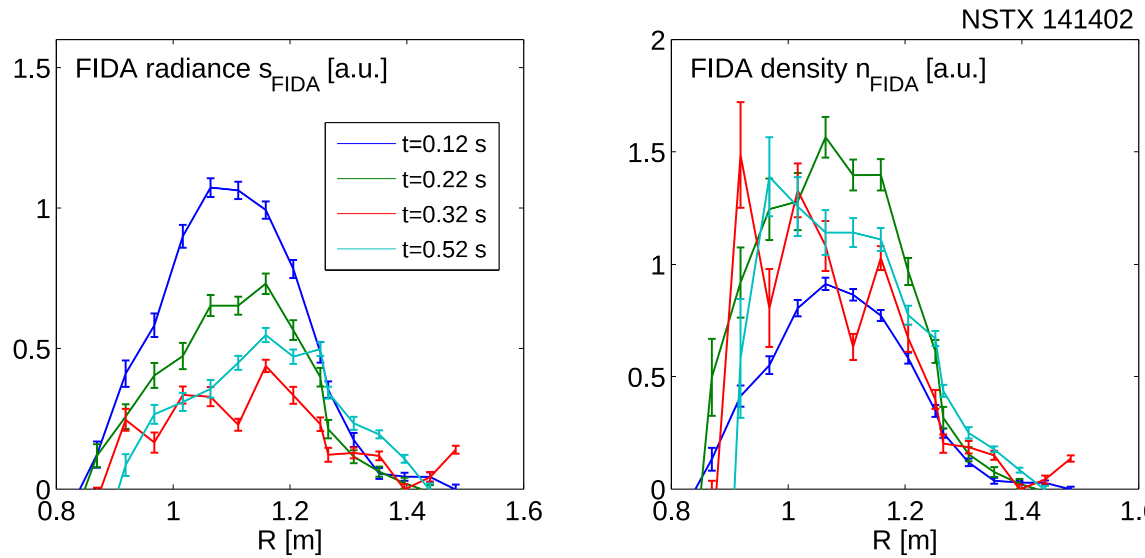
$1 < v_{fast}/v_{Alfven} < 5$

Typical evolution of FIDA profiles on NSTX

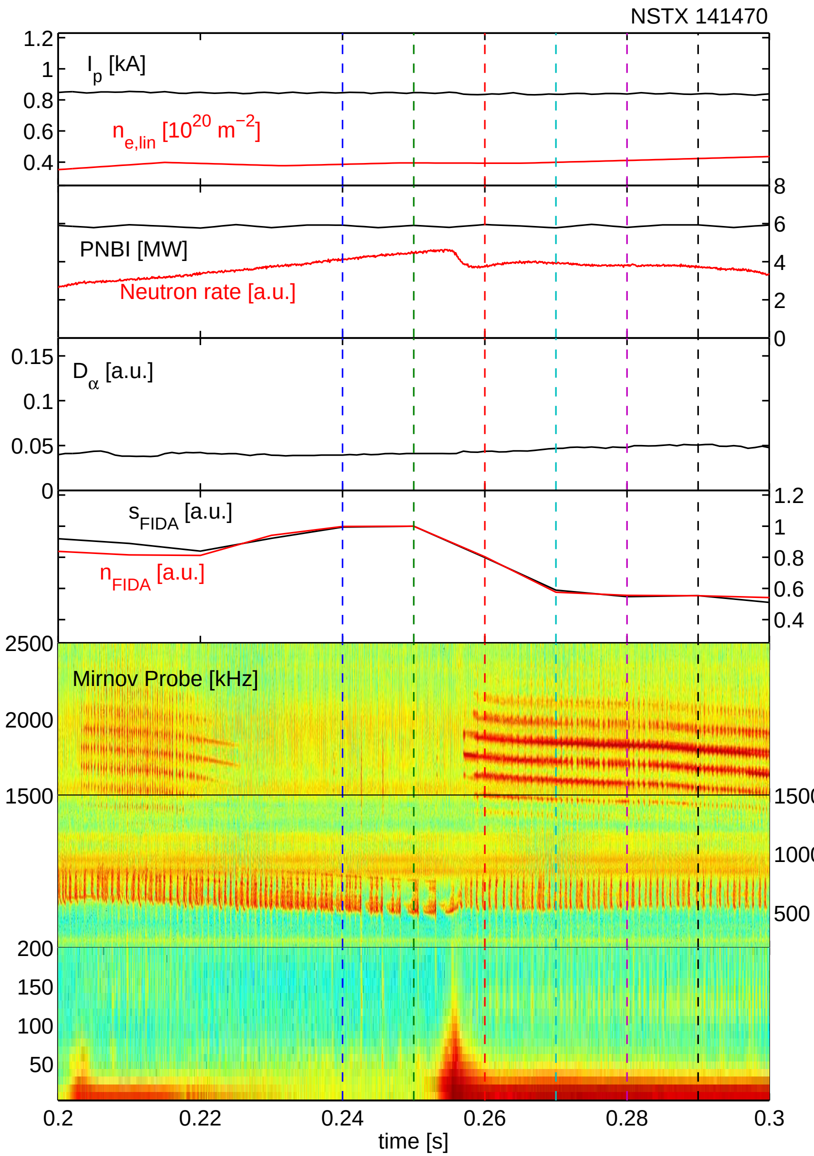


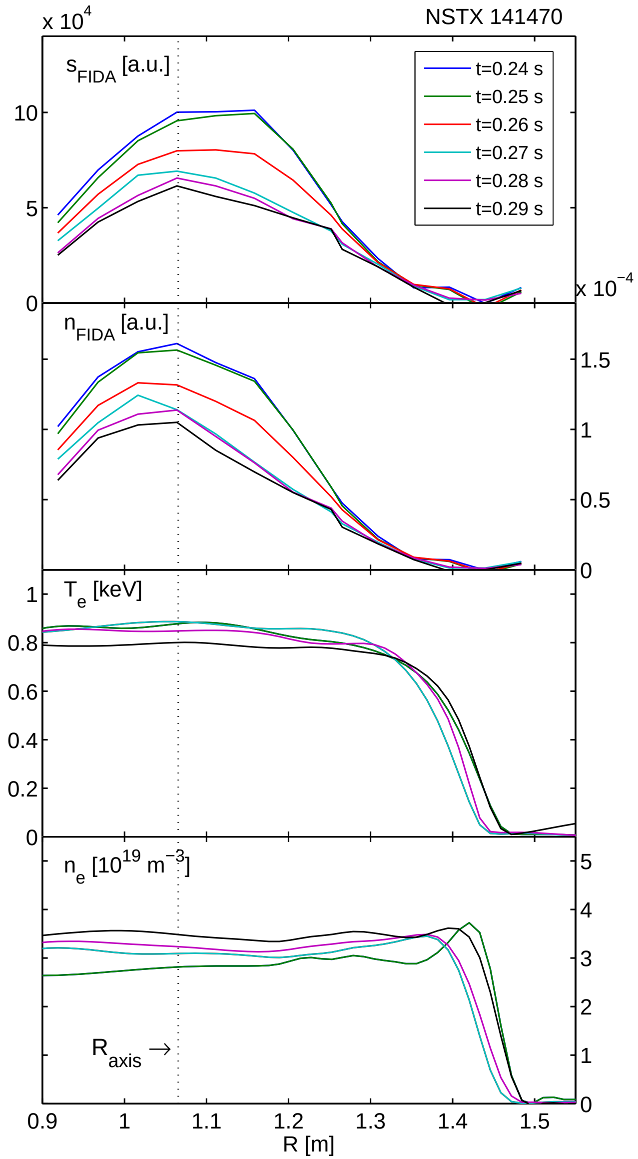
- NSTX FIDA signal typically is large at the early phase of the discharge (low n_e / high NB penetration)
- Diminishes with the natural density ramp due to wall recycling
- Challenging measurement for $n_e > 6 \times 10^{19}$ m^{-3}.

- The n_{FIDA} does not respond promptly to NB steps, follows neutrons
- Different type of instabilities affect dramatically the n_{FIDA} profile (MHD, ELM, EPM, etc.)



Effect of Low Frequency MHD





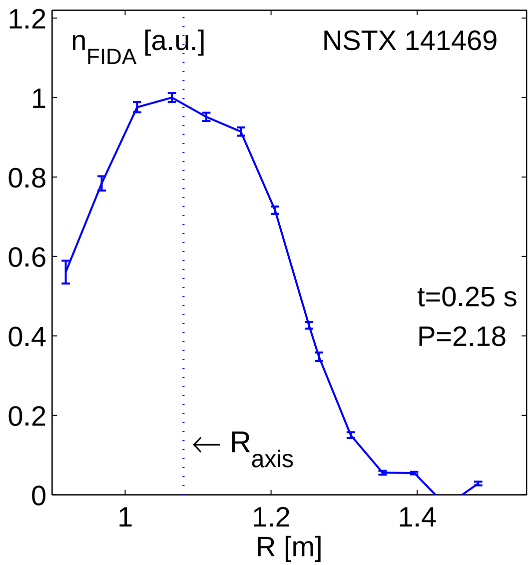
- Low Freq. MHD activity strongly affects n_{FIDA}
- Often accompanied by high freq. modes
- Drop in neutron rate observed at mode onset
- n_{FIDA} profile collapse in ~10 ms timescale

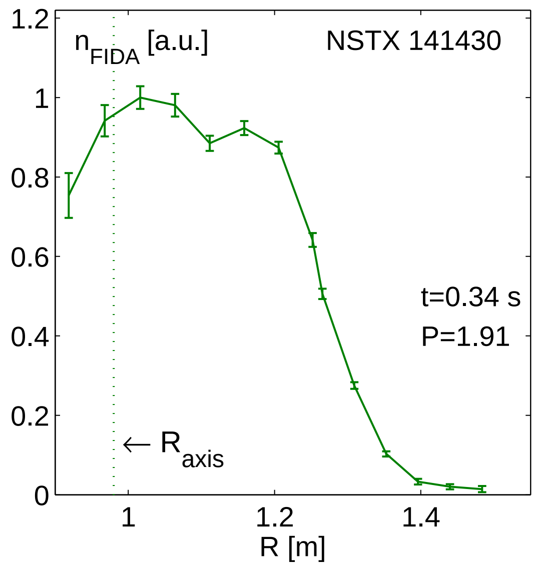
Examples of n_{FIDA} profiles

H-mode

P_{NBI}=6 MW

$n_e=4x10^{19}$ m^{-3}





L-mode

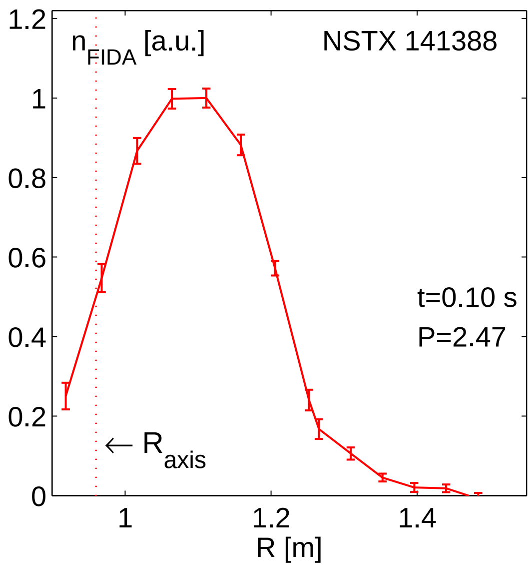
P_{NBI}=2.6 MW

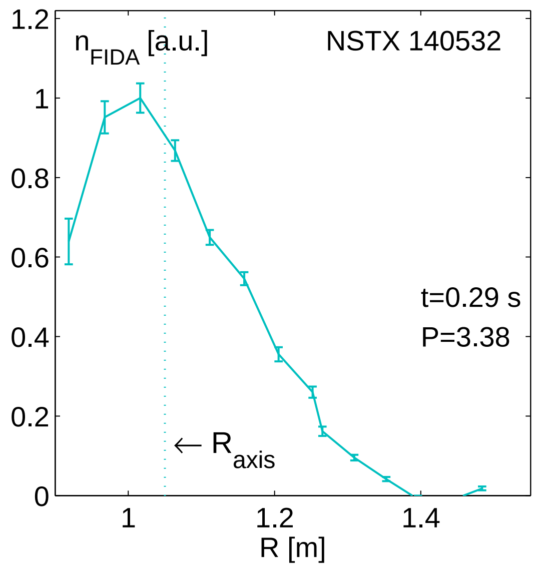
$n_e=2x10^{19}$ m^{-3}

H-mode

P_{NBI}=6 MW

$n_e=1.5x10^{19}$ m^{-3}





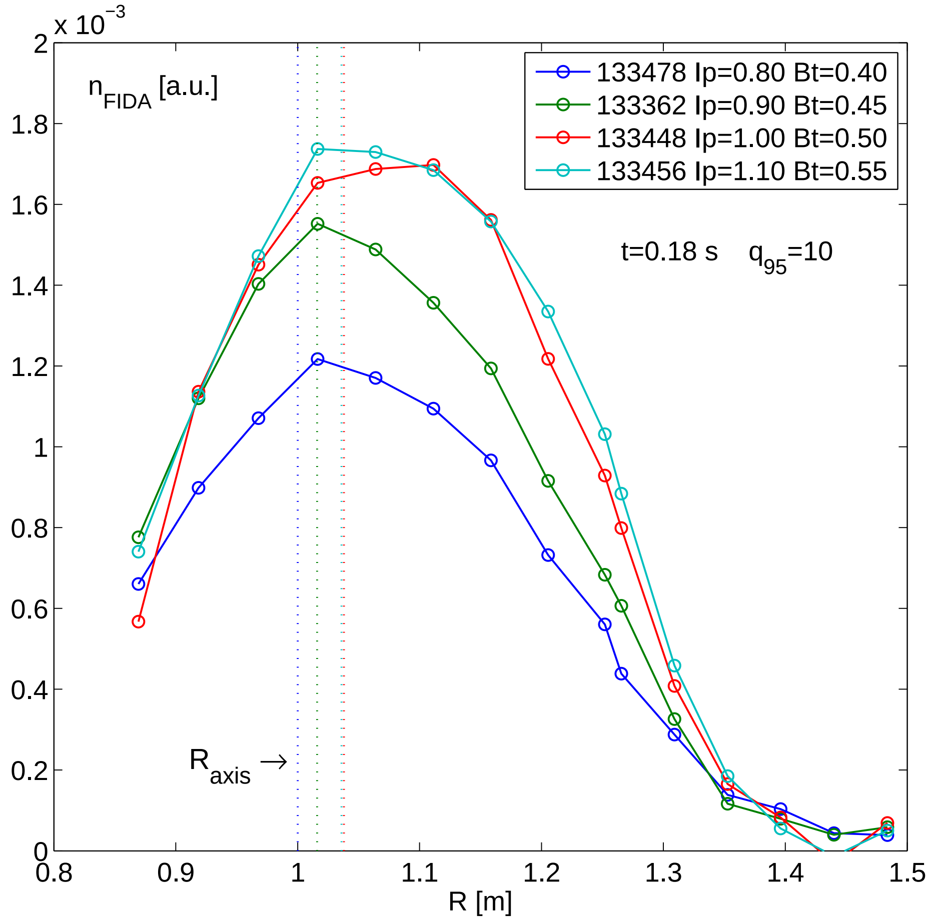
H-mode

P_{NBI}=6 MW

$n_e=6x10^{19}$ m^{-3}

Strong Mode Activity

Example of scaling with plasma parameters



Controlled parameters study

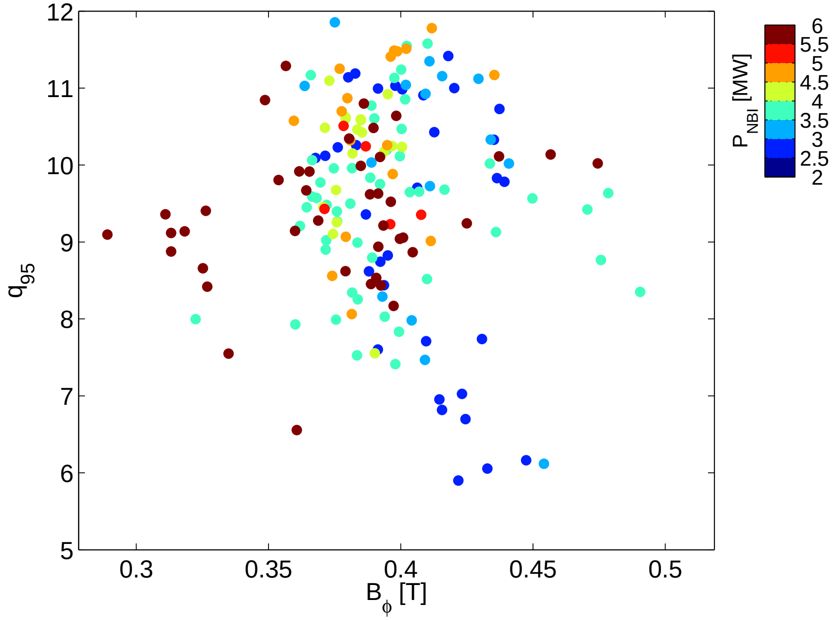
- Series of discharges at various couple of B_{tor}, I_p
- q_{95}=10
  $n_{e,lin}=5\times10^{19}\ m^{-2}$
  T_e=700 eV
- t=200 ms (beginning of current flat top)

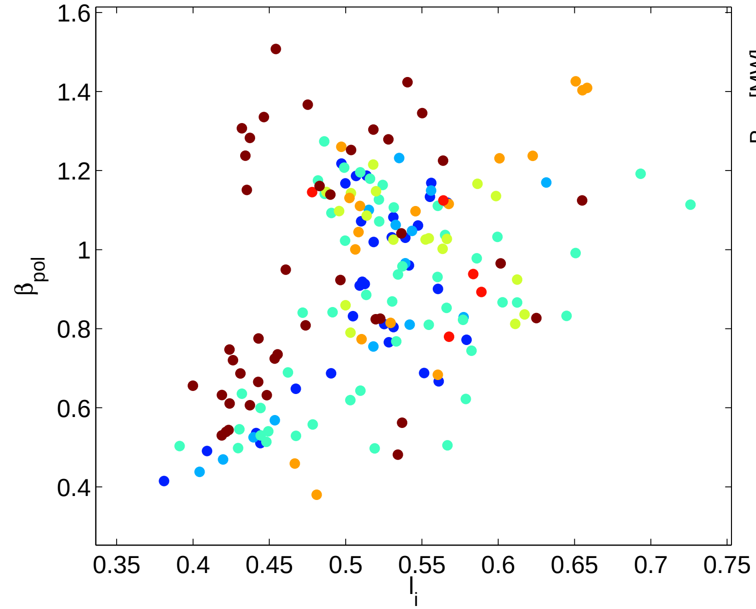
- $n_{FIDA,max}$, dn_{FIDA}/dR increase with B_t and/or I_p
- The onset of MHD modes and AE activity limits the comparison to specific time windows
- Difficult to control discharge parameters, in particular n_e

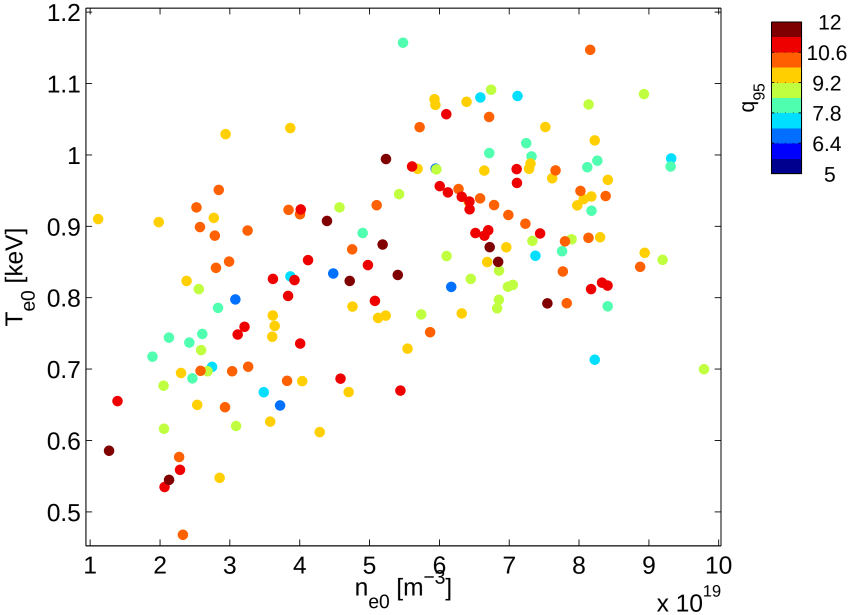
Statistical approach: a database of n_{FIDA} profiles

- Database of 200 n_{FIDA} profiles from 2010 experimental run
- H-mode, P=3-6 MW, B_{tor}=0.3-0.5 T, I_p=700-1300 kA
- Data are averaged in time windows of 10-100 ms, with stable or slowly evolving plasma parameters (n_{FIDA}, neutron rate, mode activity,…)
- Radial profiles of n_{FIDA}, n_e, T_e , T_i … fitted with cubic spline interpolation on major radius R=0.95-1.5 m
- Mode Activity described by 3 integer value flags, for low (2-20 kHz), intermediate (20-150 kHz) and high (150-2000 kHz) frequency range: values assigned manually from 0 to 3, <0 if chirping or broadband
- Investigate trends of n_{FIDA} maximum, peaking and peak location

Parameter space coverage





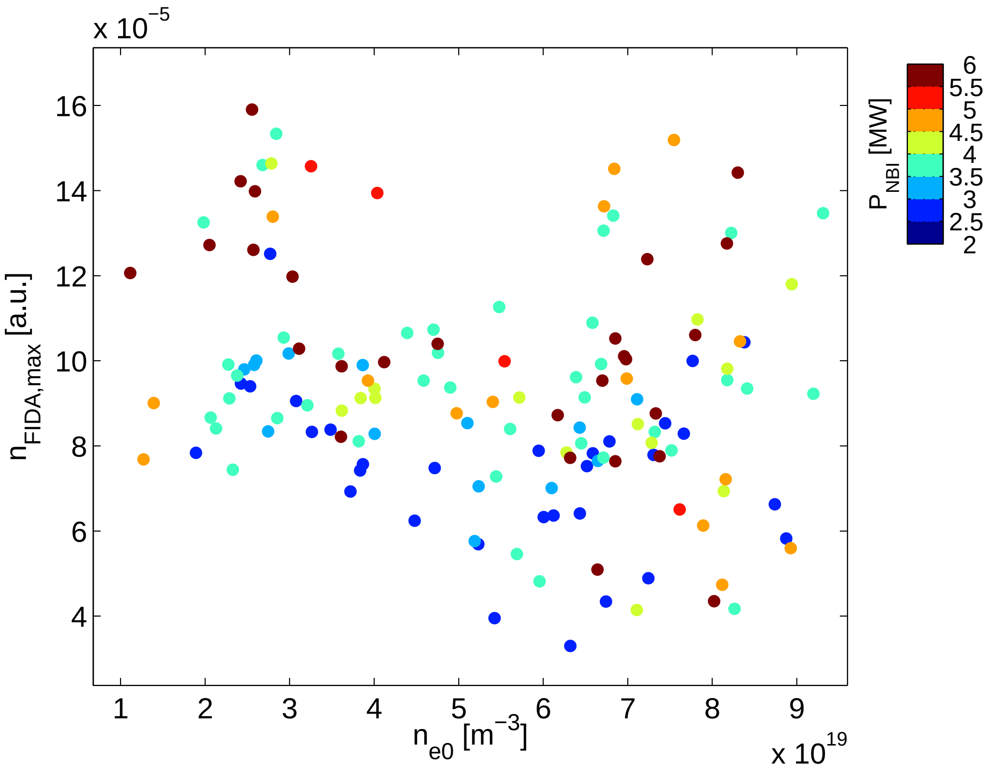


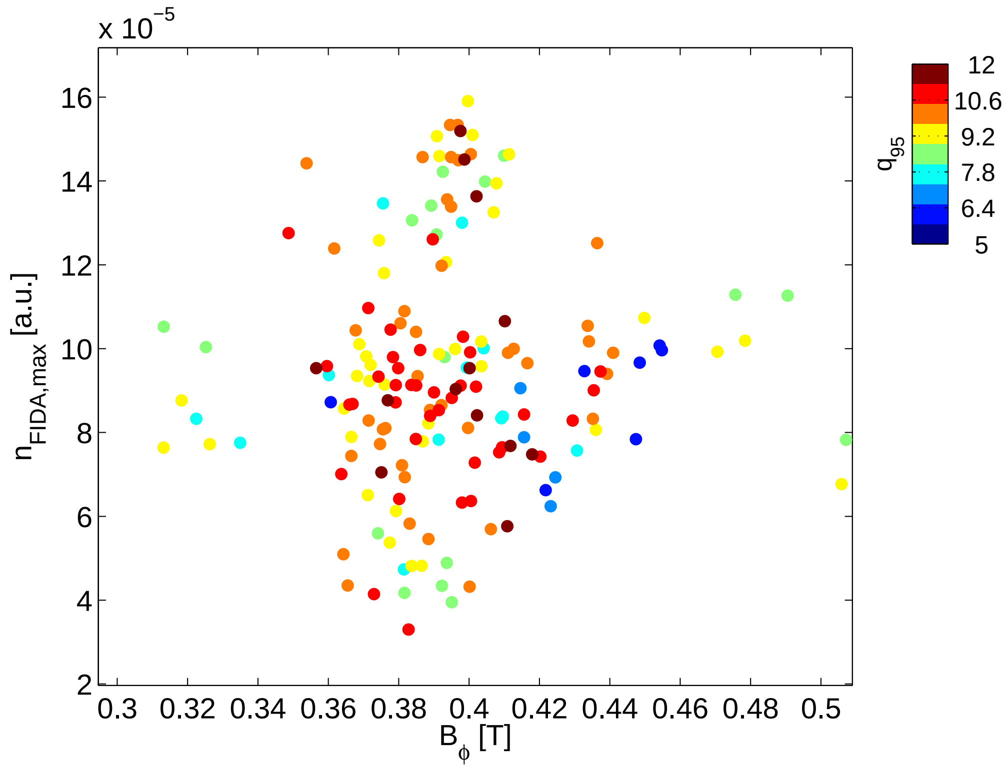
- ❑ Magnetic configuration (from EFIT)
- ❑ T_e, n_e (from Thomson scattering)
- ❑ T_i, v_{tor} (from Charge Exchange)
- ❑ Neutron Rate
- ❑ …

Maximal value of n_{FIDA}

- The dependency of the peak value of n_{FIDA} on B_{tor}, n_e, q_{95}, P_{NBI} has been considered for the entire set of samples

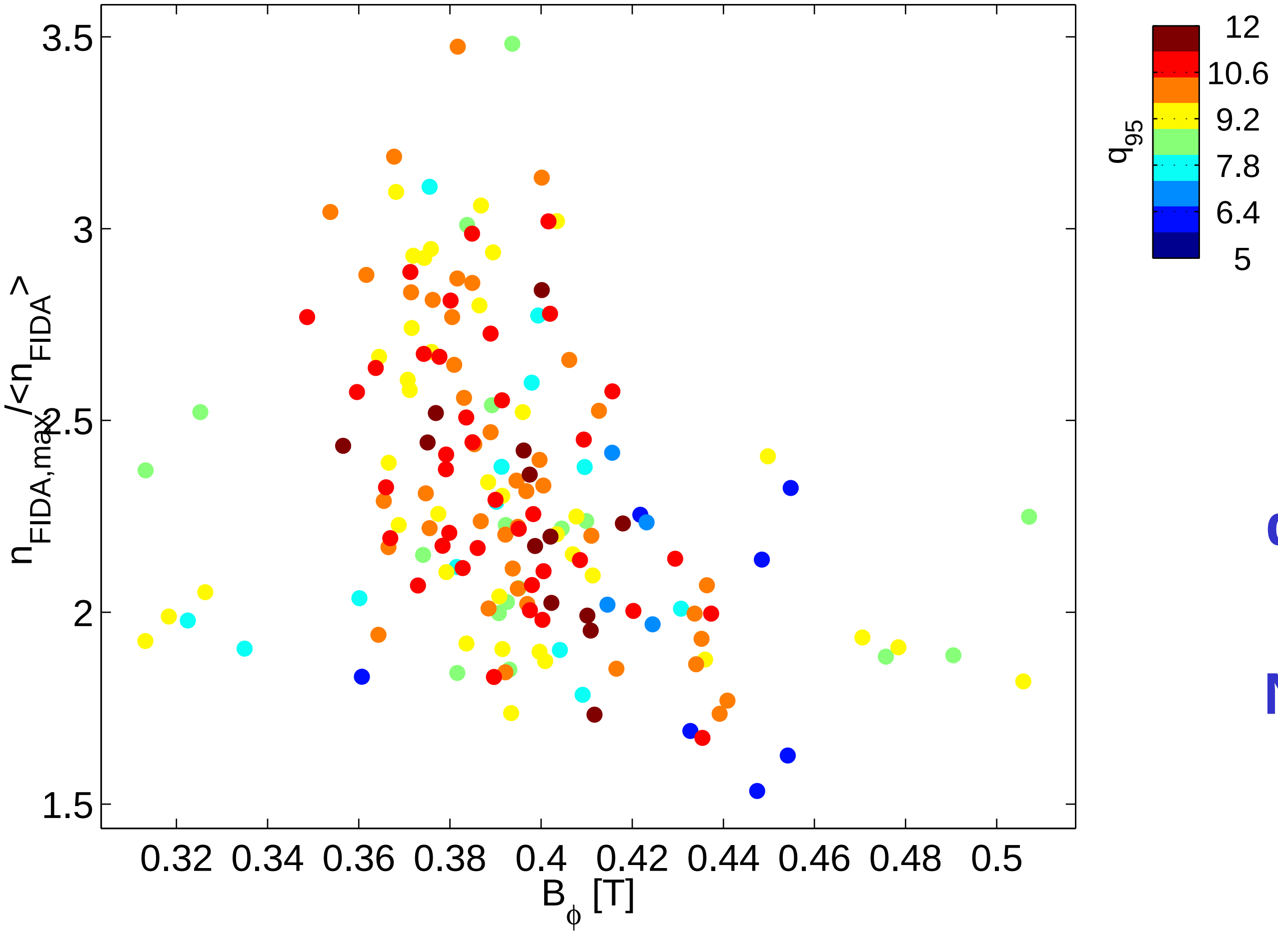
- No clear trend is apparent





FIDA density peaking: B_{tor} dependence

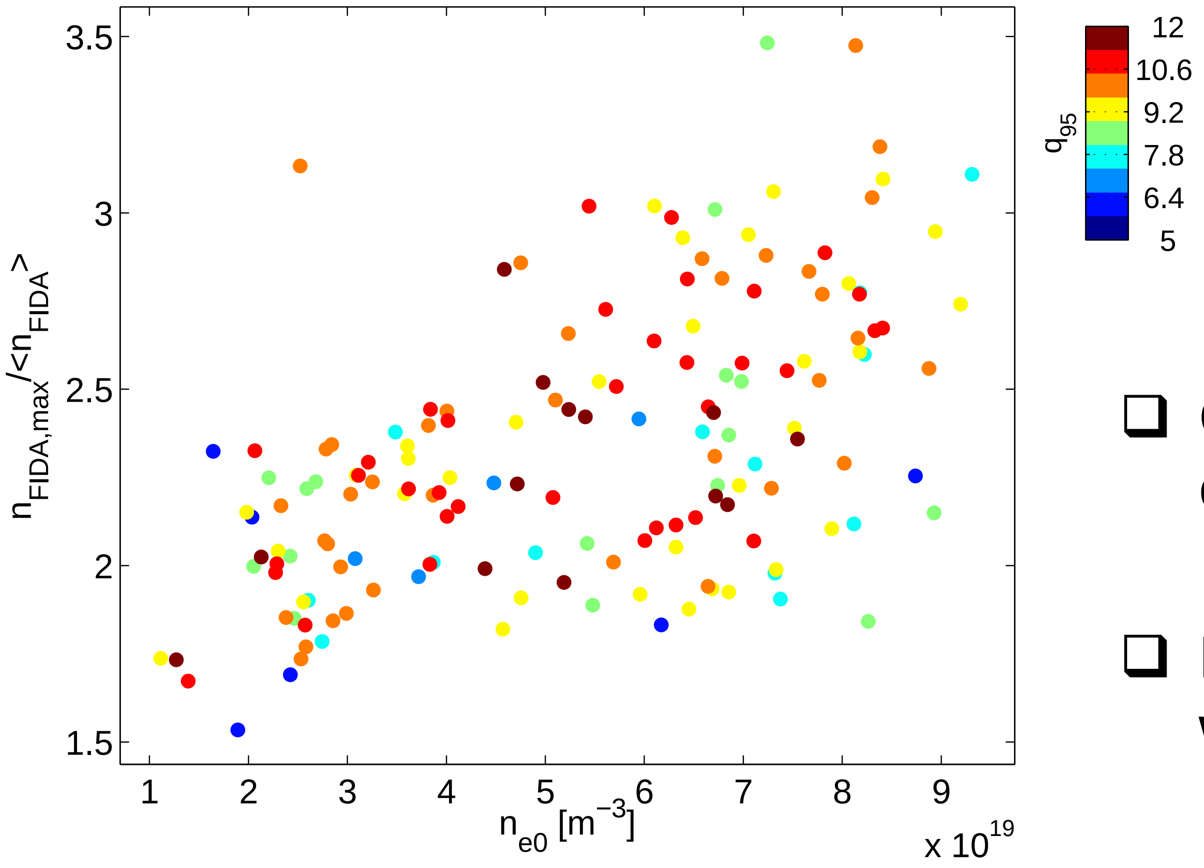
- Peaking parameter defined as $P(x)=x_{max}/<x>$, (maximum value, normalized by the linear average in the region R=1.05-1.40 m)
- $P(n_{FIDA})$ spans values from 1.5-3.5



n_{FIDA} peaking decreases with B_{tor}

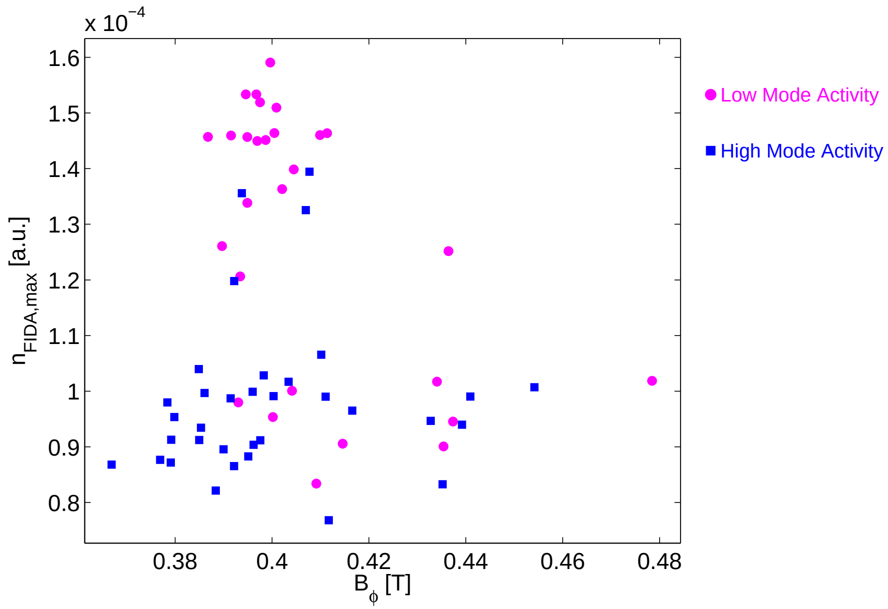
No clear correlation with I_p or q_{95}

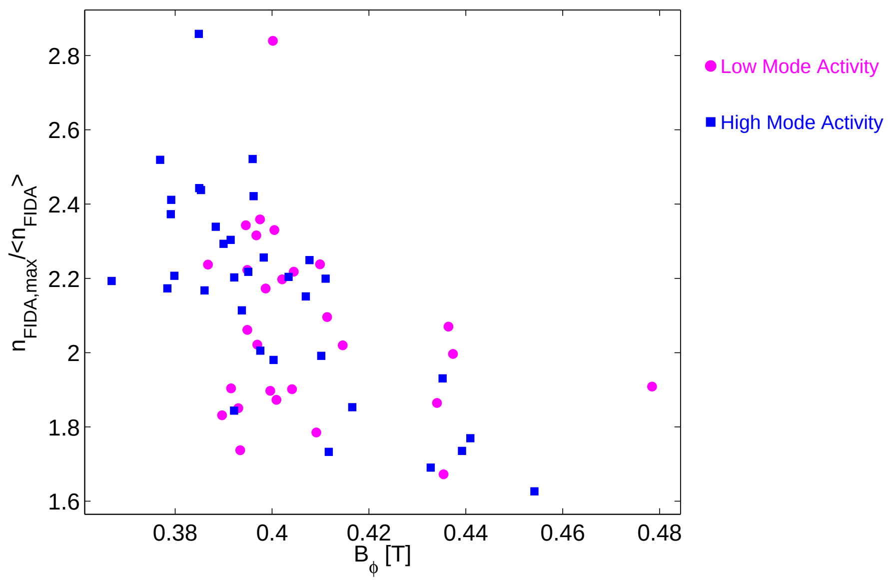
FIDA density peaking: n_e dependence



- Correlation suggested with electron density n_e
- No apparent correlation with I_p or q_{95}
- May be related to incorrect estimate of neutral density (e.g. halo neutrals are not included)

Effect of strong Low Frequency Mode Activity



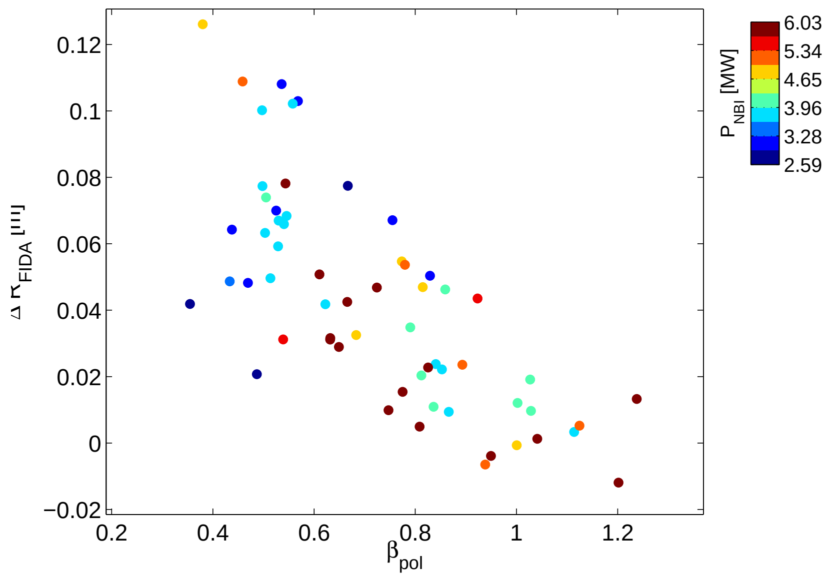


- Select two classes of profiles characterized by different degrees of mode activity (freq. < 20 kHz)
- Restricting to high FIDA signal profiles to improve quality (30% of total samples)

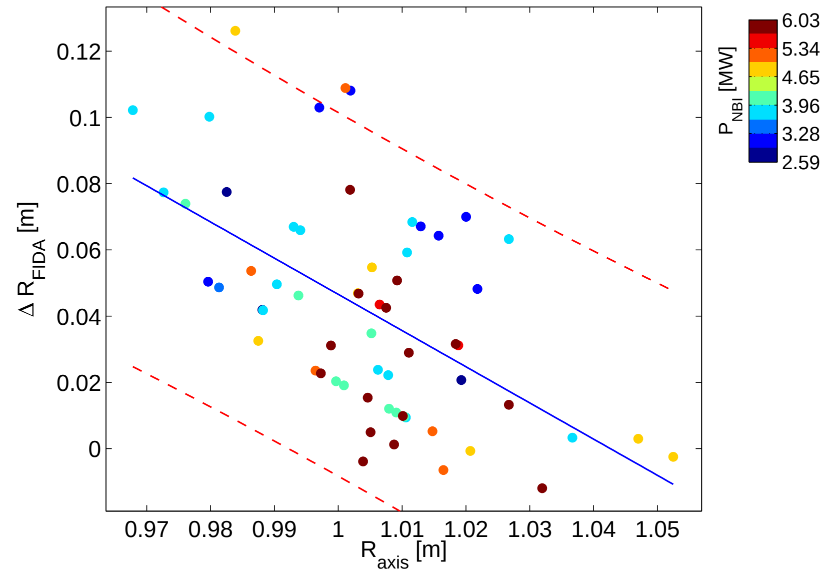
Reduced FIDA density in presence of mode activity

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

Radial location of FIDA density peak



- The peak displacement is defined as: $\Delta R_{max}=R(n_{FIDA,max})-R_{axis}$
- Selection of Low Mode Activity samples
- Correlation emerges with β_p
- ΔR_{max} decreases with β_p



- The displacement (with large scatter) also correlates with R_{axis}
- $\Delta R \sim -1.0\ R_{axis}$
- n_{FIDA} peak close to R=1.05m
- Related to the Fast Ion source location

Conclusions

- A database of FIDA density profiles has been built to study the dependences on plasma parameters
- Peaked n_{FIDA} is generally observed, with peaking factor of 2-3
- Peaking n_{FIDA} scales with n_e and B_{tor}
- Different degrees of peaking are observed in combination with low frequency MHD of Alfvènic modes
- Off axis n_{FIDA} peak tends to sit close to R=1.05 m

- The n_{FIDA} density definition depends on FI distribution function: variation in velocity space can affect n_{FIDA}
- Halo neutrals are not accounted by the beam deposition code used
- The FI population depends strongly on Mode Activity and its history: difficult to obtain a coherent set of profiles

- Need to increase the number of data samples to allow for reliable analysis on restricted sets

Outlook

- Use of **FIDASIM synthetic diagnostic** to compare the experimental profiles and spectra with theoretical models of the distribution function (specific cases) **[Y.Luo, Improvements to the Fast-ion D_α (FIDA) Simulation Code (BP9-PS1)]**
- FIDASIM may be used to predict the dependency on B_{tor} and n_e on the assumption of a given FI distribution function
- Improve the neutral density calculation including halo neutrals (FIDASIM)
- Use of the data from the **new tangential FIDA** to identify velocity space variation of the FI distribution function

References

1. *M. Podestà RSI 79 (2008)*
2. *W. W. Heidbrink RSI 79 (2008)*
3. *W. W. Heidbrink PPCF 49 (2007)*
4. *W. W. Heidbrink RSI 81 (2010)*
5. *A. Bortolon RSI 81 (2010)*
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8. *M. Podestà PoP 16 (2009)*
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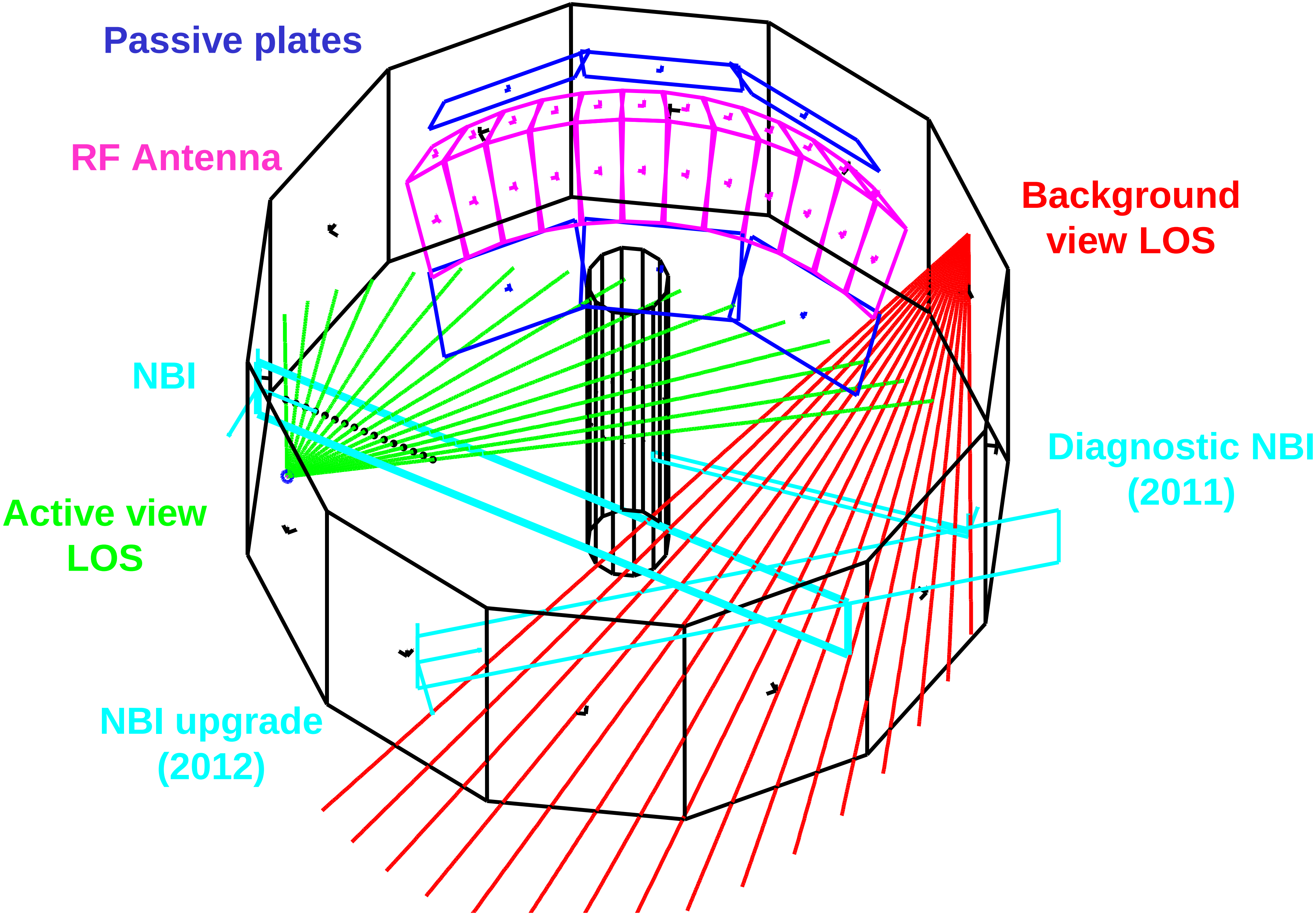
Coming soon: A Tangential FIDA diagnostic for NSTX

- In NSTX, Fast-Ions are generated by the heating Neutral Beams (co current tangential injection)
- The distribution function is populated in the region of high parallel velocity $\Rightarrow$ $p > +0.5$
- Installation of a tangential FIDA diagnostic is about to begin to study the high parallel velocity region of the phase space

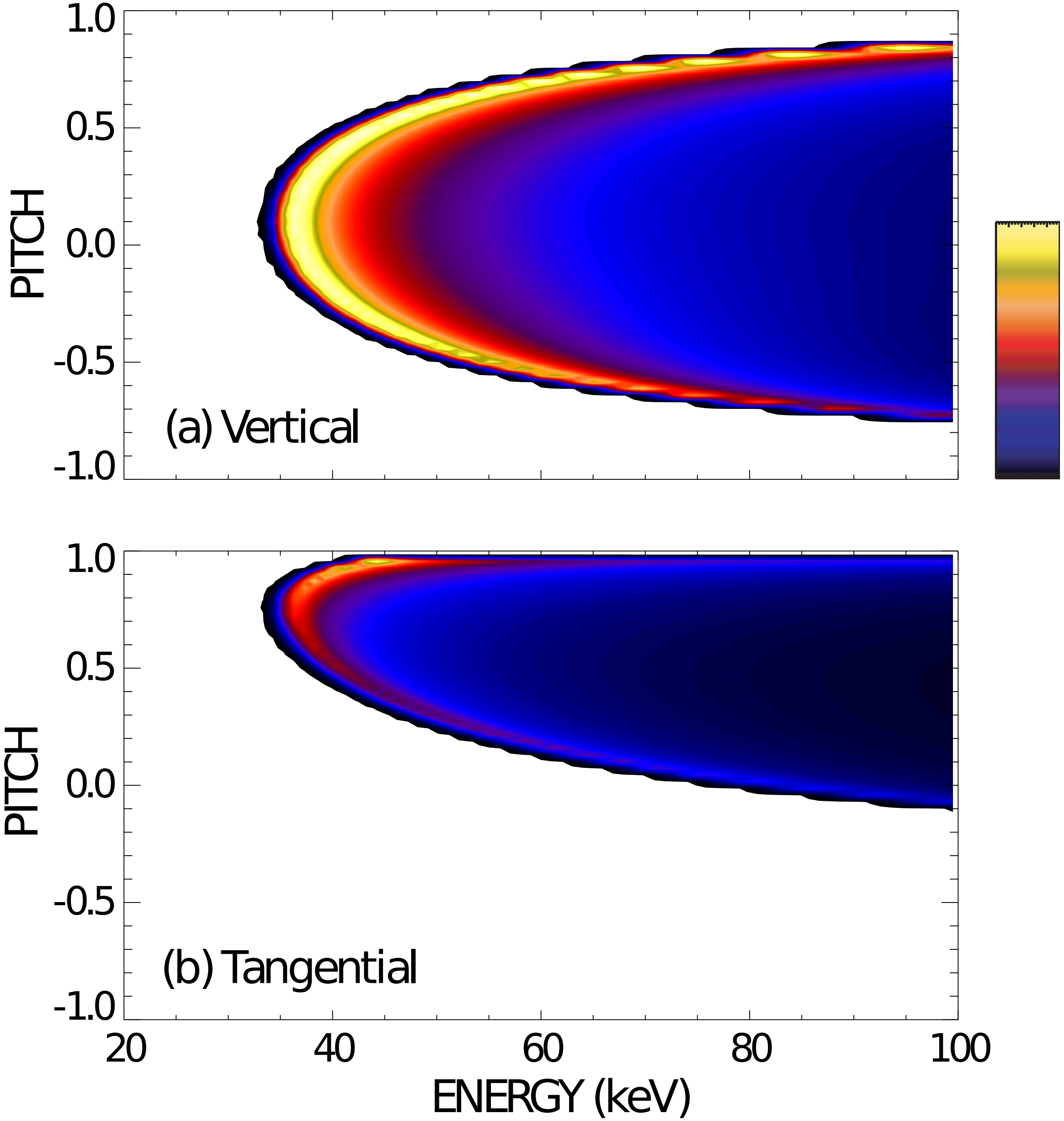
- Key points:
  - Maximize view alignment with local magnetic field B
  - ***Spectroscopic*** and ***Filter*** instruments scheme
  - Paired active and background views scheme

- Sampling the (p,E) space where the distribution function is more populated $\Rightarrow$ enhanced FIDA spectrum source
- Contribution from Fast Ions with large parallel velocity $\Rightarrow$ spectrum extends to higher energies

Tangential FIDA diagnostic views



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