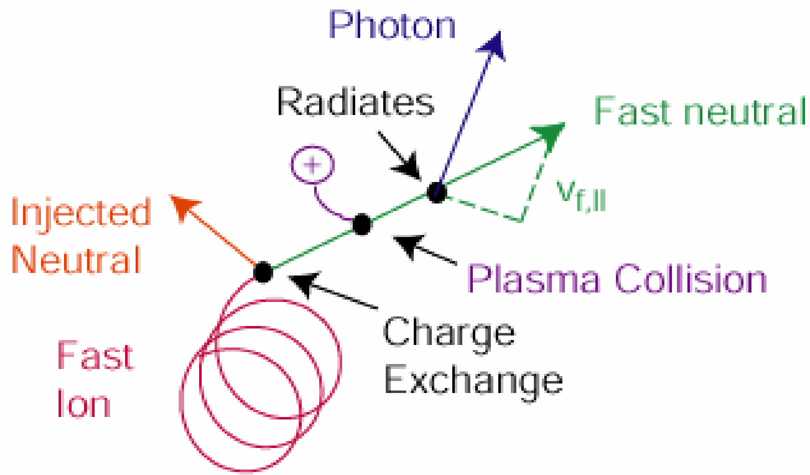
D_{α} Measurements of the Fast-ion Distribution Function in DIII-D

W. Heidbrink, Y. Luo, K. Burrell, and the DIII-D Team



- **Diagnostic Concept***
- **Technical Details+**
- **Recent Results**
- **Future Applications***

****Plasma Phys. Cont. Fusion 46** (2004) 1855*
*+**Rev. Sci. Instrum. 75** (2004) 3468*

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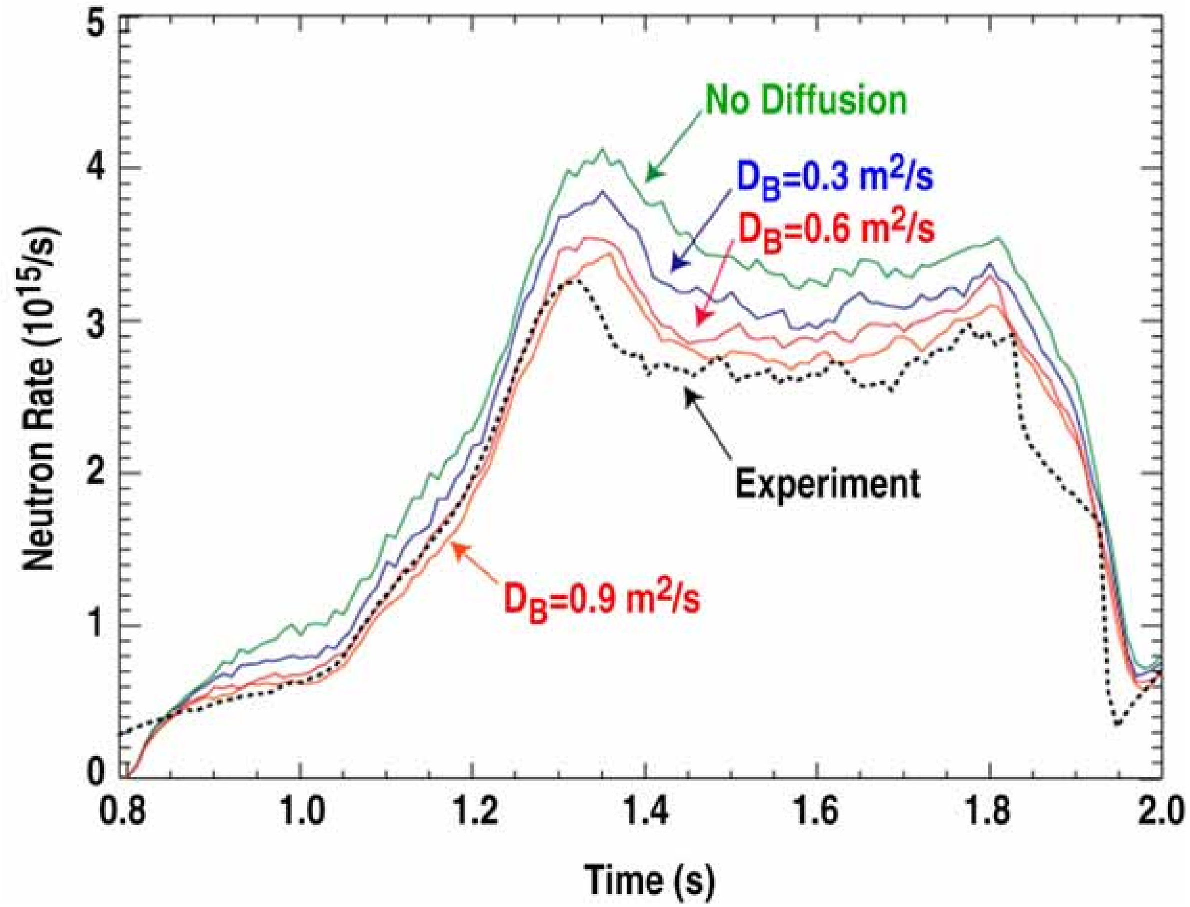
UCIrvine
University of California, Irvine

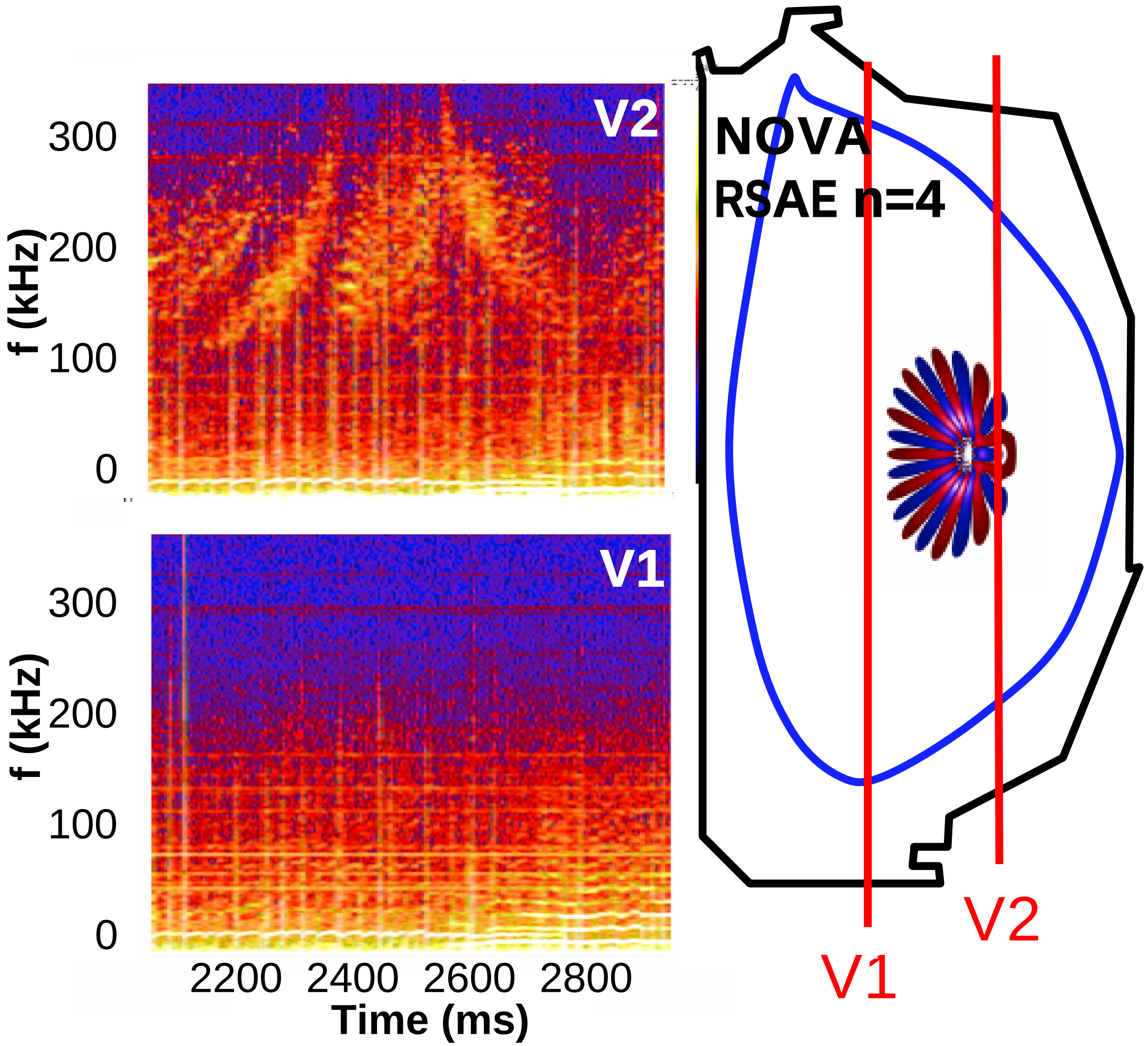
The Fast-ion Distribution Function is Uncertain in Most AT Discharges



- ***Ad hoc*** **diffusion model matches neutron rate**
- **Introduces uncertainties in pressure and current profile control & analysis**

Nucl. Fusion 42 (2002) 972.

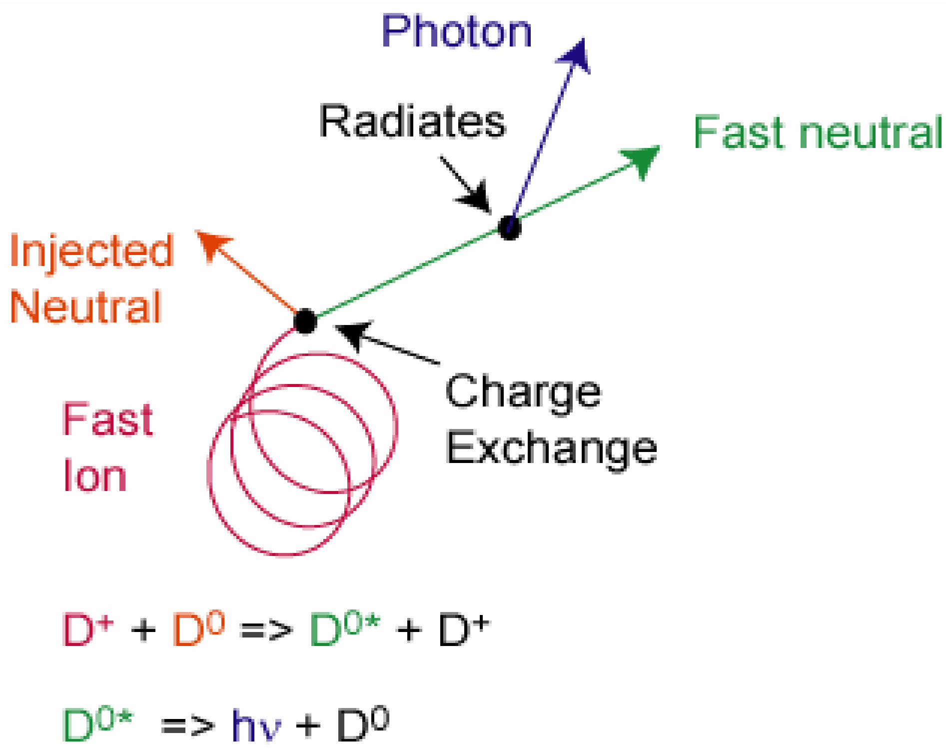
Distribution Function Essential to understand Fast-ion Driven Instabilities



- Localized modes often observed: Need comparable spatial resolution
- Which part of velocity space drives instability?
- Nonlinear dynamics of coupled wave-particle system

M. VanZeeland

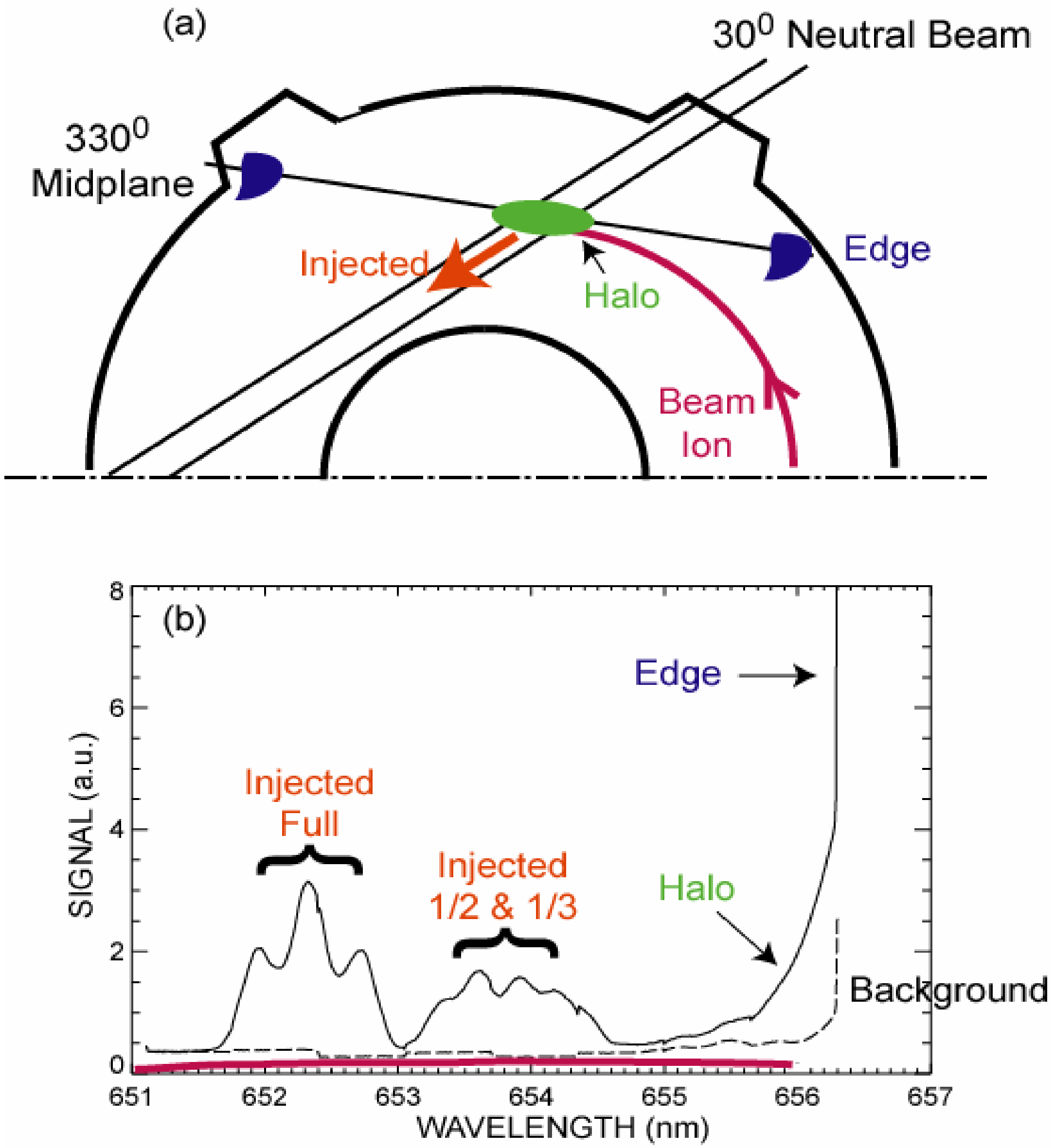
D_α Light from Neutralized Fast Ions



- **Like Charge-Exchange Recombination Spectroscopy of fast helium ions (TFTR, JET)**
- **Fast ions neutralize when they intersect a heating beam**
- **D_α is the 3 →2 transition**
- **Wavelength determined primarily by Doppler shift**
- **Cross sections known**

Bright Backgrounds: Injected, Halo, and Edge Neutrals

What viewing geometry Doppler shifts the relatively dim fast-ion light away from these backgrounds?

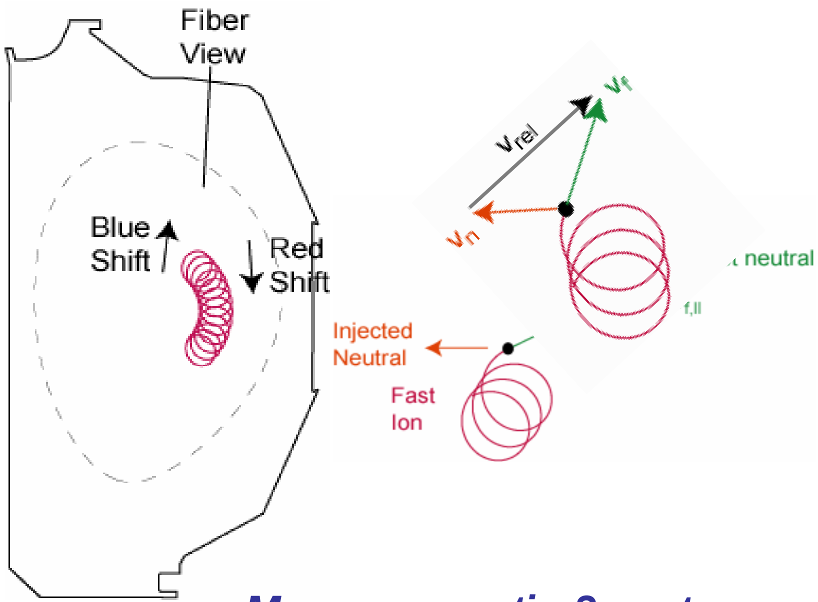


A vertical view has many advantages

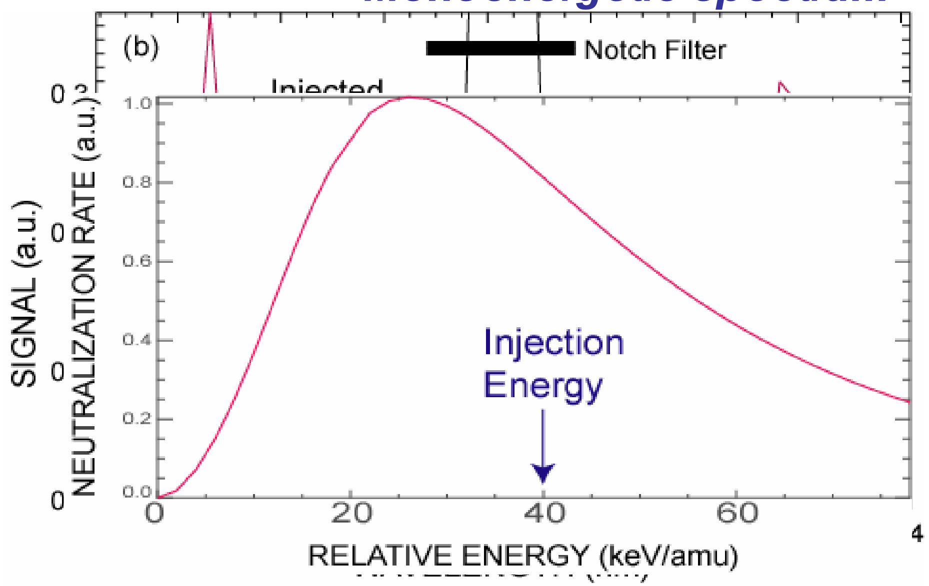
- Exploit gyro-motion to avoid interference from injected neutrals

- $\lambda \rightarrow V_z \rightarrow$ Minimum Perp. energy
- Weighted toward large Doppler shifts

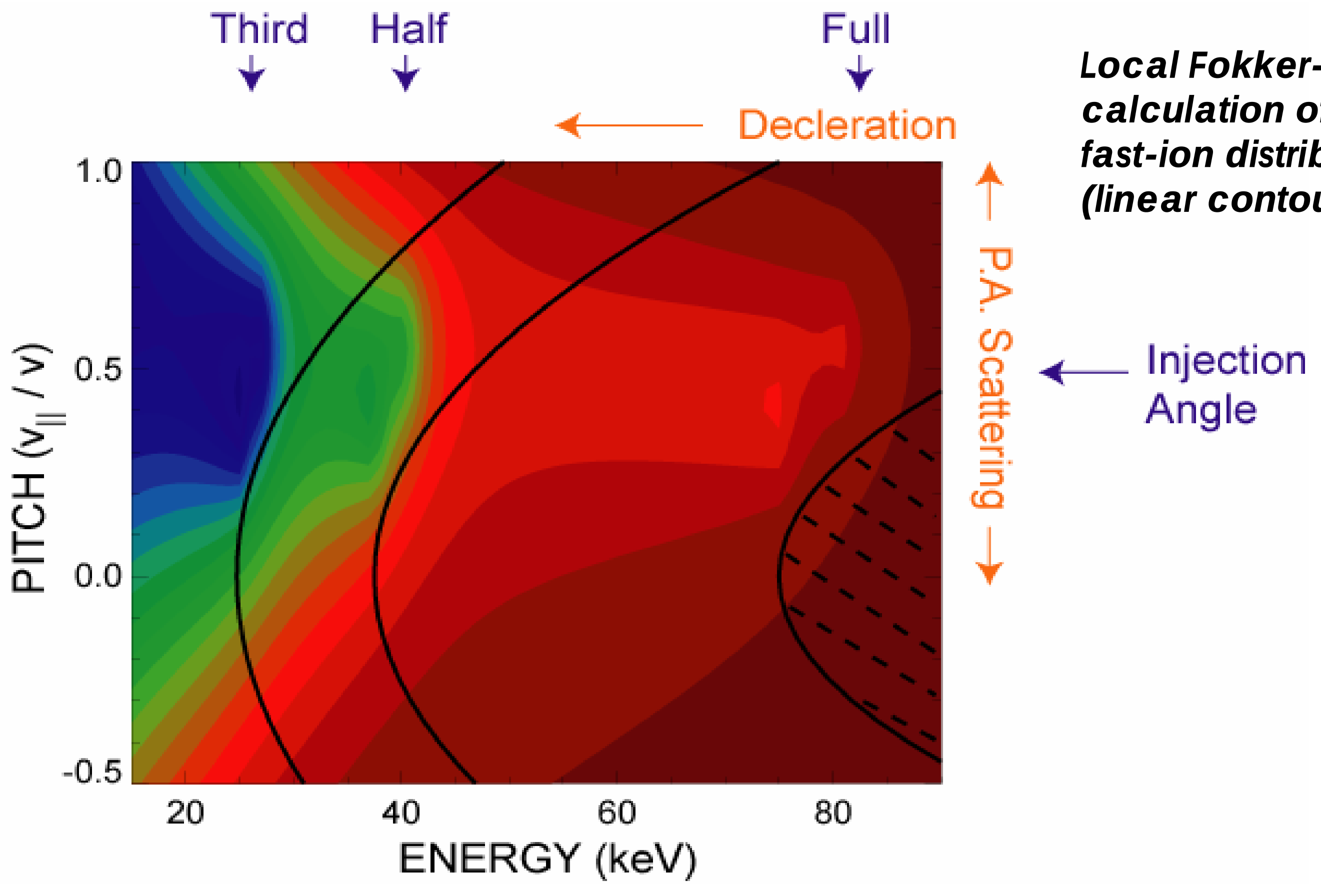
- Weak variation in charge exchange probability



Monoenergetic Spectrum



Vertical views measure Perpendicular Energy



Local Fokker-Planck calculation of the fast-ion distribution (linear contours)

$\lambda \rightarrow V_z \rightarrow$ Perpendicular energy

- **A parabola in (E,pitch) space contributes to a particular λ**
- **Higher energies also contribute but more weakly**

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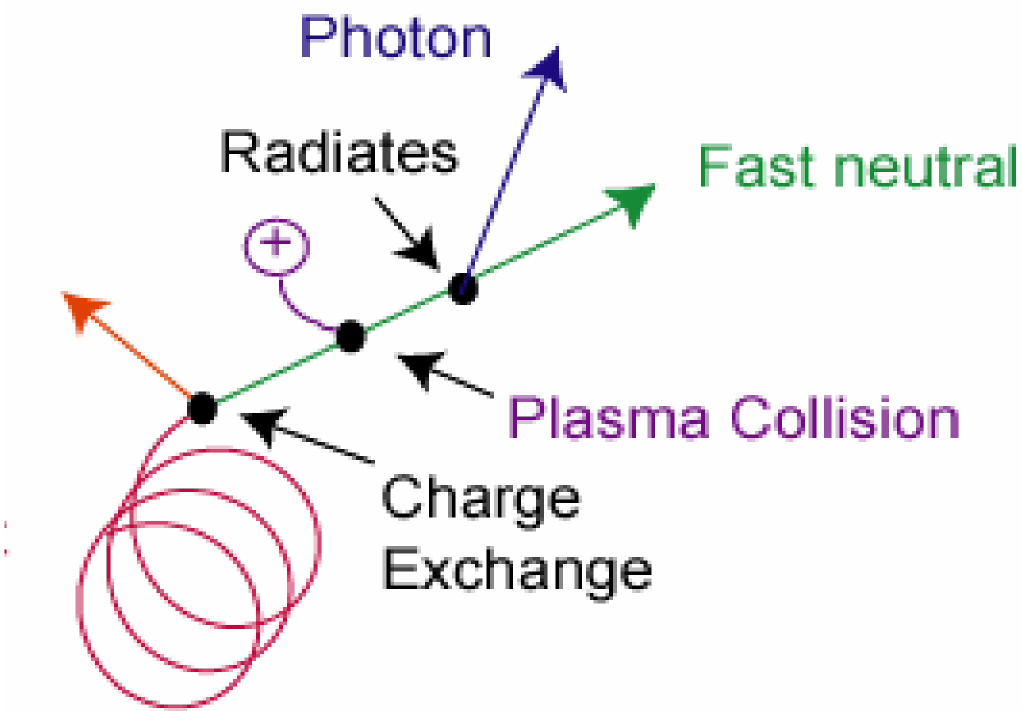
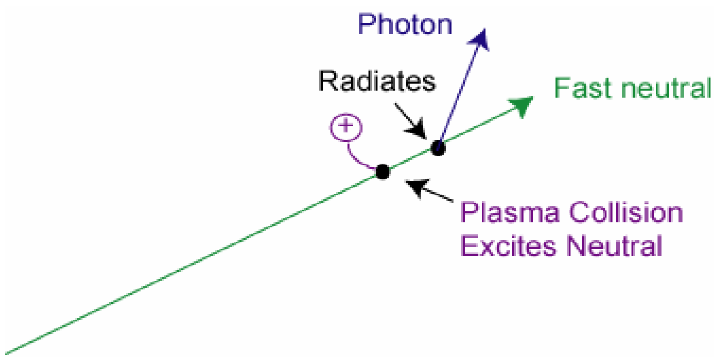
Intrinsic Spatial Resolution is ~ 5 cm



- **Determined by distance traveled before undergoing 3 →2 transition**



- **Some n=1 neutrals with long mean-free paths are excited to n=3 & contribute to spatial “smearing” at a few % level**

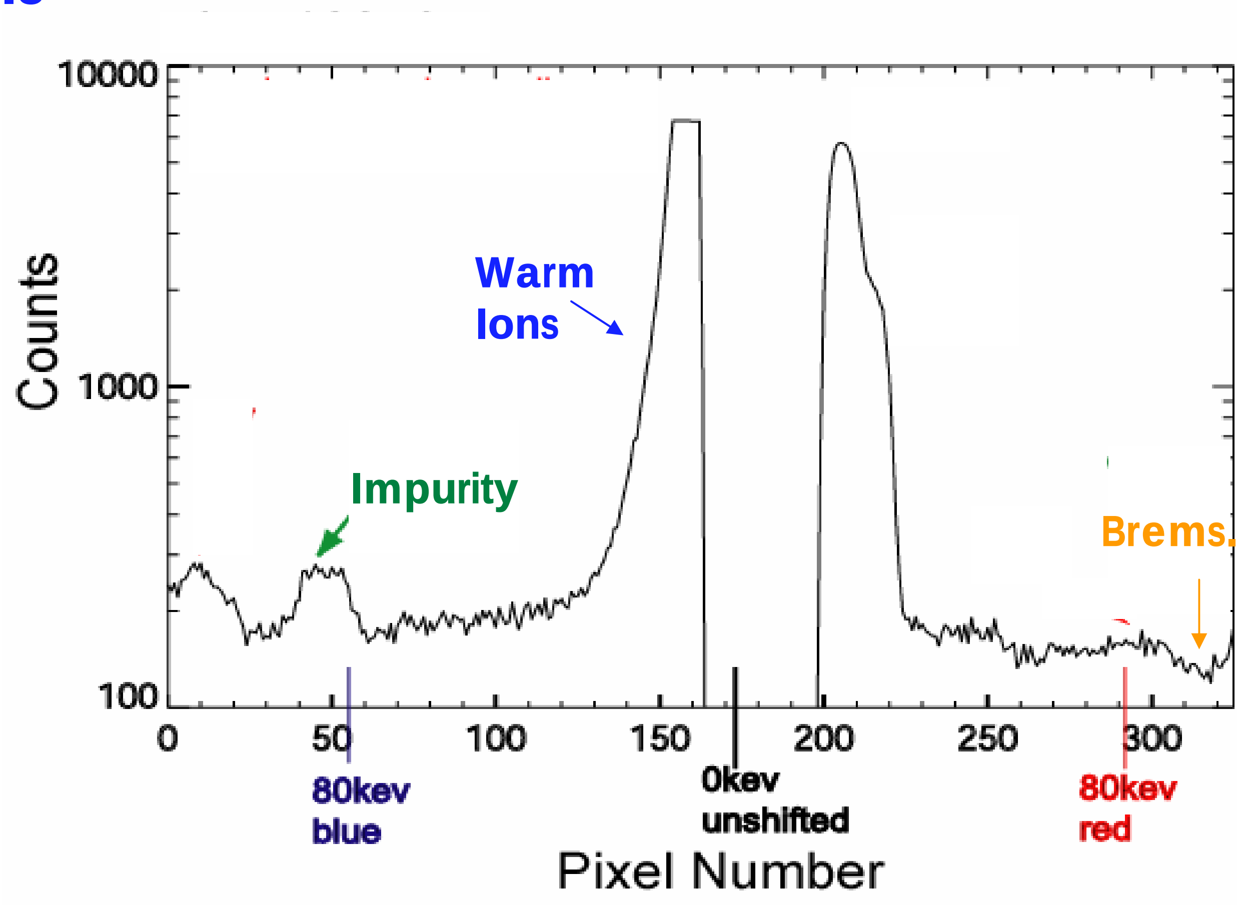
Extracting the distribution function from the signal

Contaminants in Spectrum:

Bremsstrahlung & scattered light

Impurity lines

Warm (Halo) neutrals



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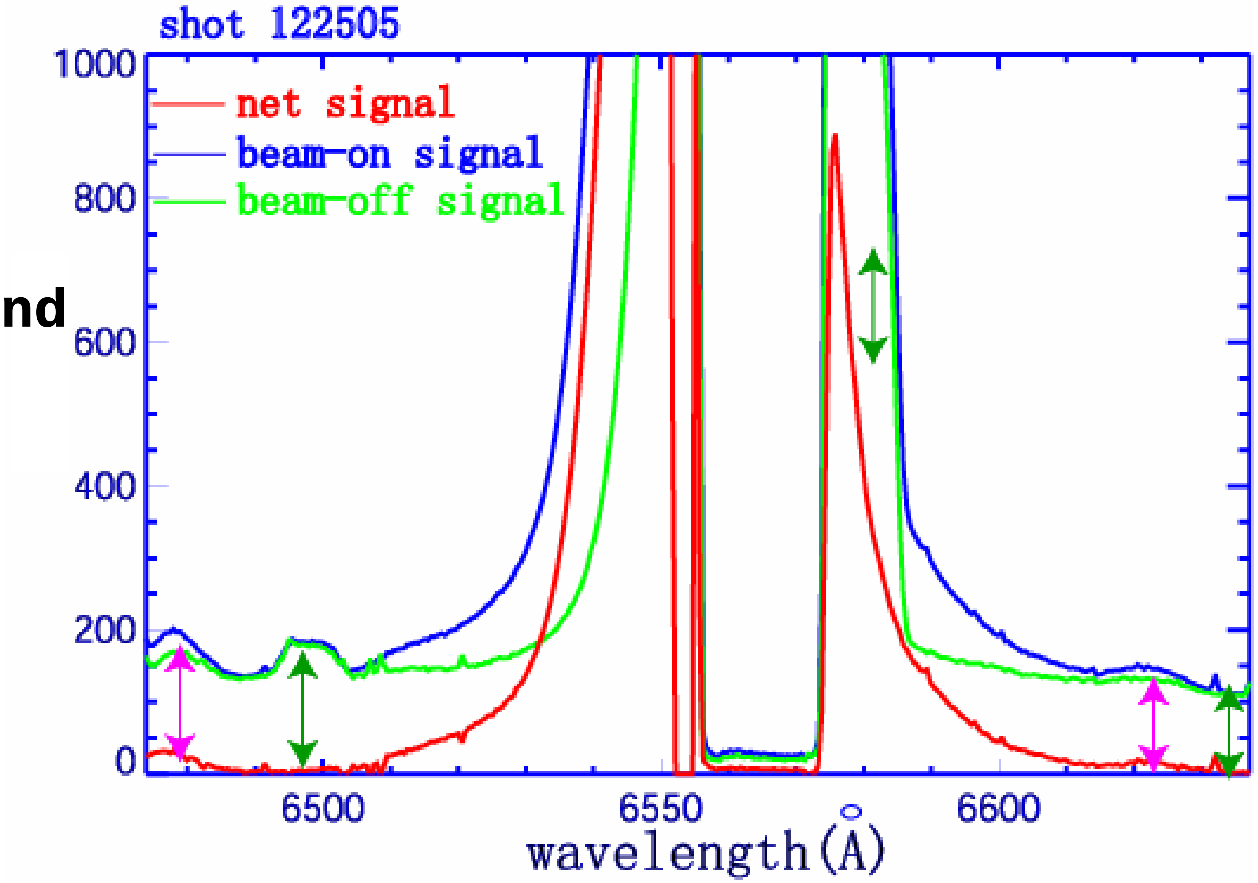
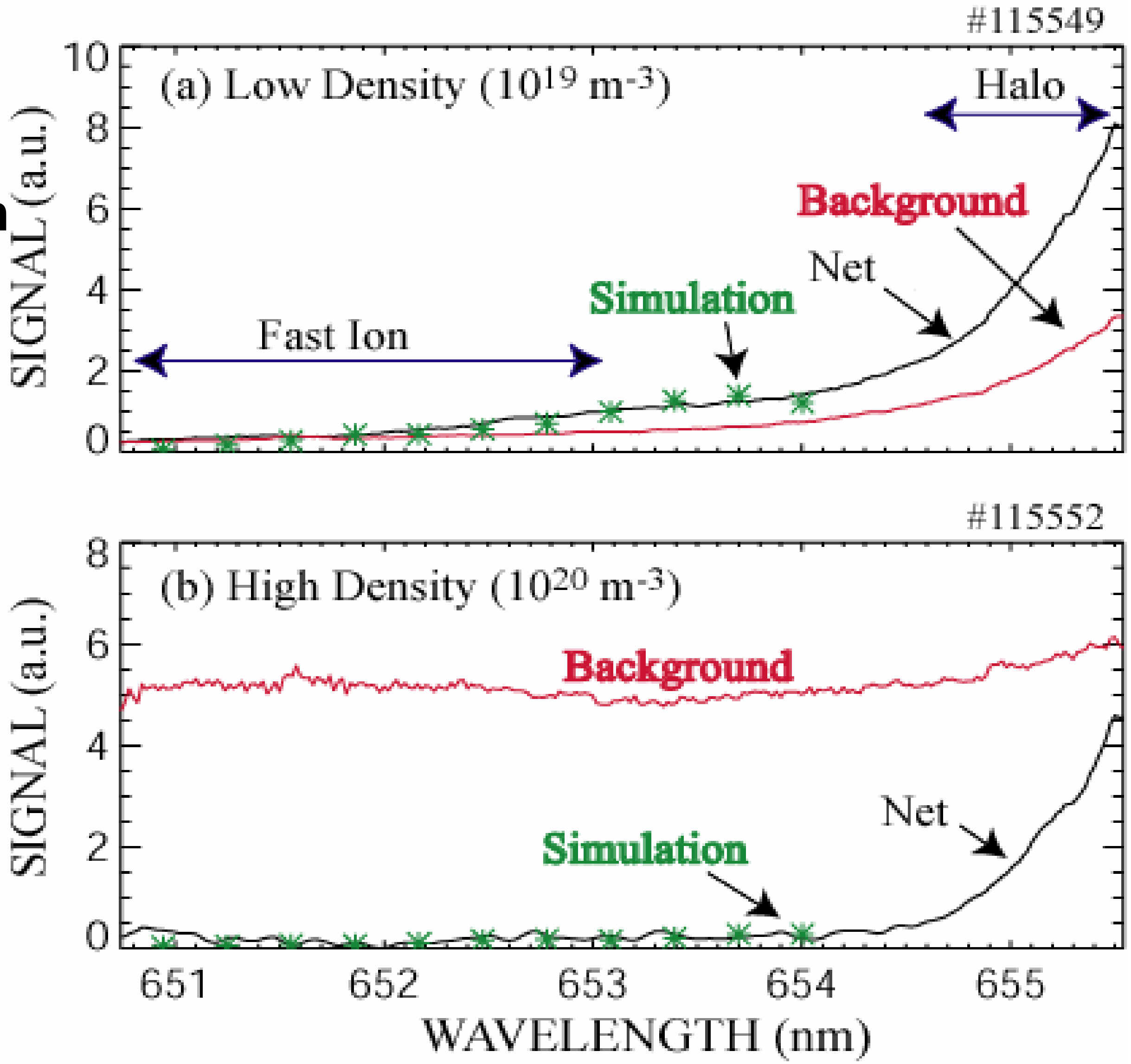
Beam Modulation removes Bremsstrahlung and many Impurity Lines

- Charge-exchange impurity lines are fit.
- ELMs alter background & must be treated differently
- Halo line can be fit (or analysis restricted to $E > 4\,T_i$)



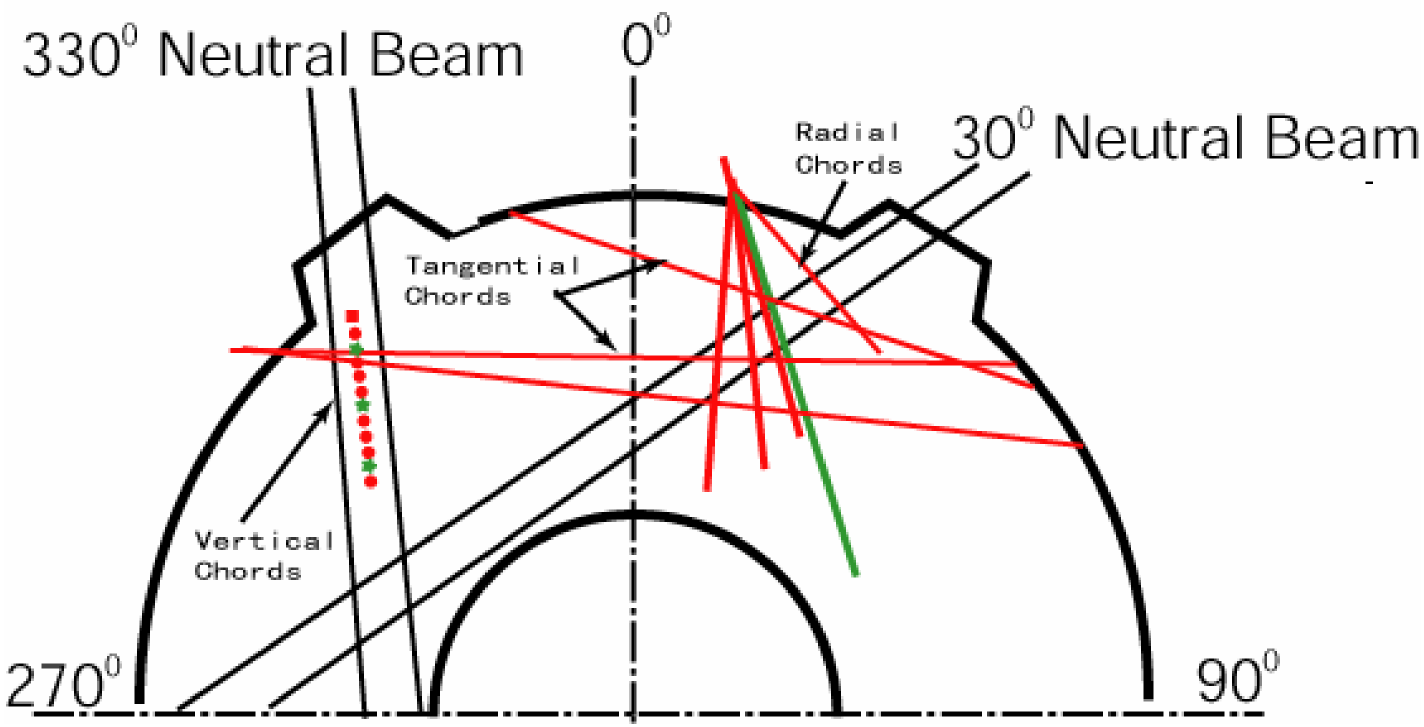
Measurements are easiest at low density

- Proof-of-principle measurements were performed in 2003 with a radial view & partial spectra.
- Fast-ion feature has expected temporal, spectral, and density dependencies.
- Signal weak at high density (> 7 x 10^{19} m^{-3})



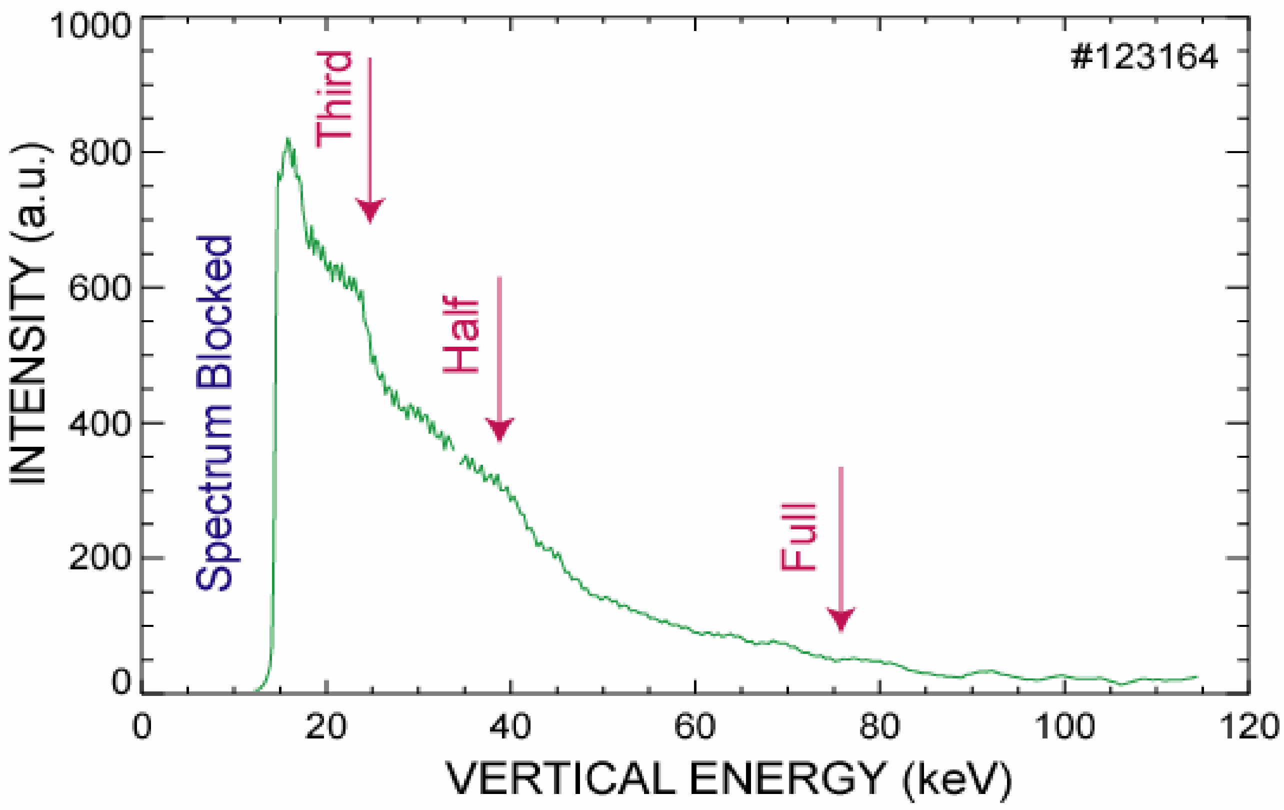
PPCF **46** (2004) 1855

DIII-D FAST ION FIBER VIEWS IN THE 2005 CAMPAIGN



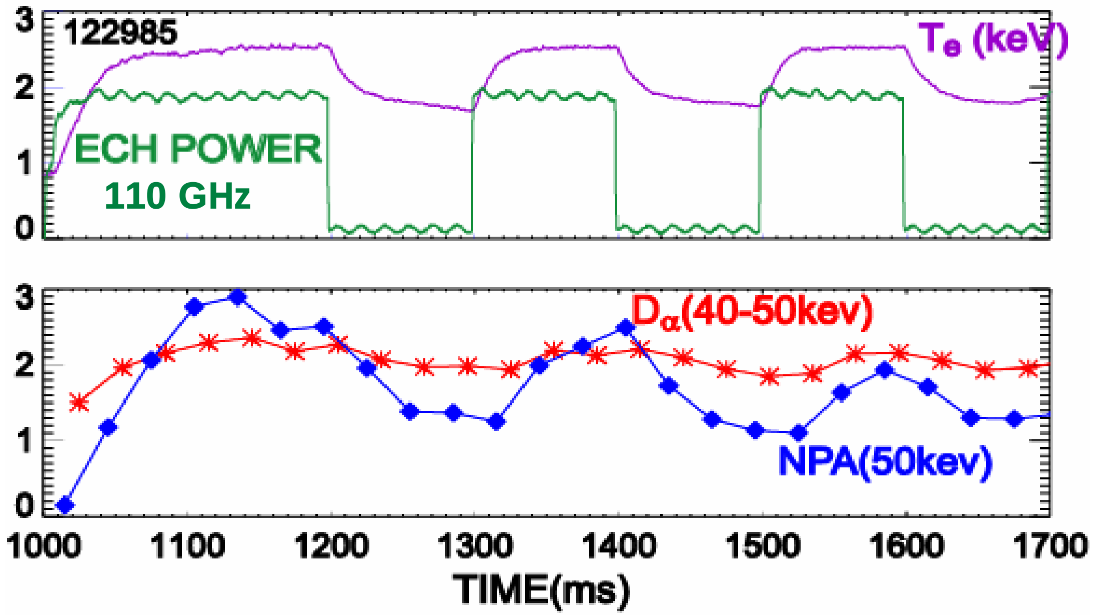
- **Dedicated 2-channel system measured full spectra**
- **Partial spectra from 7 vertical channels on selected discharges**
- **Used radial views to test understanding of velocity-space dependence**

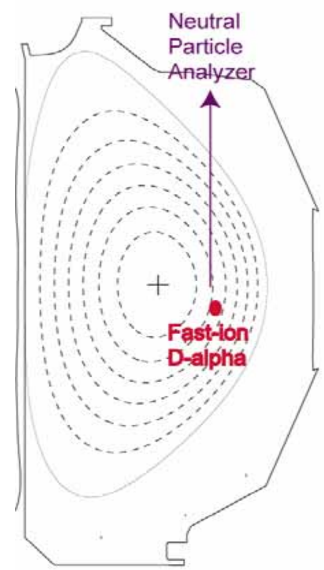
Energy resolution of < 10 keV



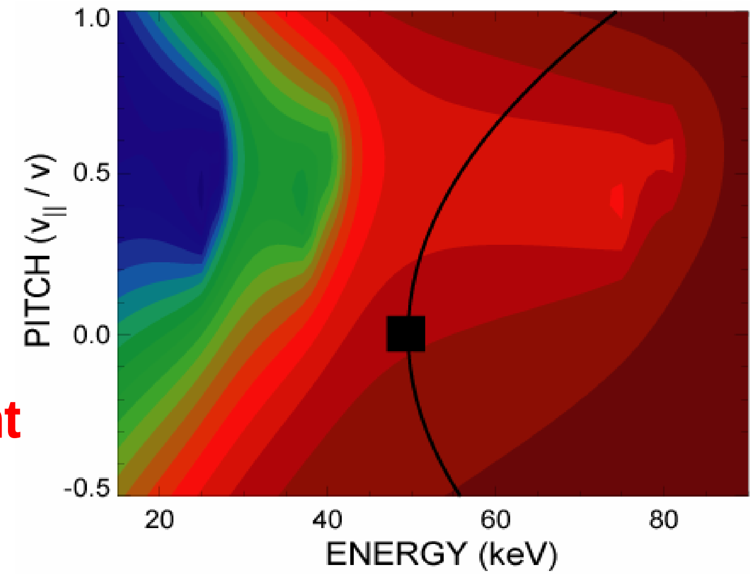
"Steps" in fast-ion distribution from half- and third-energy beam components are resolved

The D_α Signal is Less Sensitive to Pitch-Angle Scattering than Neutral Particle Analyzer Signals



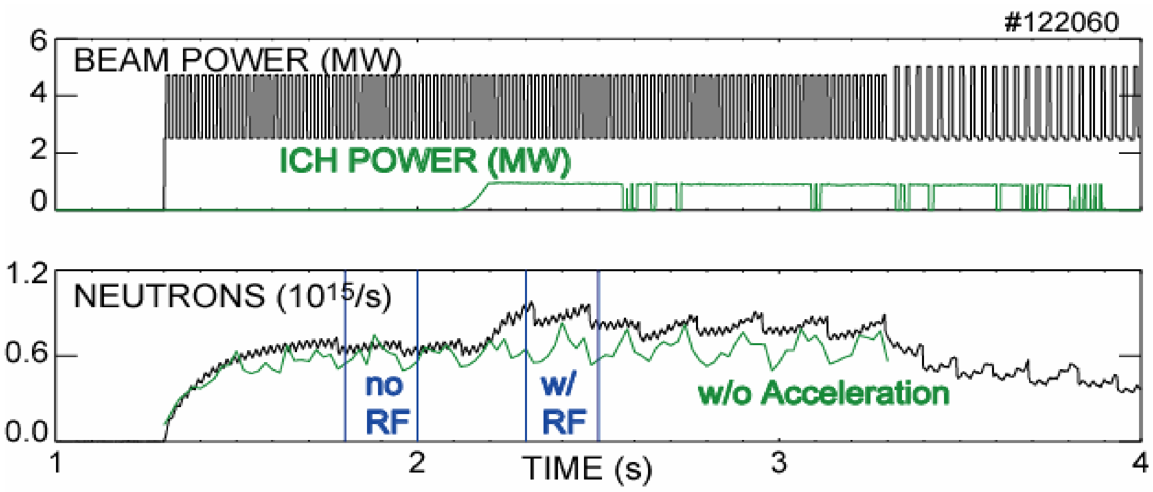


- The signal increases with T_e because Pitch-angle scattering increases →More perpendicular energy
- The NPA signal is also more sensitive to beam injection angle.



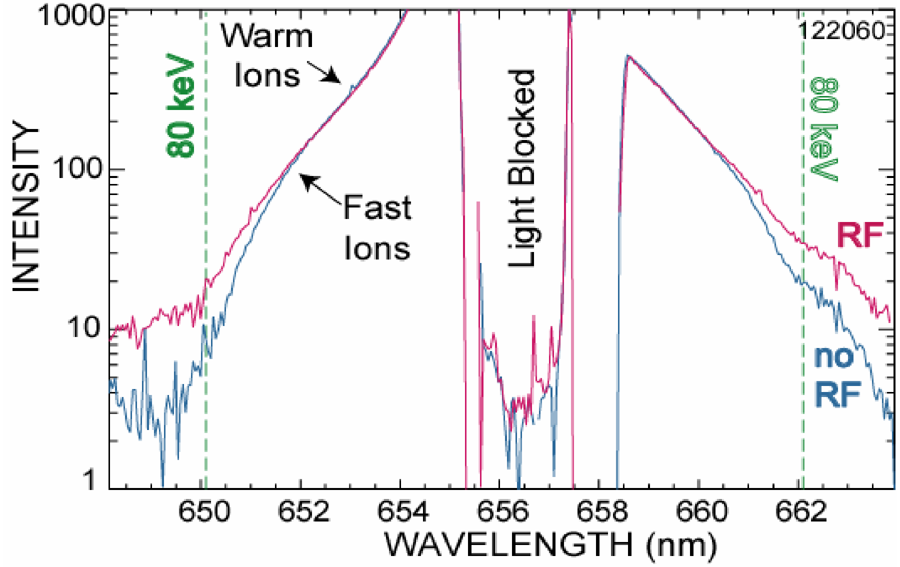
NPA measures a point in velocity space

Perpendicular Fast-ion Acceleration at 4th Cyclotron Harmonic



60 MHz ICH

D$_{\alpha}$ Spectroscopy



- Acceleration above injection energy
- 75% increase between 60-80 keV
- Nearly symmetrical spectrum as expected
- Tail correlates with neutron enhancement

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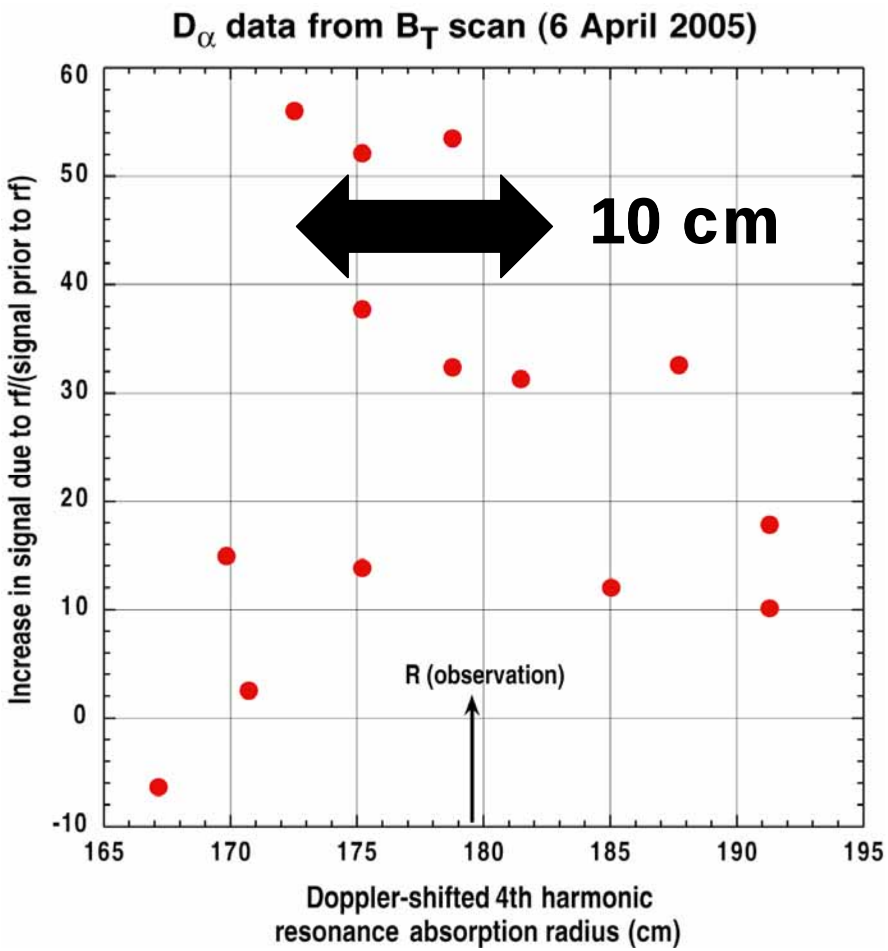
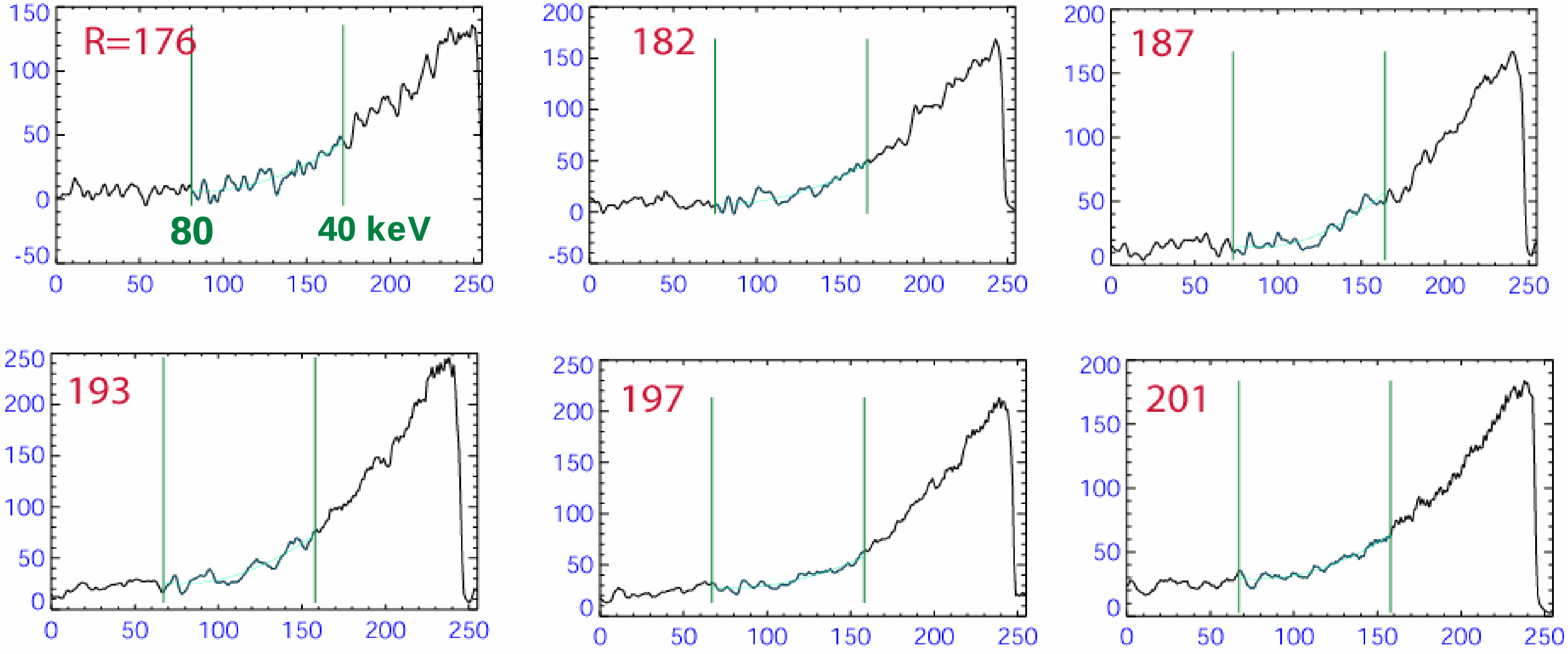
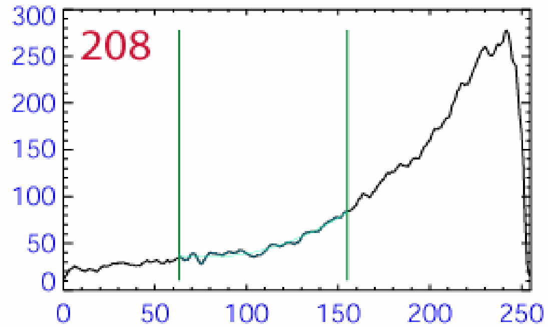
Resonance layer scan implies spatial resolution of < 10 cm



Vary Magnetic Field to move cyclotron harmonic across radius of observation:
Tail largest at Resonance layer

Clear Signals for Most Minor Radii





Although the fast-ion density peaks on axis, the injected neutral density is largest at edge
→Strong signals throughout outer half of plasma

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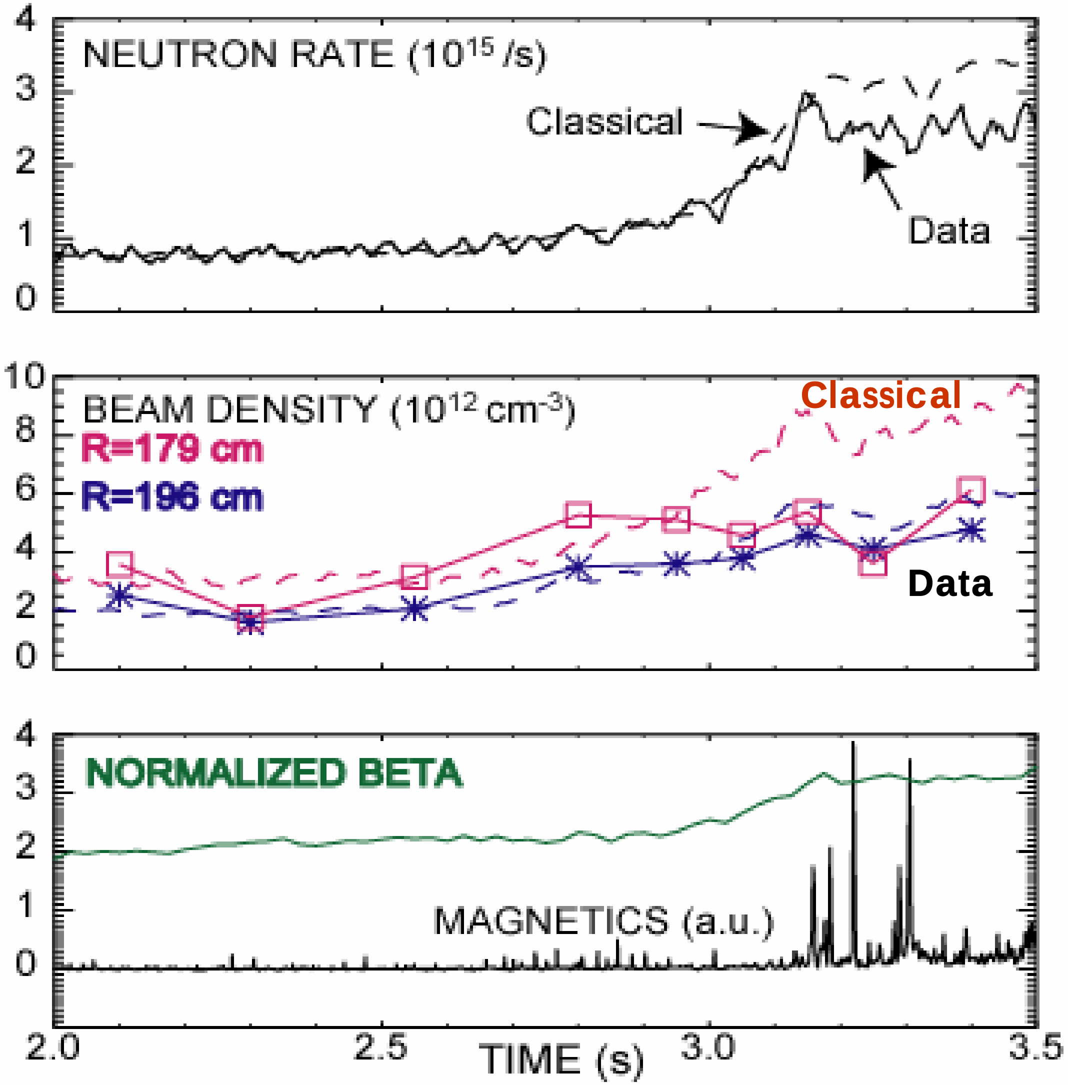
Fast-ion Profile Flattens in Fully-Noninductive, High-Performance AT Discharge



- **Flattening occurs in highest beta phase**
- **Neutron rate deviates From TRANSP prediction during this phase**
- **Integrated D_α signal shows profile becomes flat**
- **Agrees with analysis of driven beam current: Need flat beam density profile to match current profile**

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Murakami

Fast-Ion D_α Spectroscopy Works!

- Perpendicular energy resolution of <10 keV
- Spatial resolution of ~ 5 cm
- Temporal resolution of ~ 5 ms (could be shorter with higher throughput optics)
- Data on classical behavior, fast-wave heating, and many fast-ion instabilities

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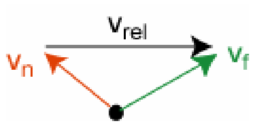
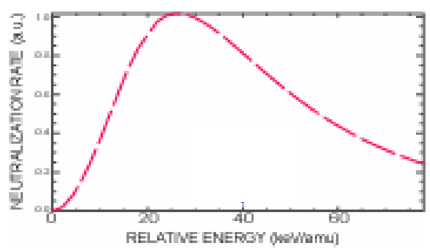
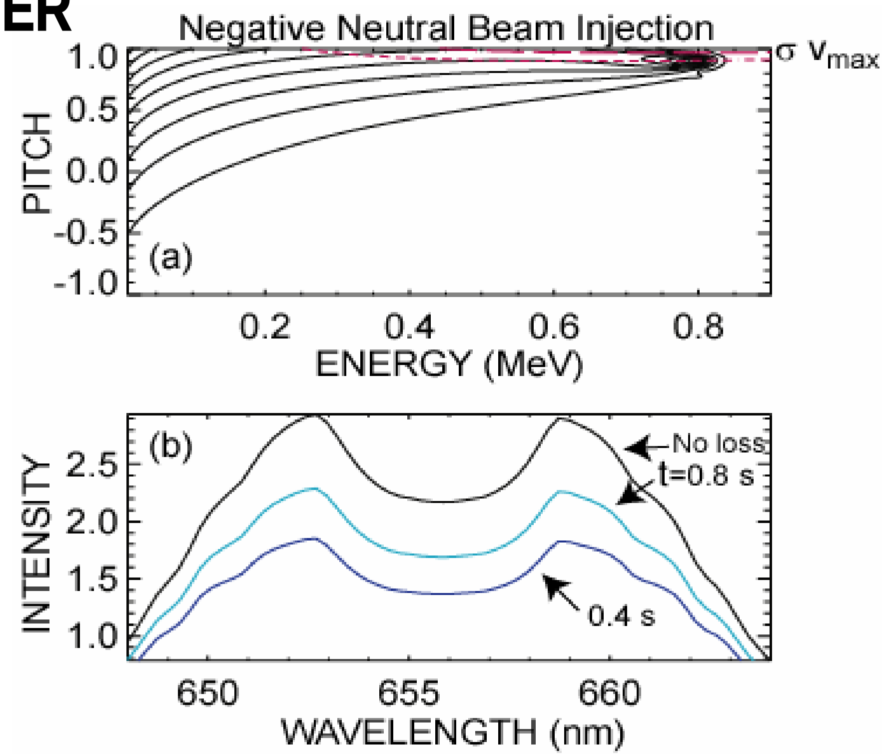
Prospective Applications

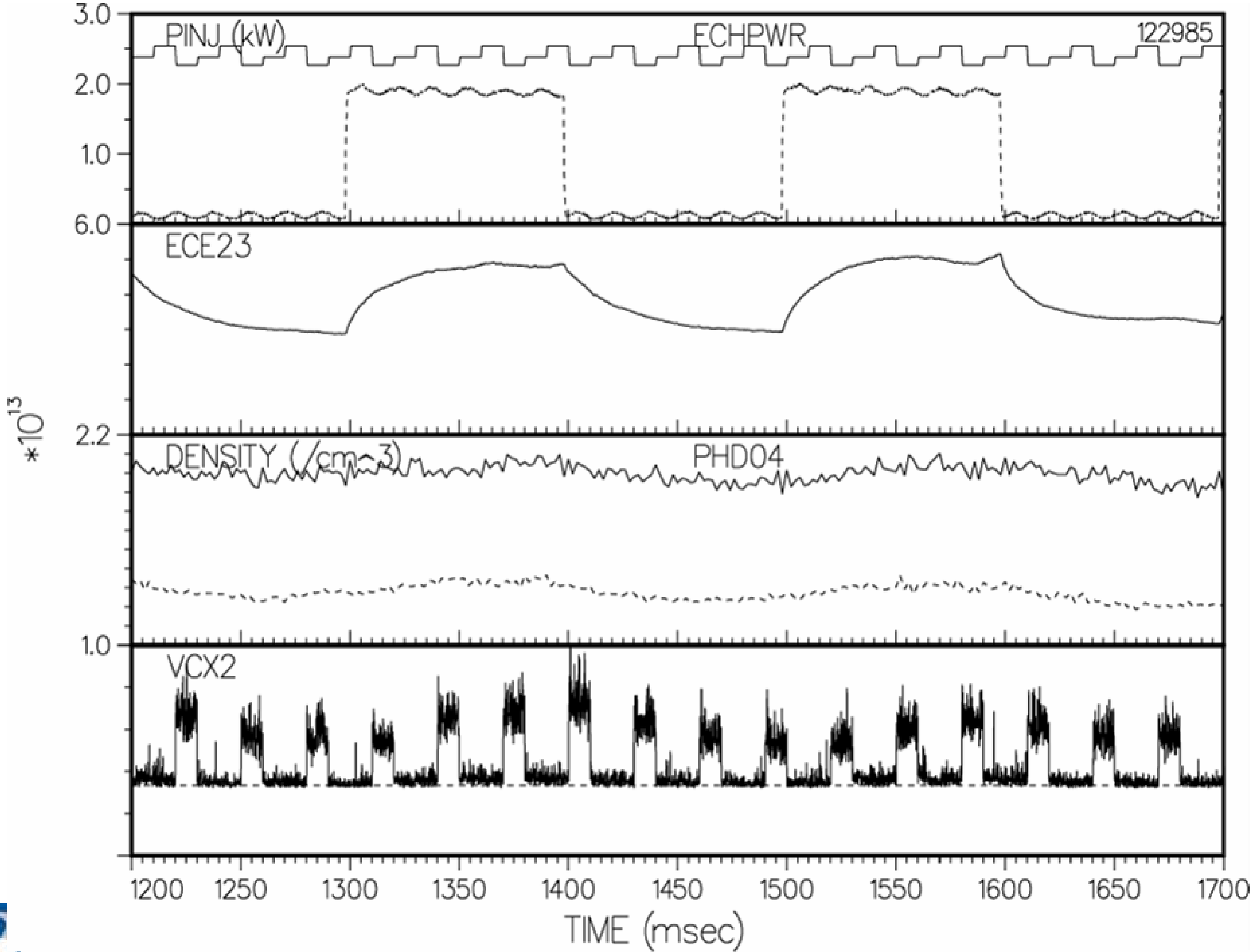
- A dedicated 12-channel spatial array is planned for DIII-D
- A 12-channel spatial array that uses a high throughput transmission grating spectrometer is proposed for NSTX
- The technique could provide useful information about 800 keV deuterium ions in ITER







Quiet shot with T_e Variation



50 keV perpendicular neutrals