NSTX

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Comparison of Fast-ion D-alpha (FIDA) measurements with theory in MHD quiescent plasmas

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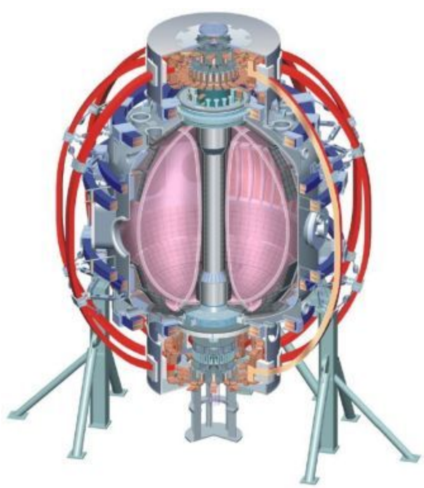

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Successful comparisons between theory & experiment in conventional tokamaks

- Make low-power MHD-quiescent plasmas so beam ions are classical
- Compute the fast-ion distribution function with the TRANSP NUBEAM[1] module.
- Predict the FIDA spectra with the FIDASIM[2] synthetic diagnostic code.
- Measure spectra with Czerny-Turner spectrometers & CCD cameras.
- Use beam modulation to subtract the background.
- Absolutely calibrate the optics.

[1]Pankin, Comp. Phys. Commun. 159 (2004) 157 [2]Heidbrink, Comm. Comp. Phys. 10 (2011) 716

Agreement to within 20-30% in DIII-D & ASDEX-U

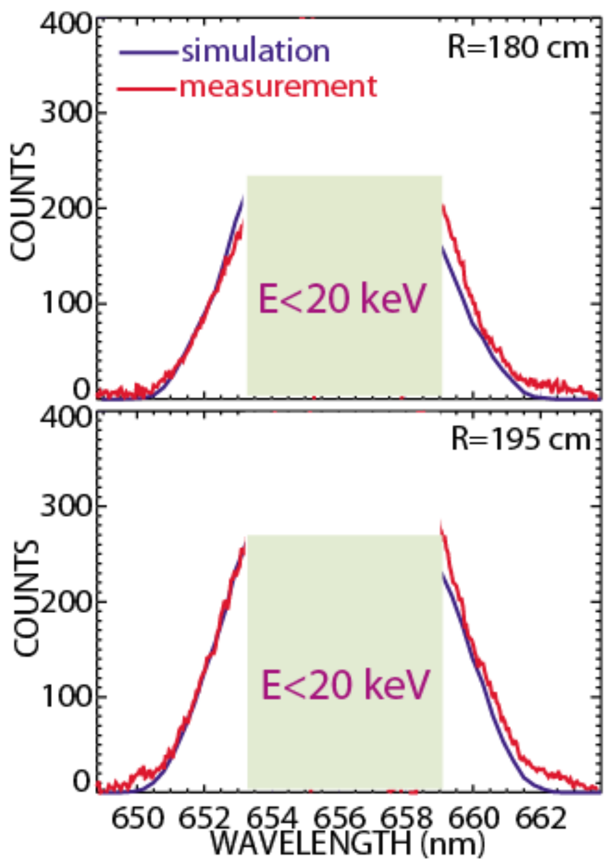


FIG. 3. (Color online) Comparison of the measured spectra and simulated spectra. There are no detectable instabilities at the time (1380 ms) of comparison (P_B=2.4 MW, B_T=2.0 T, I_p=1.0 MA, and single-null configuration). Error bars associated with random errors are less than the size of symbols (not shown).

Y. Luo et al, Phys. Plasmas 14 (2007) 112503.

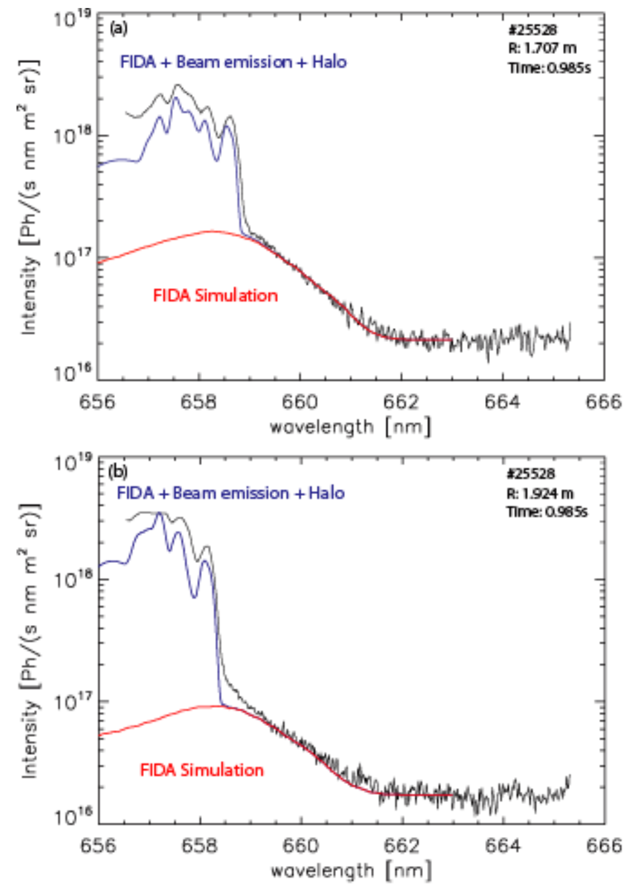


Figure 14. Comparison of measured FIDA spectra (black) to FIDASIM results during on-axis NBI heating at two different radial positions (1.707 m (a) and 1.924 m (b)). In red, the simulated FIDA components are shown. The sum of simulated beam emission, FIDA and halo components is shown in blue. The simulation results have been scaled up by 30%.

B. Geiger et al, Plasma Phys. Cont. Fusion 53 (2011) 065010

Do FIDA spectra agree in a spherical tokamak?

If YES,

- Confirm validity of measurement & of TRANSP modeling
- Verify distinctive features of distribution function in the ST

If NO,

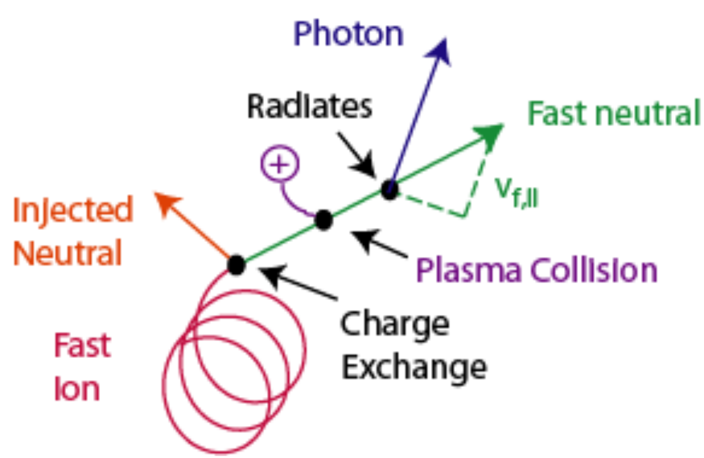
- Problem with instrument or calibration, and/or
- TRANSP modeling misses important physics

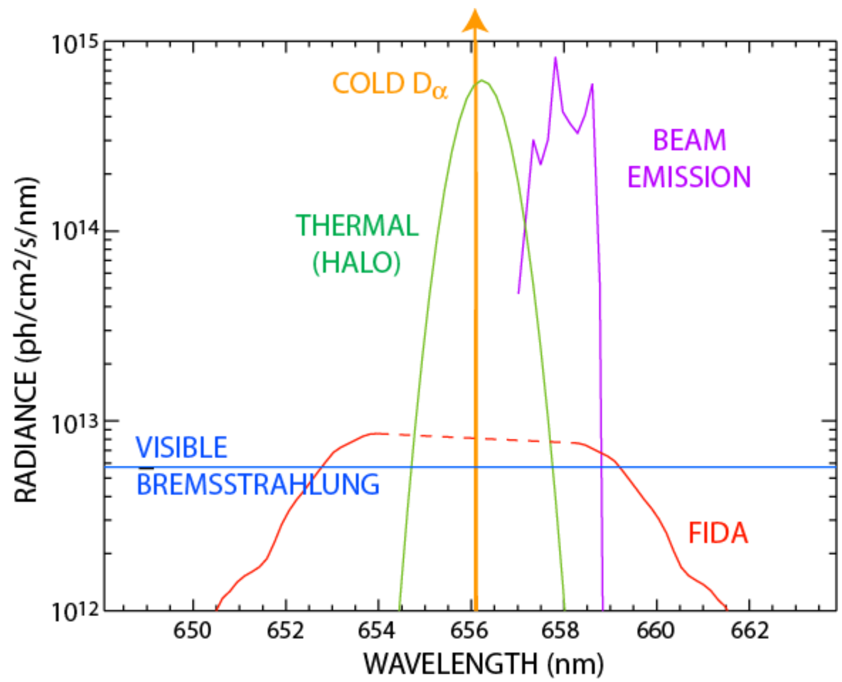
Challenges

- Nearly impossible to make a beam-heated discharge without instabilities in NSTX.
- We used one 65 kV source at 50% duty cycle but the discharges still had CAE (or GAE) instabilities

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
- <u>Active</u> views intersect neutral beam
- <u>Passive</u> views miss the neutral beam - used for background subtraction

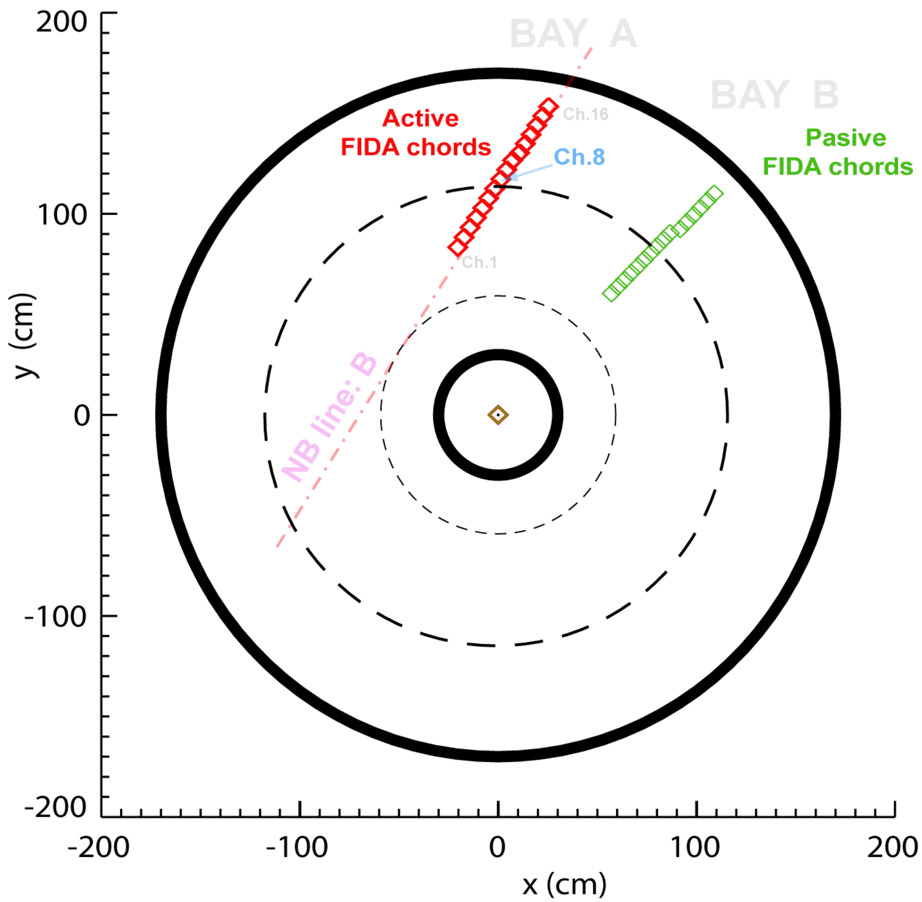




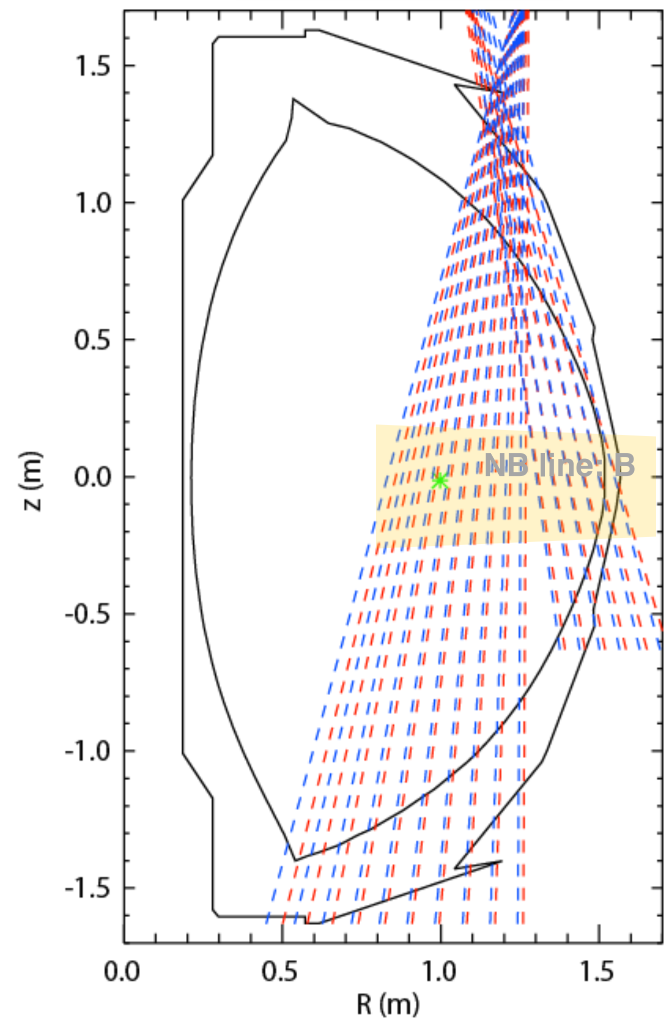
***Heidbrink, Rev. Sci. Instrum. 81 (2010) 10D727**

NSTX has both active and passive vertical views

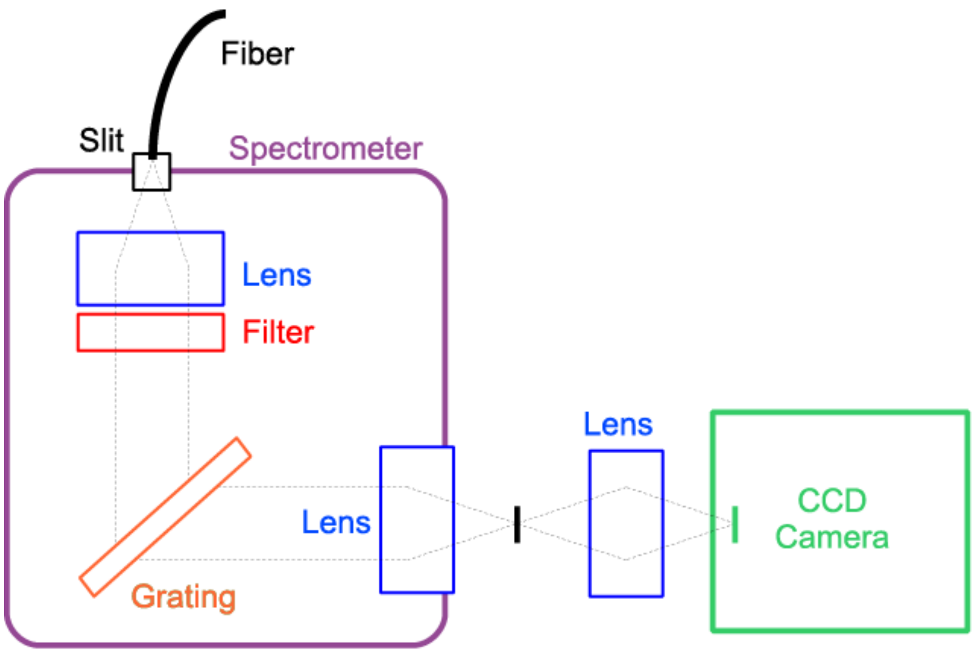
Top view



Vertical view



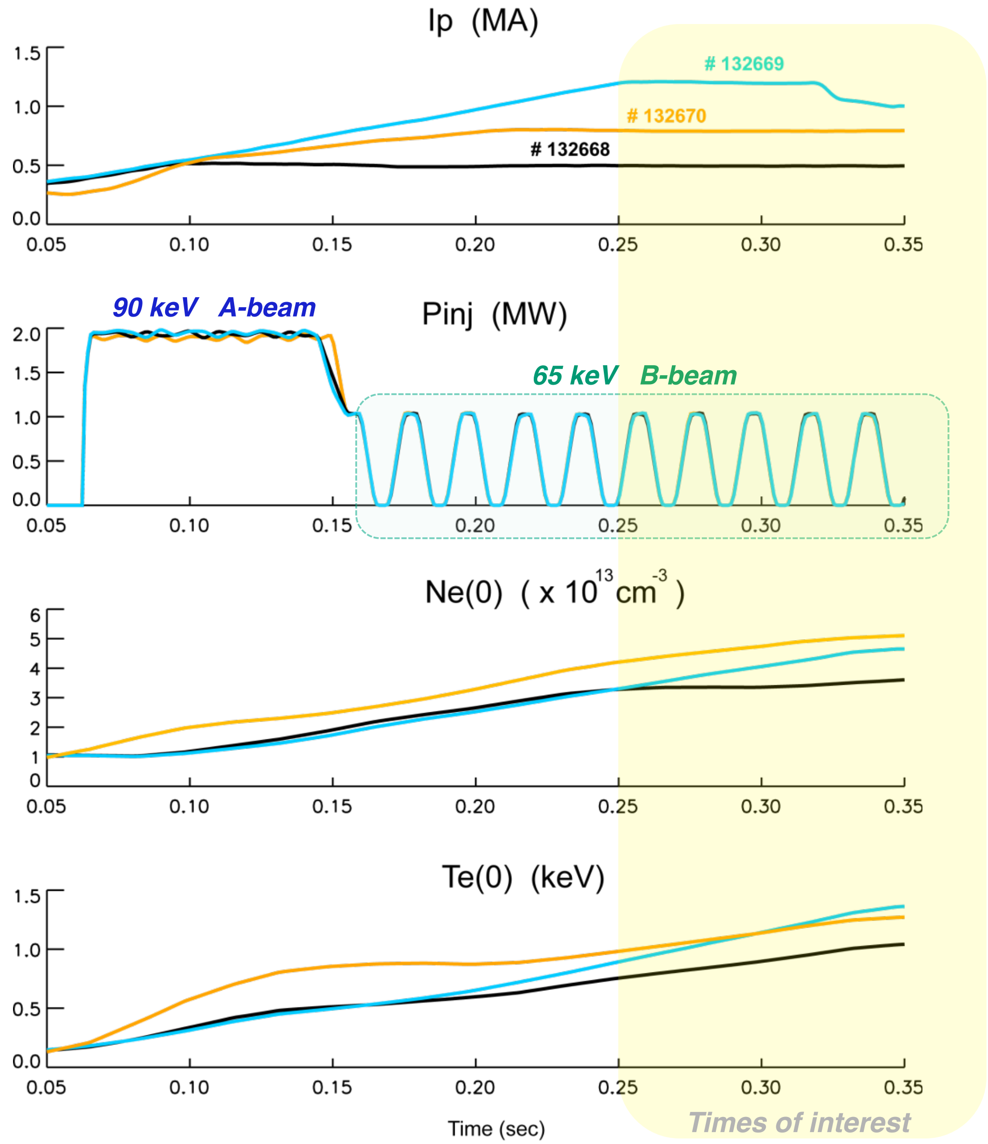
The NSTX s-FIDA instrument* partially blocks the cold D_α line to avoid camera saturation



- "Holospec" transmission grating spectrometer disperses light
- OD2 neutral density filter in focal plane partially blocks center line
- Beam emission also partially blocked
- Spectral resolution ~0.23 nm
- Camera data acquired in 10 ms bins—chopper wheel blocks light for ~1.8 ms during readout
- In-vessel absolute calibration uses "Labsphere" source

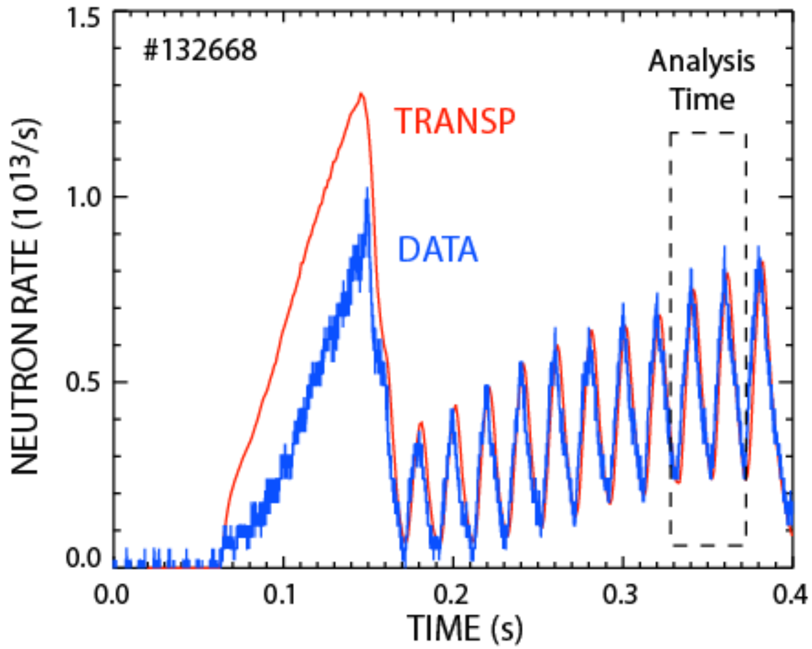
*Podestà, Rev. Sci. Instrum. 79 (2008) 10E521

Variety of plasma conditions tested



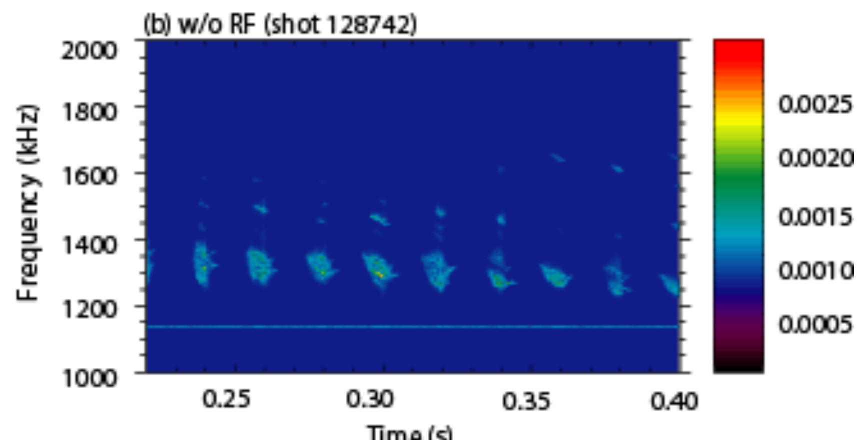
- *Goal: Make MHD-quiescent discharges to investigate the red-blue FIDA spectra variation*
  - *65 keV to minimize MHD*
  - *No TAE, but some GAE*
- *N_e variations change NB deposition profile*
- *I_p and B_T variations change the orbits and field-line pitch*

The neutron rate agrees well with TRANSP



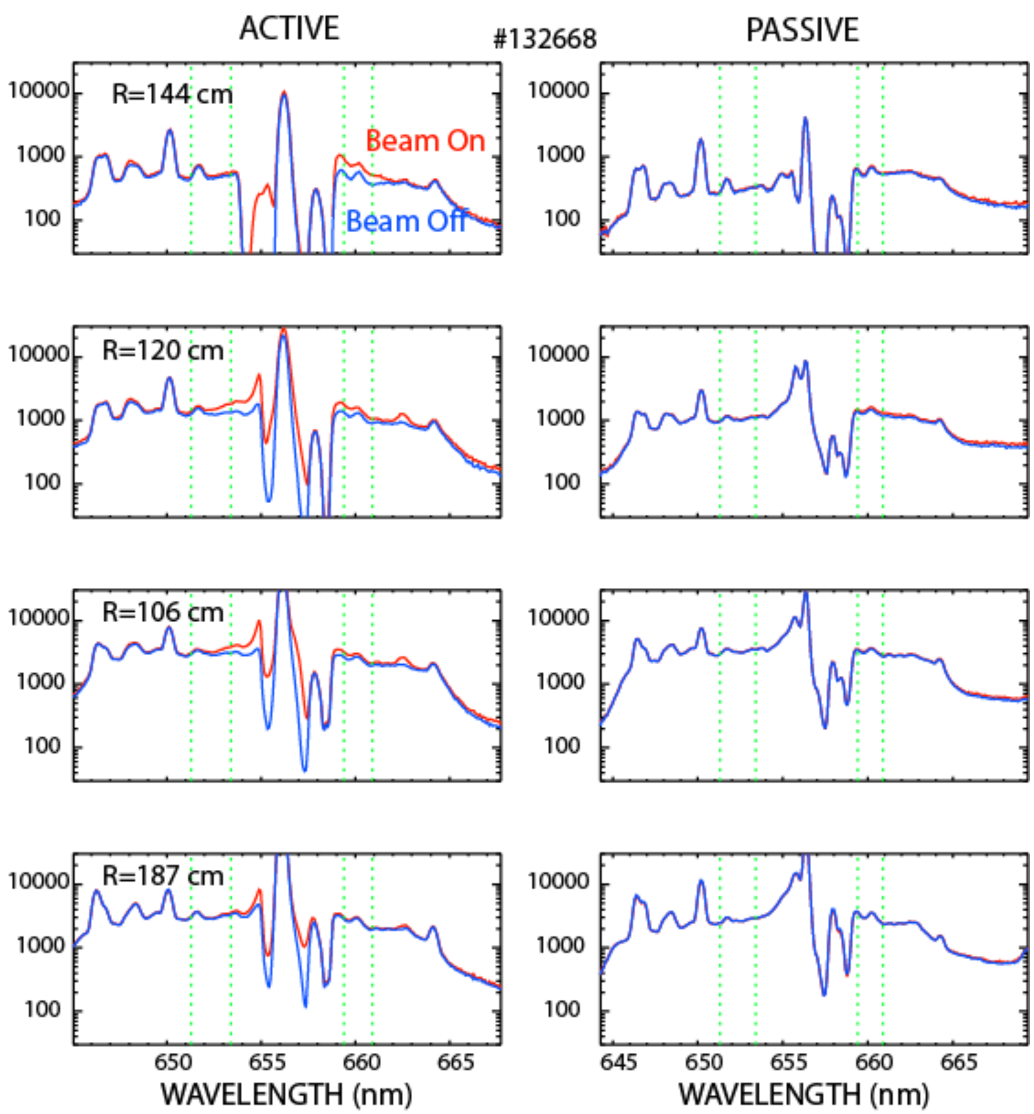
- Neutron rate disagrees with TRANSP when Source A injects at full voltage but agrees with TRANSP during the low-power phase.
- The emission is virtually all (93%) beam-plasma → good proxy for total # of fast ions

- Even at this low power level, CAE activity occurs at every beam blip
- Shot 128742 is a similar discharge* from 2008



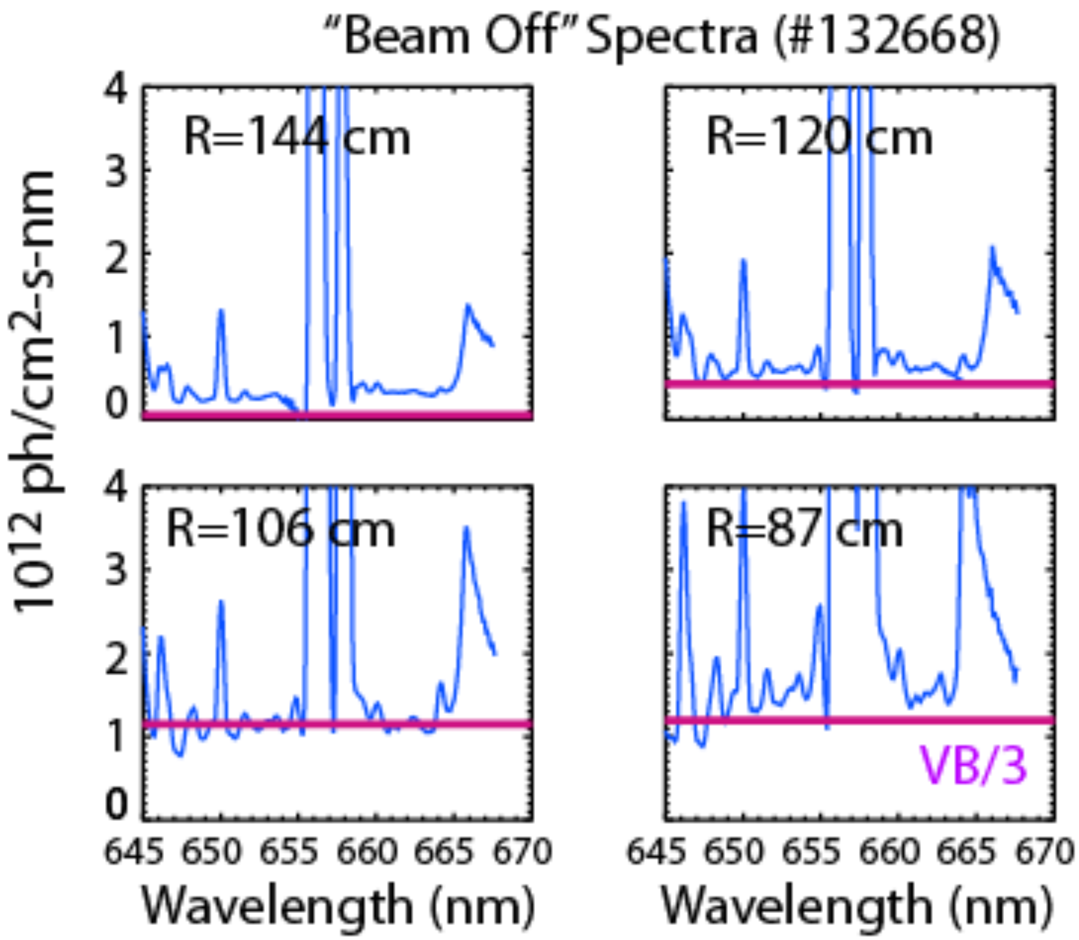
*Liu, Plasma Phys. Cont. Fusion 52 (2010) 025006

Raw Data show FIDA feature



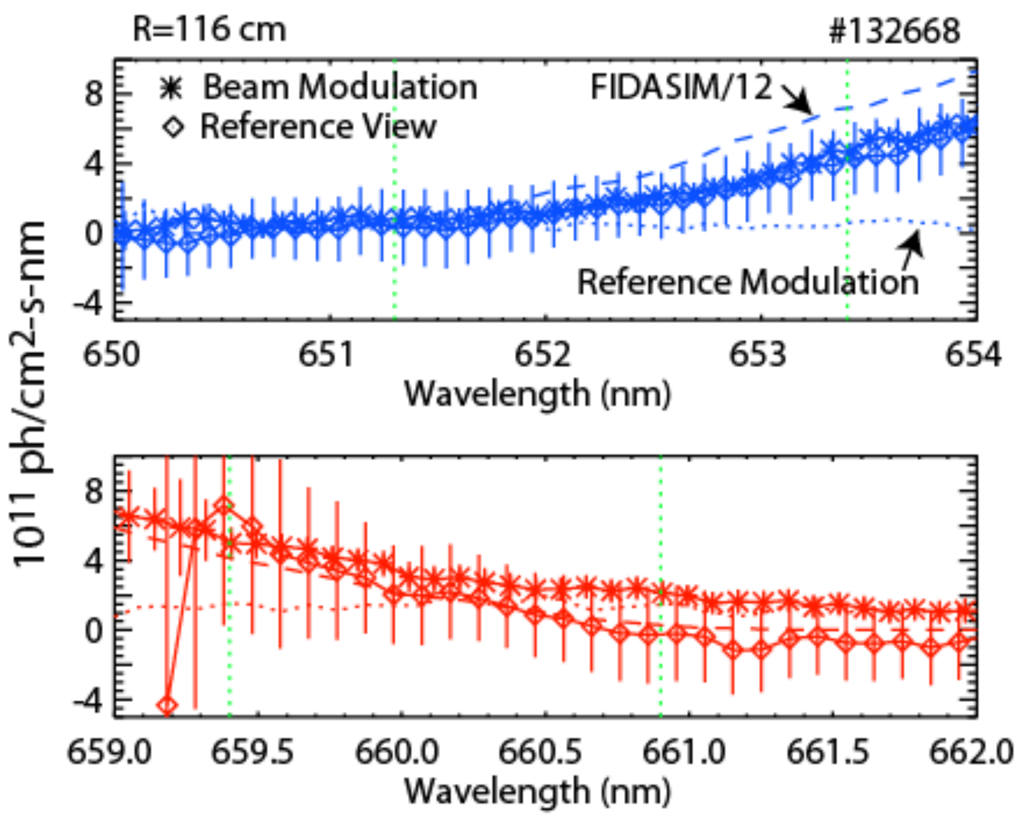
- Compare "beam-on" and "beam-off" spectra from adjacent time bins
- FIDA feature evident from magnetic axis to outer edge on active channels
- Spectra include impurity lines

Calibrated Spectra have Appreciable Background



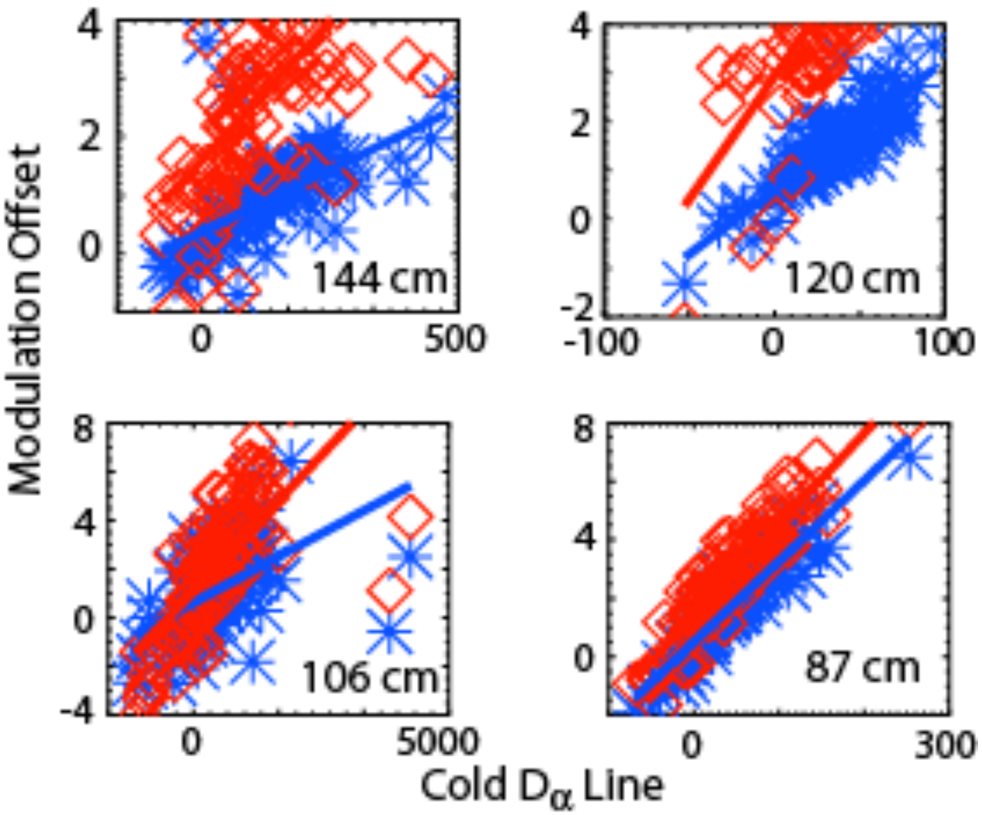
- White plate and in-vessel source used to calibrate data
- Visible bremsstrahlung calculated from plasma parameters inside last-closed flux surface
- Background spectra should be > visible bremsstrahlung

Background subtraction works better for blue-shifted spectra



- Net spectra *should* go to zero at large Doppler shifts
- *Should* get same spectra from beam modulation ("beam on – beam off") & reference view ("active view – passive view)
- Beam modulation spectra for reference view *should* be flat and ~ zero.
- **Blue-shifted** spectra meet criteria for this case
- **Red-shifted** spectra do not

Background offsets are caused by scattering of the bright central line



- Measure modulated spectra ("beam on – beam off") in three bands: Large blue shift (above injection energy), cold D_α line*, Large red shift
- Compile database for 11 times in 9 shots
- Strong correlations for all channels for both red and blue sides of spectra
- Red offset is larger in outermost channels

**includes some beam emission*

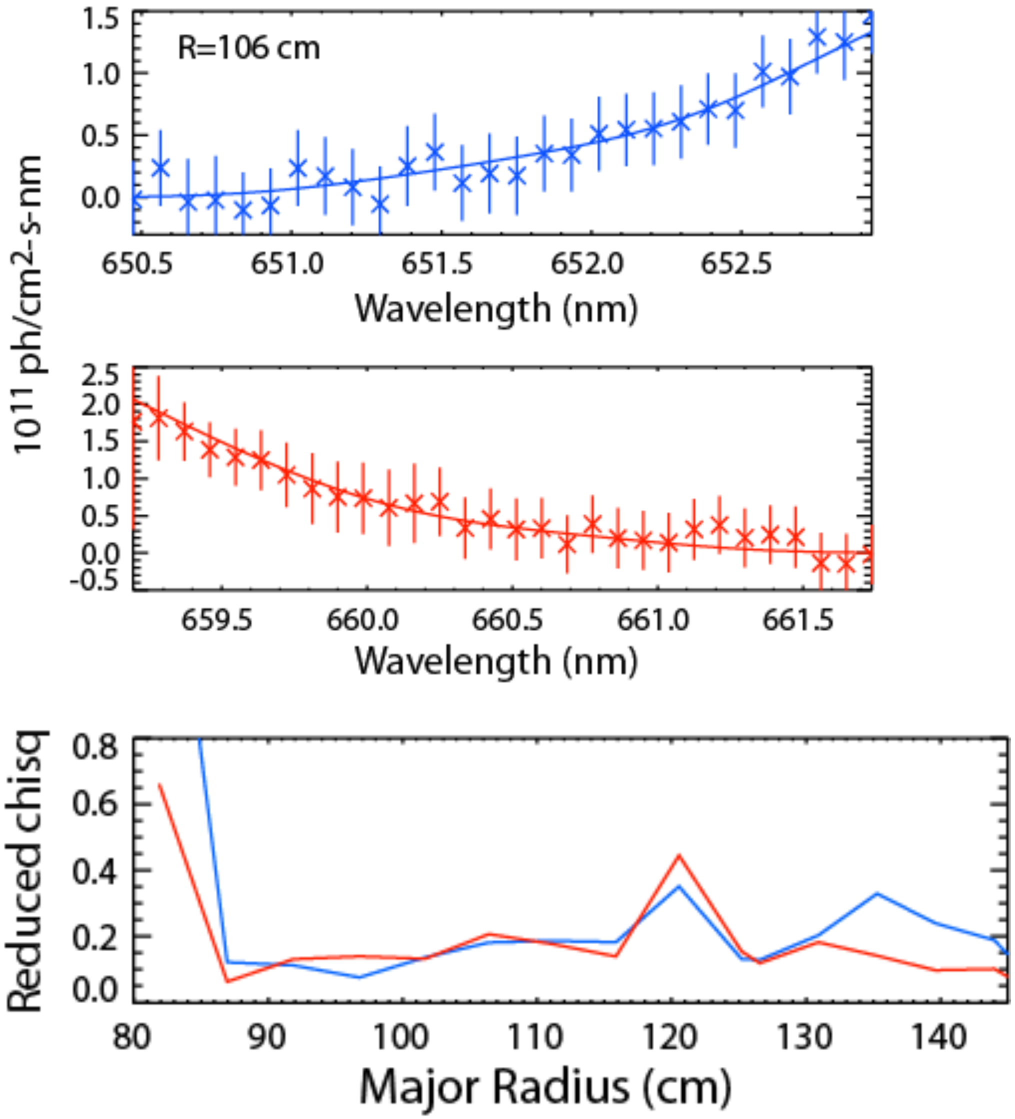
Offsets are not caused by passive FIDA light

- DIII-D,[1] NSTX,[1] and ASDEX-U[2] data show that charge-exchange with edge neutrals can produce appreciable FIDA light
- In DIII-D, certain beams produce prompt losses that intersect a FIDA sightline, producing passive FIDA light.[1]
- Prompt loss orbits from Source B do *not* intersect the FIDA sightlines in the present experiment.

[1]Heidbrink, Plasma Phys. Cont. Fusion 53 (2011) 085007

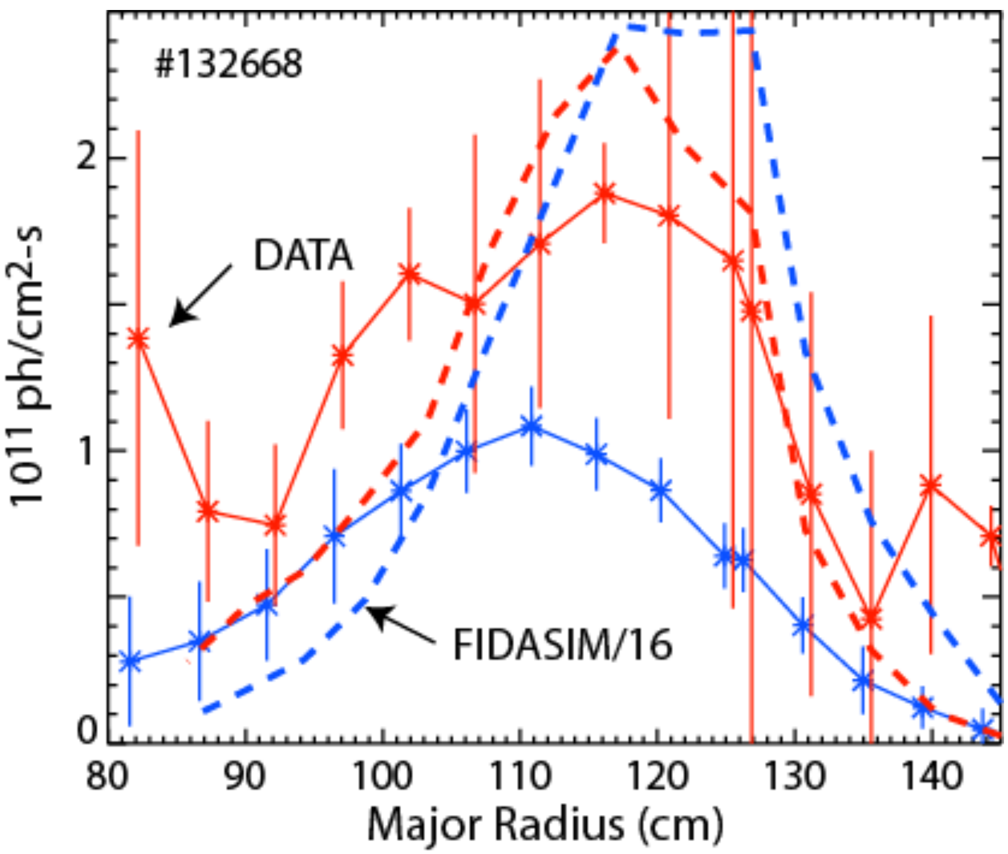
[2]Geiger, Plasma Phys. Cont. Fusion 53 (2011) 065010

The spectral shape agrees well with FIDASIM



- Subtract offsets from modulation spectra
- Normalize theory to experiment
- Calculate reduced chi-squared for the red-shifted and blue-shifted sides separately
- Agreement is good for virtually all channels

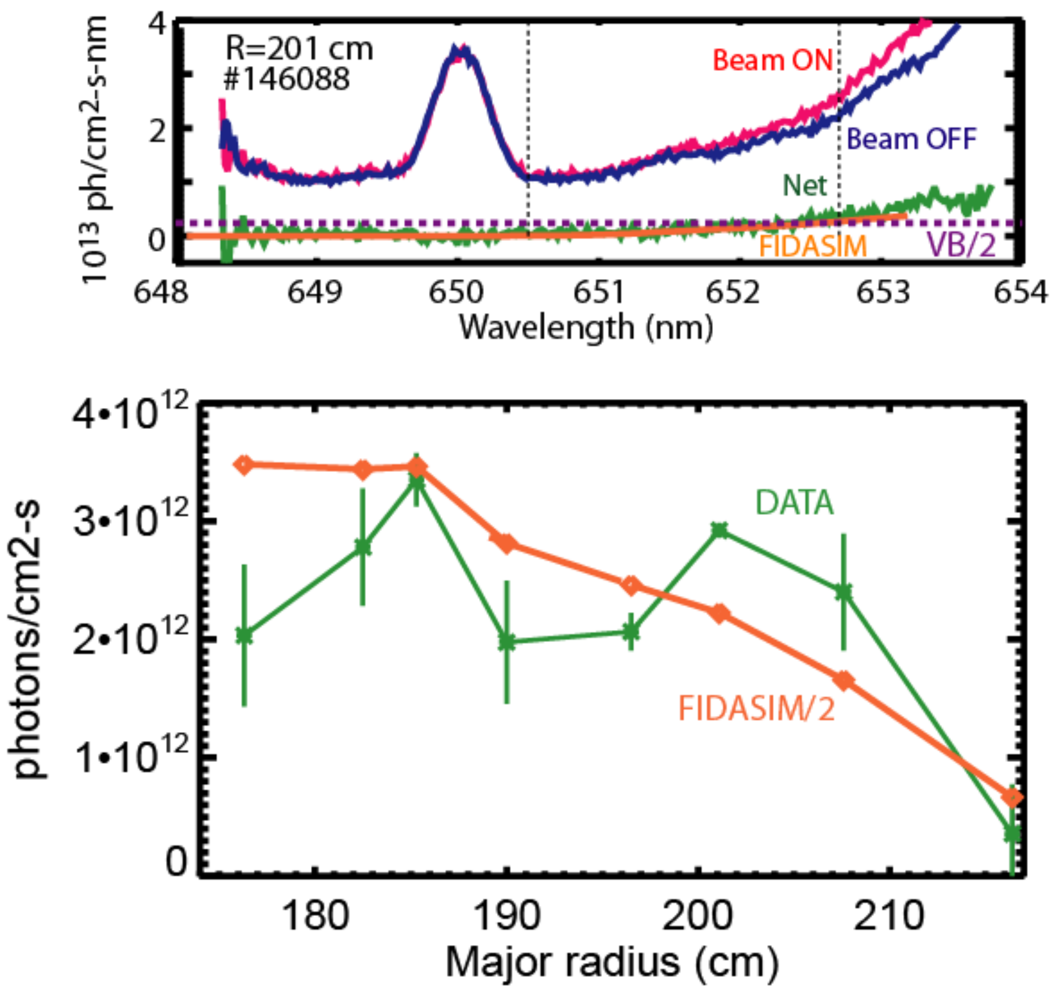
The spatial profile and absolute values disagree with FIDASIM



- Integrate spectra between* E_λ = 21-68 keV
- Error estimate from greater of random error & background offset
- Theory is much larger than experiment
- Experimental profile shape is broader than theory
- Shot #128742 from 2008 gives similar results

*E_λ is the minimum energy of a neutral that produces the observed Doppler shift

A similar DIII-D shot has a much smaller discrepancy



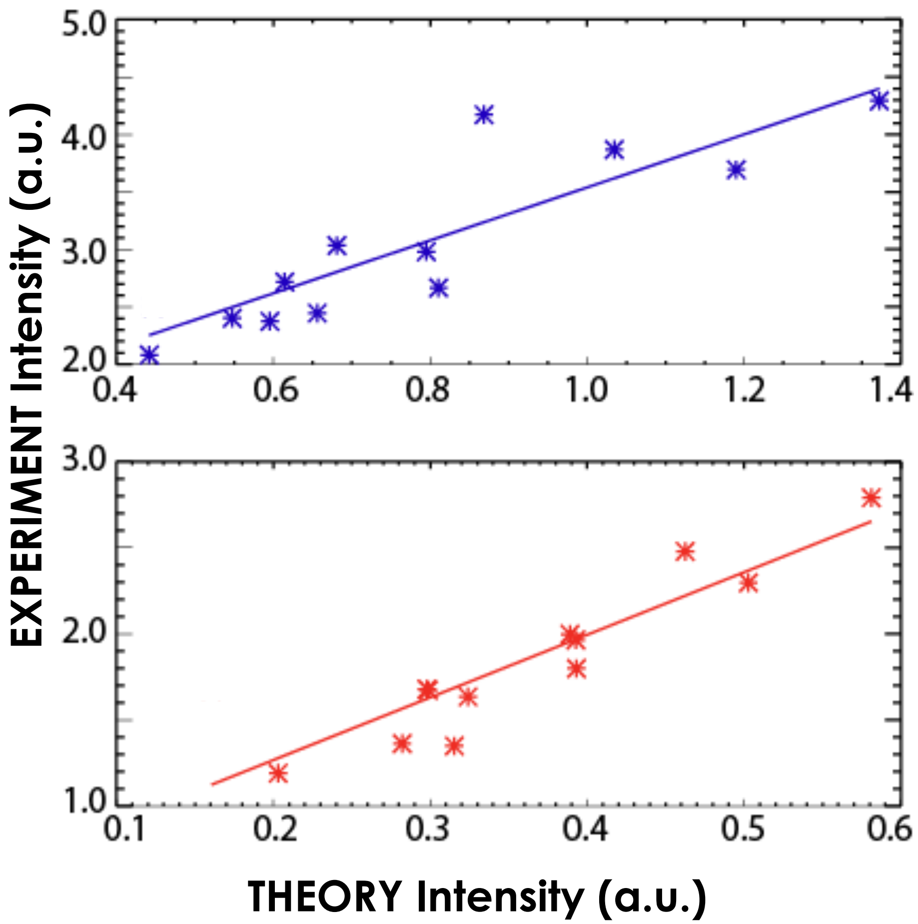
- Vertical view
- Only blue-shifted data
- Steady injection of 1.3 MW by one 60 keV source
- Negligible MHD
- Similar analysis procedure
- Spectral shape in good agreement
- Magnitude off by factor of two
- Profile shape in poor agreement

Many quantities are similar between NSTX & DIII-D

Quantity	NSTX #132668	DIII-D #146088	Comment
Neutrons	7e12 n/s	4e13 n/s	good agreement
FIDA (theory)	4e12	7e12	(ph/cm2-s-nm)
FIDA (exp.)	2e11	3e12	"
BES (theory)	4e15	3e15	"
V.Brems. (th)	1e12	5e12	"
Baseline (ex)	1e12	1e13	"
Inj. neutrals	3e8	5e8	(full energy, cm^{-3})
Fast ions	7e11	2e12	(central, cm^{-3})

- *But experimental FIDA signal is an order of magnitude lower on NSTX*

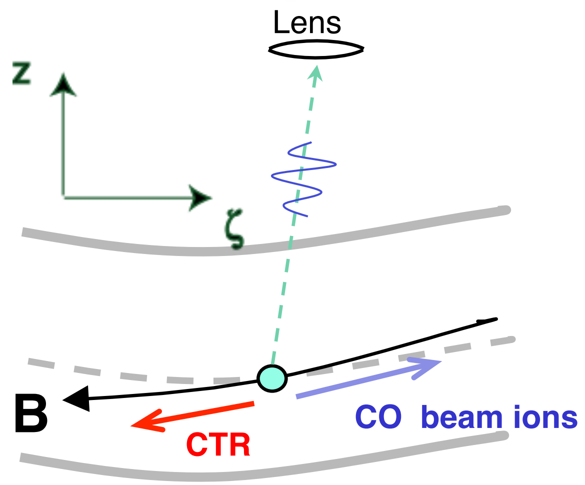
Peak intensity scales like theory for both red & blue spectra



- *Peak of spatial profile fitted for all 12 shots in the dedicated experiment (B-beam)*
- *Correlation coefficient for experiment vs. theory is r ~0.9 for both red & blue spectra*
- *Variation in n_e most important factor (more than B_T or I_p)*
- *No correlation observed between experimental and theoretical red:blue ratio*

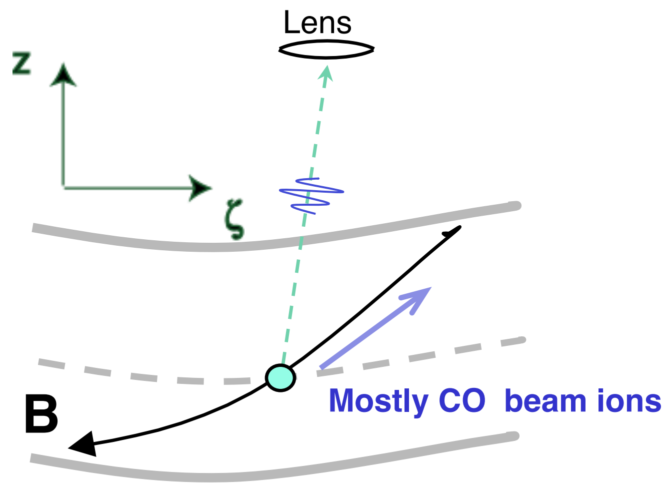
Original motivation was to observe predicted differences in red/blue features

TOKAMAK: $B_{[?]} \ll B_{\phi}$



View towards the central stack

ST: $B_{[?]}$ d B_{ϕ}



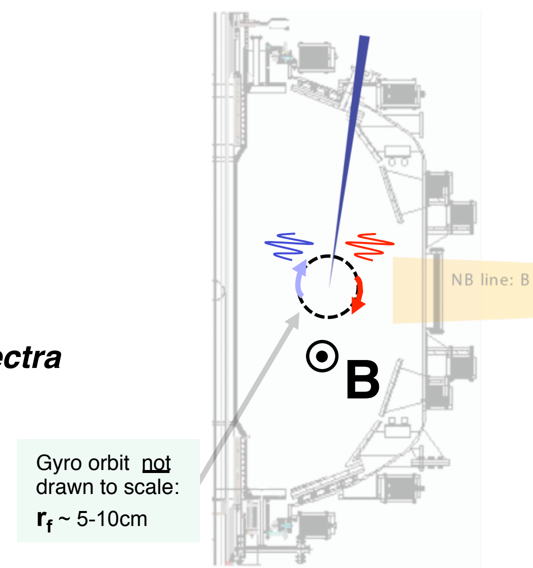
View towards the central stack

Spectra similarity in tokamaks helped by :

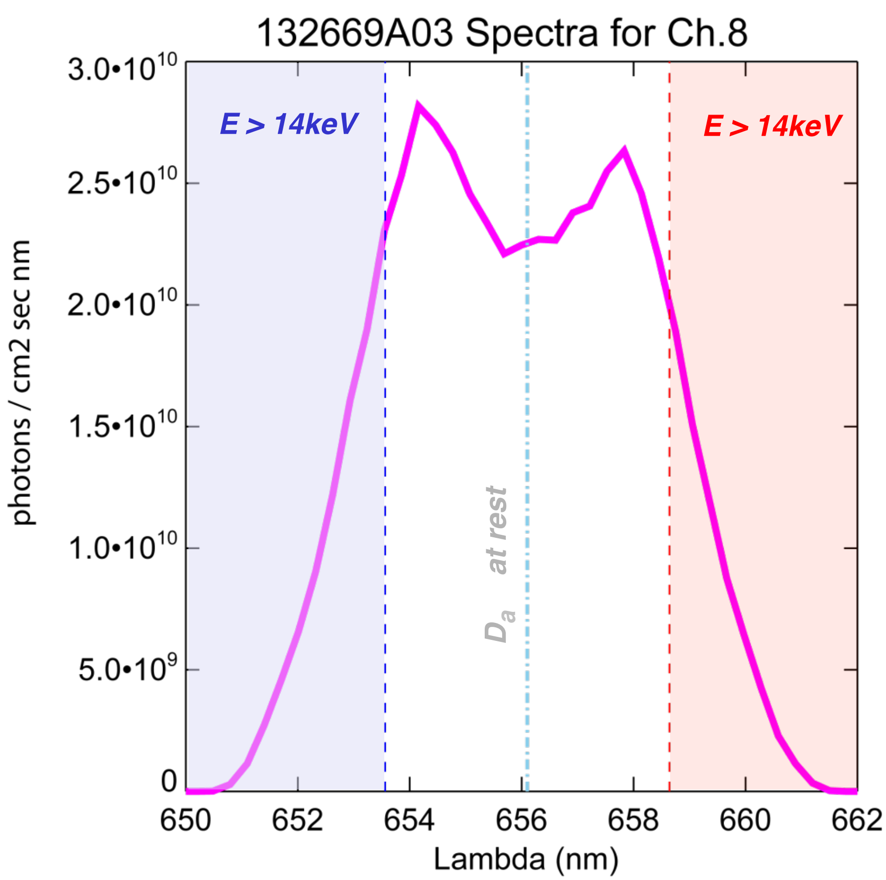
- ***Smaller blue & red shift due to smaller B field tilt***
- ***Detection of sizable CTR going beam-ion population***

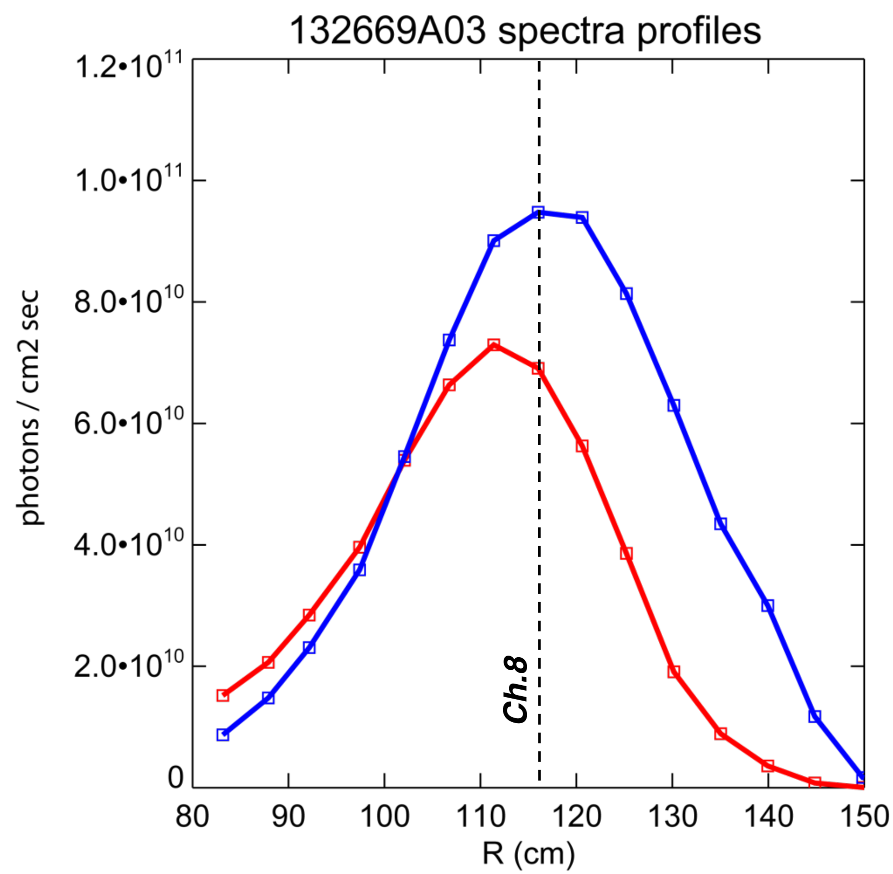
Spherical tokamak:

- ***Expect blue & red spectra peaks not to coincide***



Theory predicts different red & blue spectra





- ***Peak of red profile shifted inwards by 5-10cm. Blue spectra stronger outwards***
- ***PITCH of magnetic field lines alters detected Doppler shift → stronger effect***
- ***Large gyro radii (~ 5-10cm) are a weaker effect***

Observations and Implications

- Neutron rate agrees → fast-ion density *not* an order of magnitude too low; TRANSP simulation OK
- FIDASIM validated in conventional tokamaks → code probably OK
- Spectral shape & parametric dependence agree with theory → really measuring FIDA light
- Visible bremsstrahlung theory ~ experiment but spectra have non-negligible quantities of scattered light → experimental calibration low by >3
- FIDA magnitude an order of magnitude too low → experimental calibration low by >10
- Experimental profile is broader than theory → possibly some anomalous fast-ion transport
- Substantial uncertainties in background subtraction & possible anomalous transport → cannot observe expected difference in red:blue spectra
- Need larger FIDA signals (successful DIII-D and AUG comparisons have order of magnitude larger signals) → cannot achieve this in NSTX w/o MHD!

Sign-up sheet

FIDA code checks: red vs. blue spectra variations tested in simulations

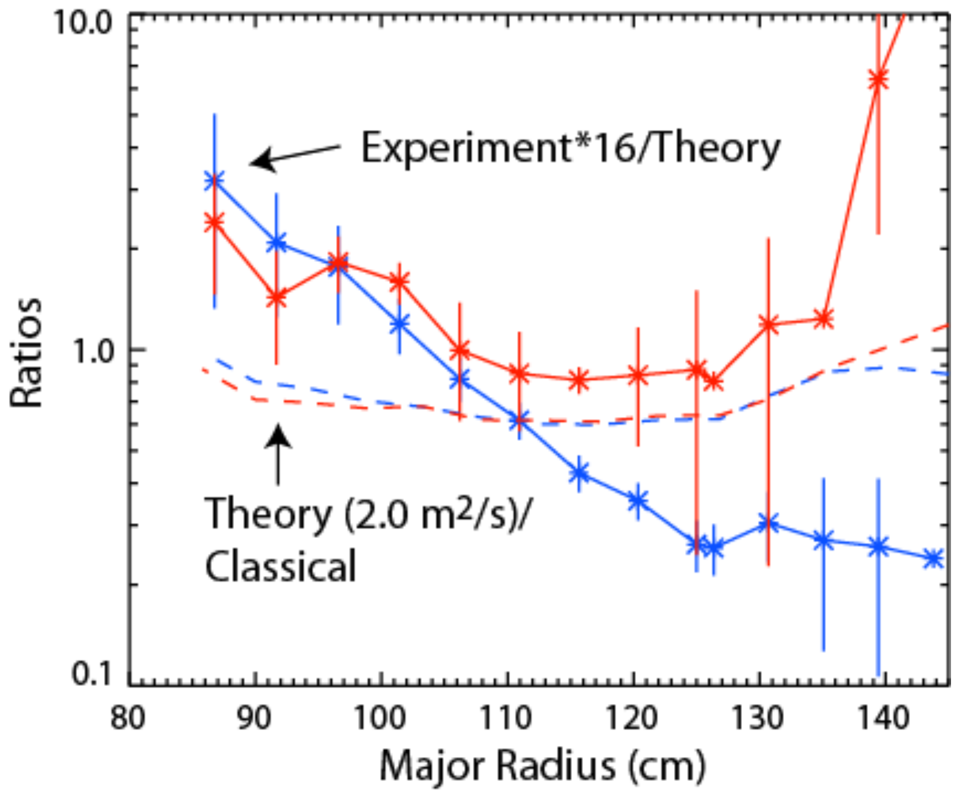
- **Expected flip of *red* and *blue* spectra properties seen when code was modified such that**

    1. V_{66}/ V sign was flipped
    2. Lens moved from machine top to bottom

- **Setting B_z = 0 moves the *red* and *blue* spectra peaks closer**

- **Eliminating the gyroradius shifts the peaks by ~one gyroradius in the expected direction**

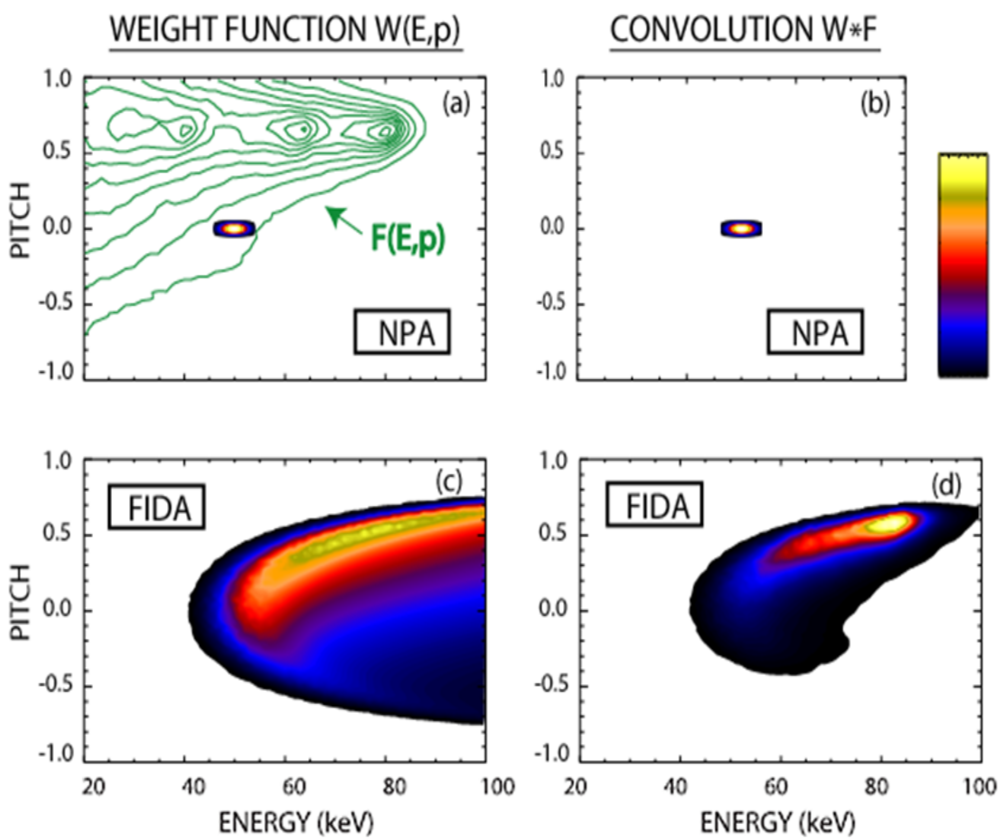
Beam Diffusion Broadens Predicted Profile



- Measured profile is broader than predicted
- Use spatially uniform beam-ion diffusion of 1.0 and 2.0 m^2/s in TRANSP simulations
- Predicted neutron rate is 87% and 77% of classical ($D_B=0$) value
- Predicted FIDASIM profile broadens but still doesn't match experiment

How does a FIDA measurement relate to the fast-ion distribution function?

D3D example

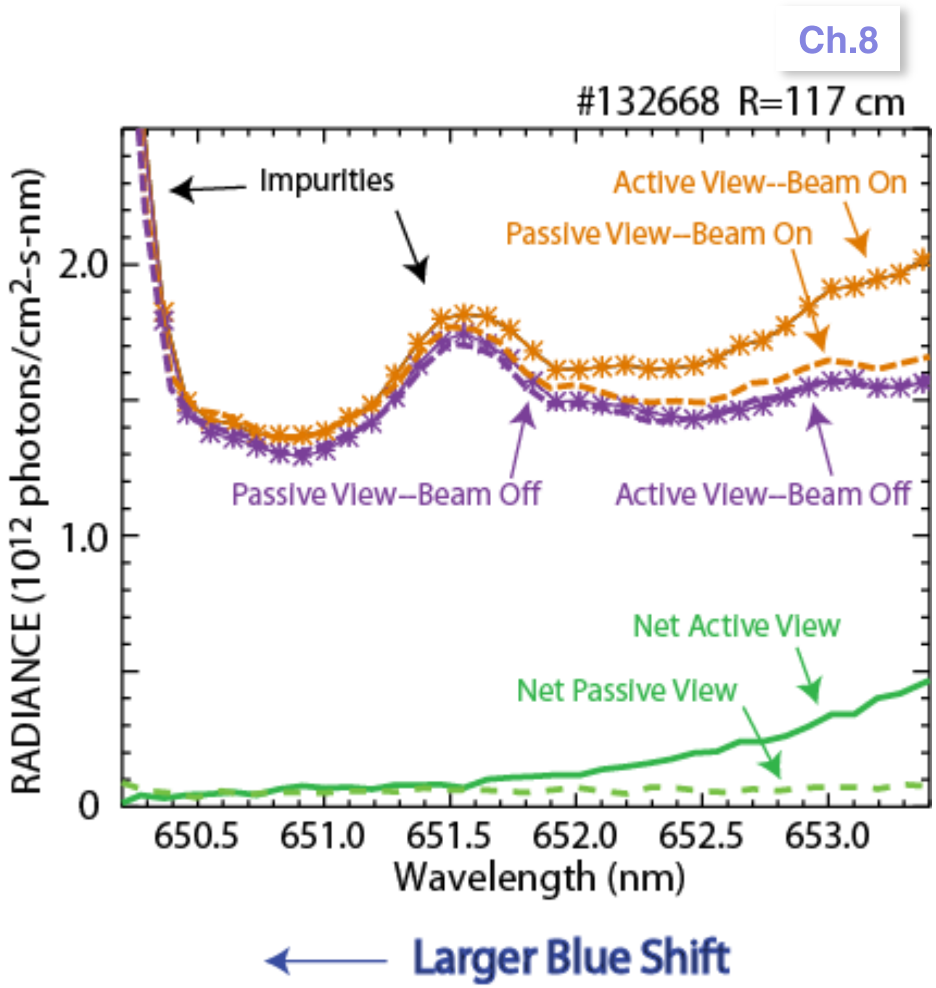


$$Signal = \iint (W \times F)\, dE\, dPitch$$

- *Define a "weight function" in velocity space. It is larger for larger pitch → larger signal*
- *Similar to an "instrument function" in spectroscopy*
- *Only one component of the velocity causes the Doppler shift → energy & pitch are not uniquely determined*

Background subtraction often works well

Blue spectra example

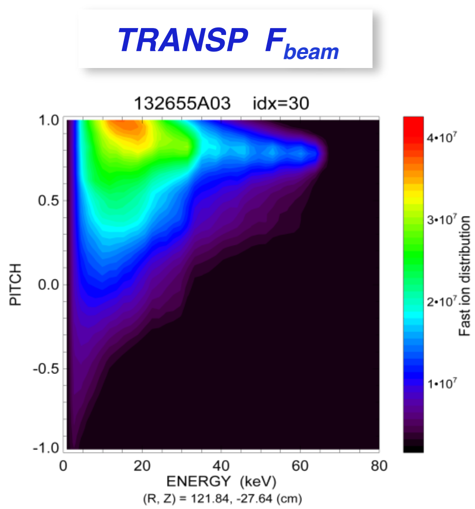


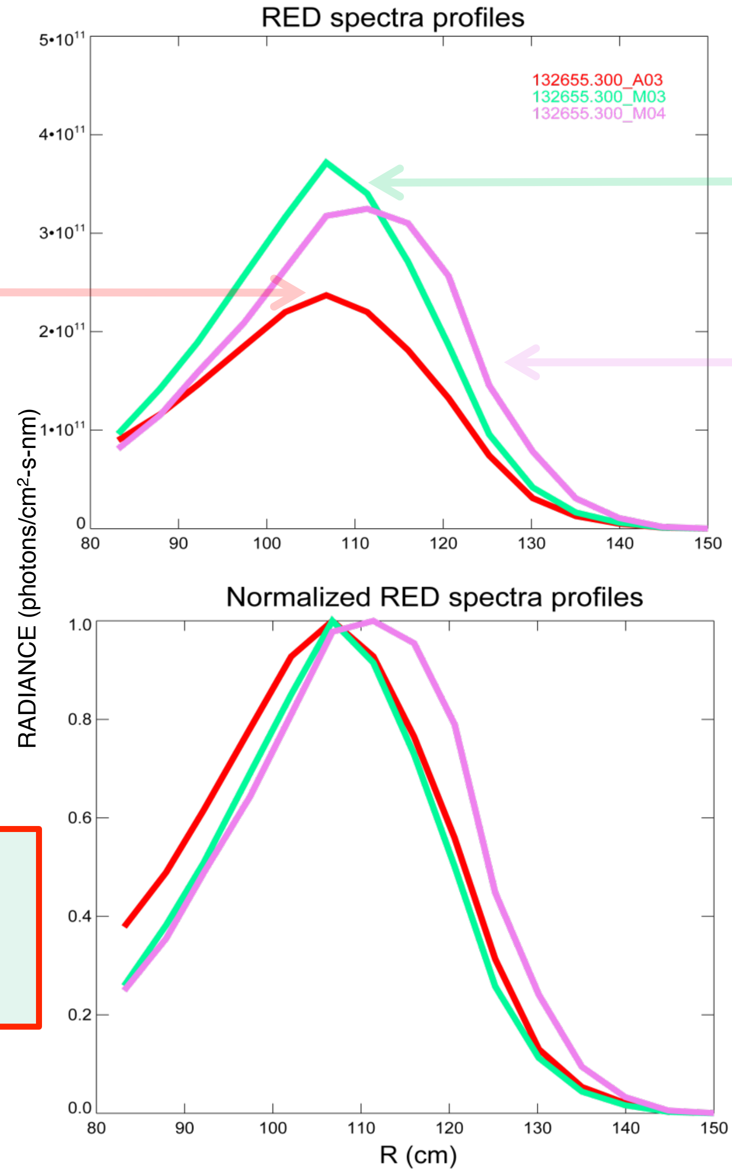
- *The desired FIDA signal is excited by a heating beam*
- *The "Net" signal is :*

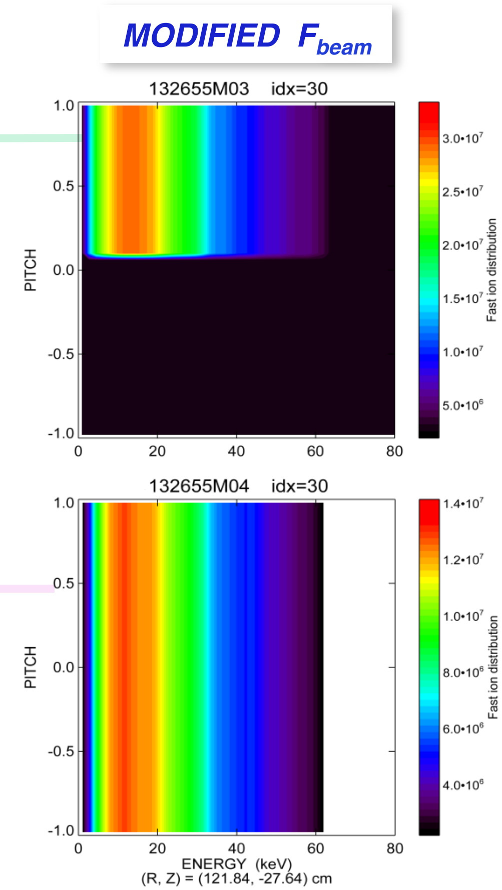
  (Beam On) - (Beam Off)

- *Prominent impurity lines nicely "disappear"*
- *"Net Active" has the expected shape*
- *Expect "Net Passive" to be zero - it is small & flat in this case*

Increased pitch angle scattering modifies the predicted red spectra





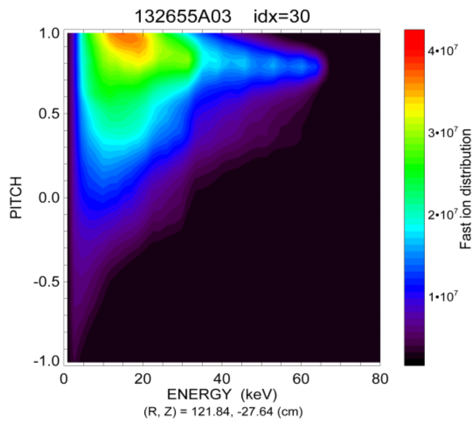


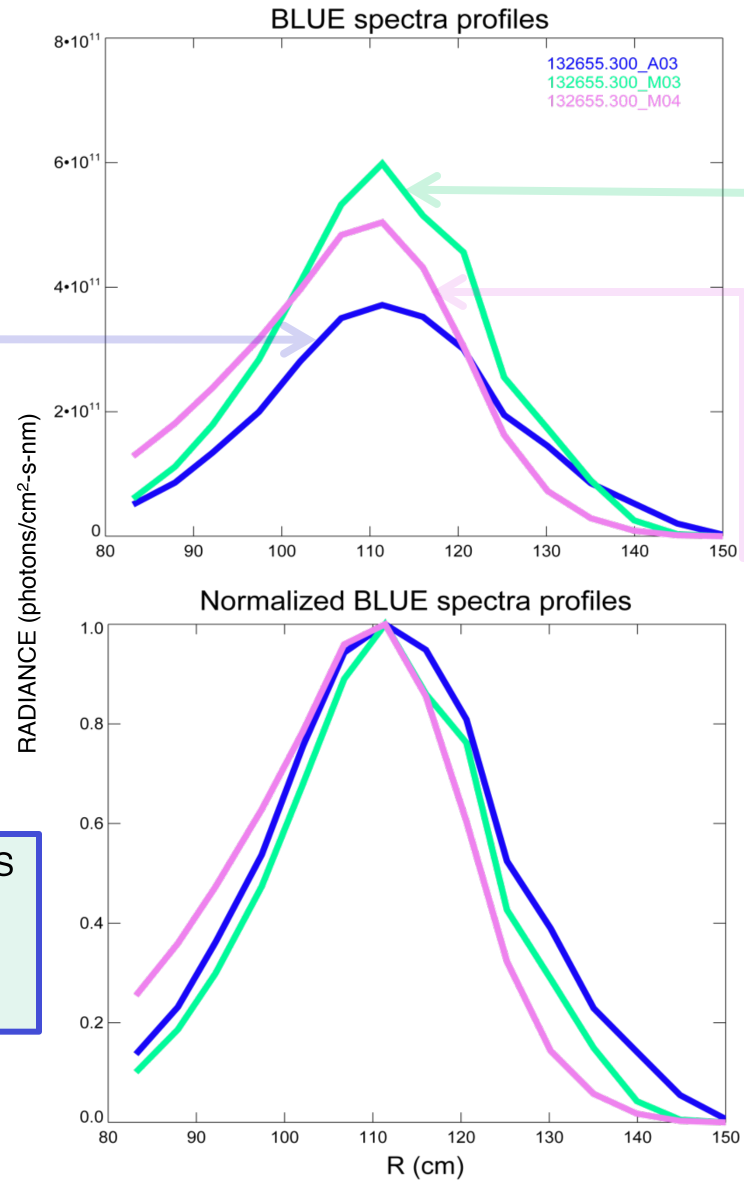
- Large pitch angle scattering shifts the peak of the **RED** spectra outwards by ~ one ion gyro radius
- The profile peak values <u>increase</u>

- f_{NB} was smeared in pitch angle uniformly for each energy, and all spatial locations
- The beam particle census was maintained in the manipulated f_{NB}

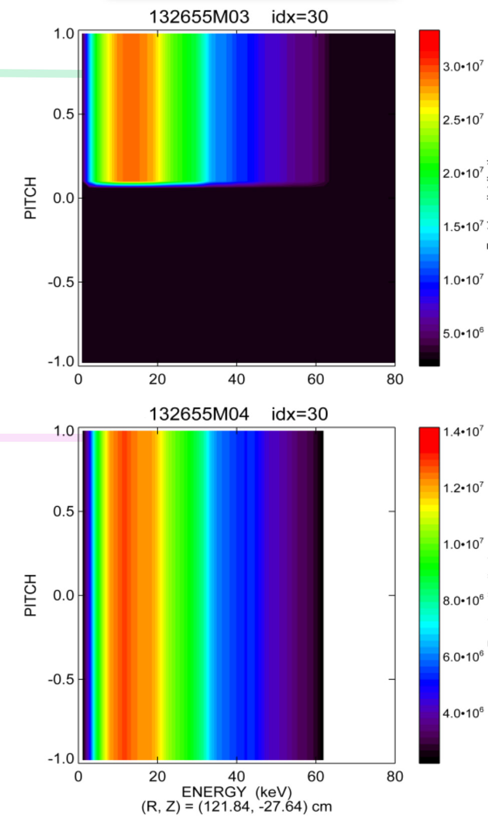
Increased pitch angle scattering modifies the predicted blue spectra

TRANSP ***F_{beam}***





MODIFIED ***F_{beam}***



- Large pitch angle scattering DOES NOT shifts the peak of the **BLUE** spectra.
- The profile peak values <u>increase</u>

- ***f_{NB}*** was smeared in pitch angle uniformly for each energy, and all spatial locations
- The beam particle census was maintained in the manipulated ***f_{NB}***