Neutral Beam Atomic Data Used in Analysis Codes on DIII-D and NSTX-U

B.A. Grierson, Princeton Plasma Physics Laboratory

Second RCM of the Neutral Beams CRP

IAEA Headquarters Vienna, Austria

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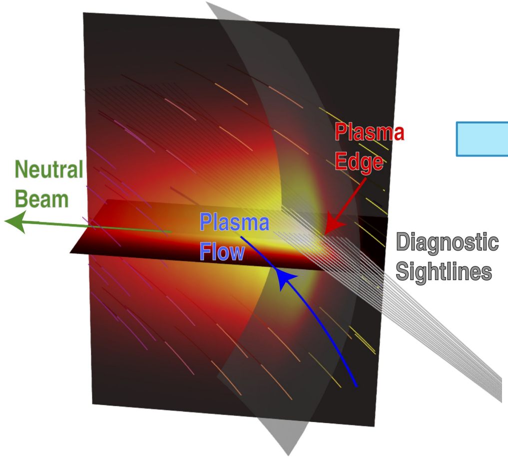
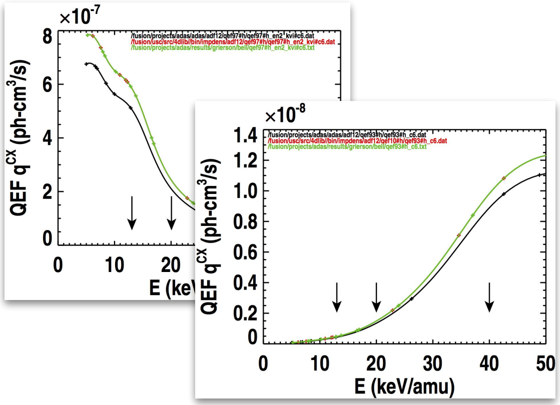
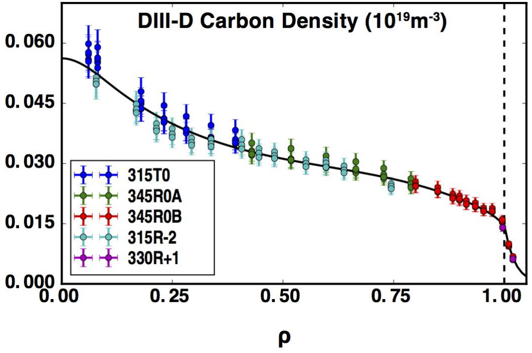
The Goal of this Presentation is to Provide the Atomic Data, Use Cases, Validation and Challanges on Existing US Tokamaks

- This CRP aims to provide *evaluated and recommended data* for the principal atomic processes of heating and diagnostic neutral beams in fusion plasma[1]
- The tokamaks should *validate* the recommended data through careful experimental *testing* and *assessment* of measurement uncertainty



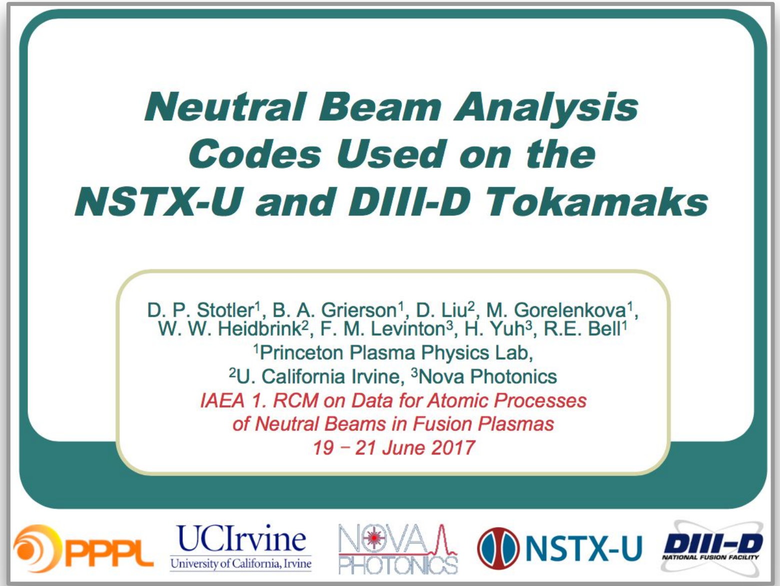




[1]Hyun-Kyung Chung, IAEA CRP RCM1

First Meeting[1] Previewed NSTX-U and DIII-D Configuration and Codes Used for Analysis and Simulation

- Neutral beam geometry and range of typical operating plasma conditions
- Introduction to TRANSP/NUBEAM
- Introduction to FIDASIM
- CHERS layout on NSTX-U and DIII-D
- MSE systems



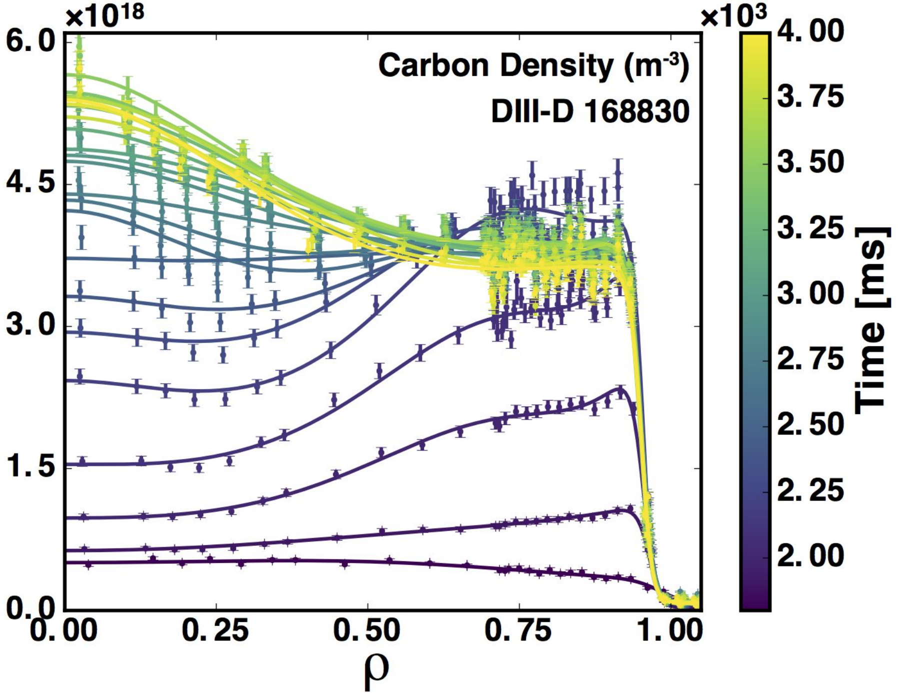
[1]D.P. Stotler, IAEA CRP RCM1

This Presentation Covers ...

- Review of procedure for tokamak impurity density analysis
- Rate coefficients used for NSTX-U and DIII-D for carbon
- Validation of carbon rate coefficients
- Atomic data used for NUBEAM and FIDASIM
- Other impurities

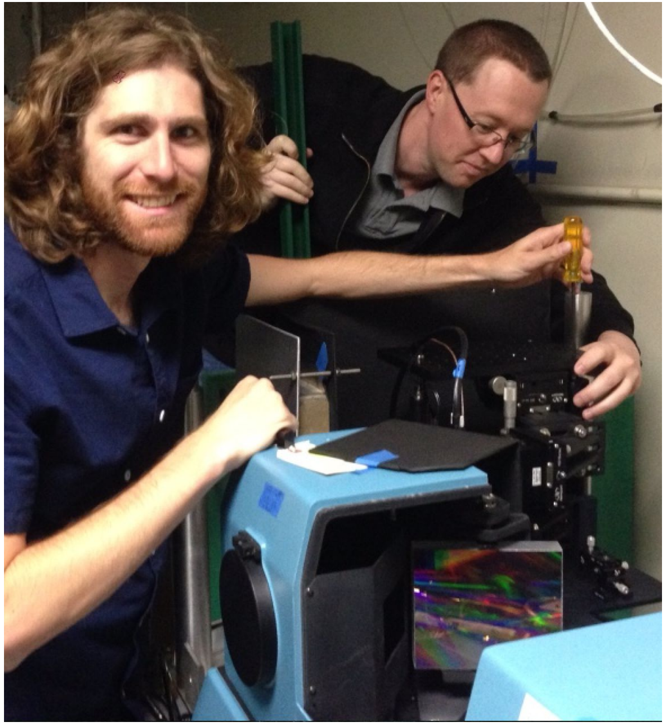
Direct and Local Impurity Density Measurements are Essential for Plasma Transport Studies

- DIII-D and NSTX have graphite first wal and measure fully stripped carbon emission
  - C-VI (8-7) 5290.5 Å
- Low-to-high confinement mode transition displays change in transport
- Accurate measure of impurity *density* and *spatial gradients* are essential for basic and advanced tokamak plasma physics
  - Neutral beam deposition, emission
  - Charge exchange from light impurities



Determining Plasma Ion Density is More Challenging Than the Temperature and Velocity

- Entire optical system must be absolutely calibrated
  - Mirrors, lenses, fiber optic cables, spectrometer and detector
  - Each component could be calibrated individually
  - → Permits replacement of single components during operation
- More convenient to perform a complete assembly; then calibrate the entire system as a whole



In situ Validation of Rate Coefficients is Challenging and Typically Requires Multiple Redundant Diagnostics

- "Direct" local ion densities from charge-exchange is the ideal end product measurement → Each step has uncertainty

$$\phi^l = \frac{1}{4\pi}\int dl \sum_{j,k} \underline{n_{b,k}^j \; n_i \; q_{CX}(v_b^j)} \quad + \textit{Plume emission}^1 \quad + \textit{Halo CX processes}^2$$

Total photons collected for sightline "*l*"

Path integral through neutral beam

Sightline passes through beam density n_b for beams "*k*" with species "*j*"=F,H,T

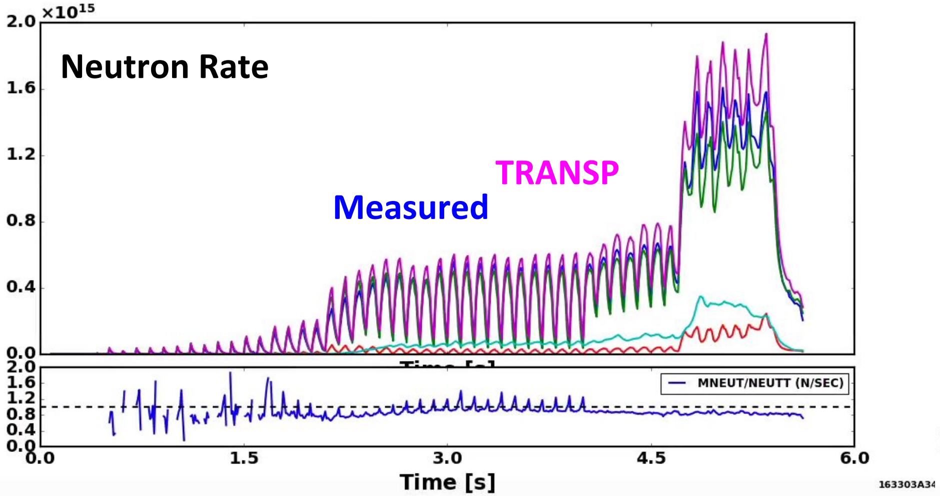
Charge-exchange reaction between

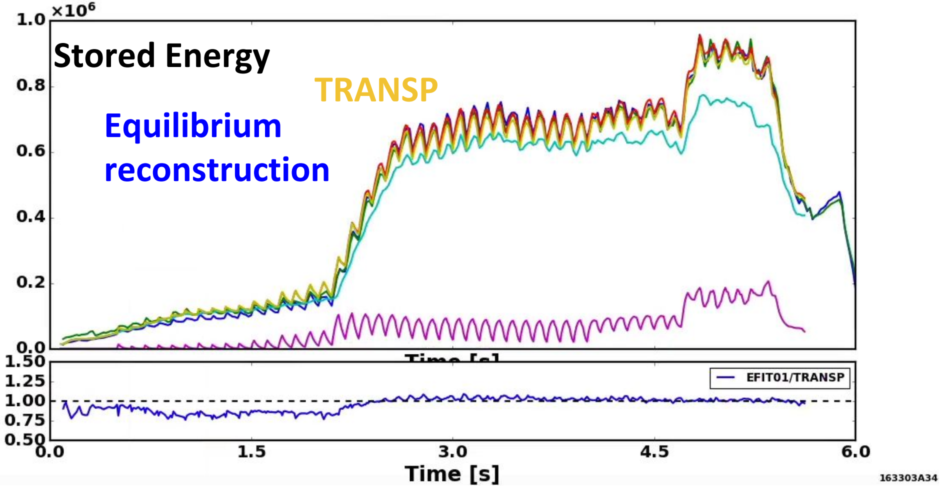
1. Beam neutrals n_b
2. Plasma ions n_i
3. Rate coefficient q

[1]R.E. Bell Rev. Sci. Instrum **77** (2006)
[2]R.M. McDermott PPCF **60** (2018)

Given All of the Uncertainties and Invocation of Novel Calibrations the Rate Coefficients for Carbon do not Appear to Be Egregiously Off

- Tokamak plasma physicist rely on accurate plasma composition/dilution measurements to assess confinement, instabilities, etc…
- Data consistency checks essential[1]→ survey spectroscopy, Zeff, CHERS

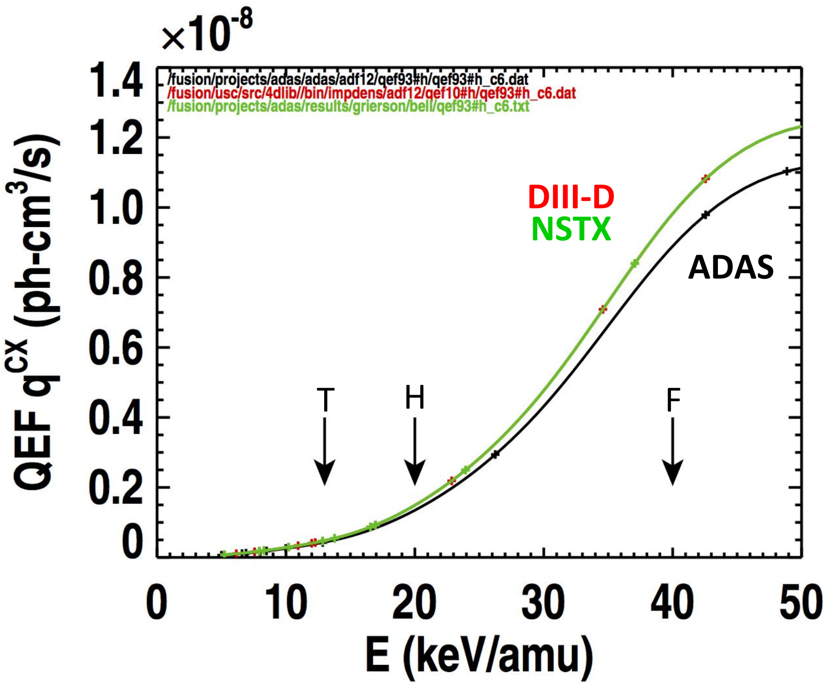




[1]B.A. Grierson FS&T (2018)

Rate Coefficients for C-VI (8-7) for n=1 and n=2 are the Same For DIII-D and NSTX

- A rate coefficient file is provided in the ADAS distribution
  - Black curve in plots
- DIII-D and NSTX staff have re-run ADAS to produce private adf12 files
  - J.M. Munoz-Burgos in 2010
  - V. Soukhanovskii in 2003



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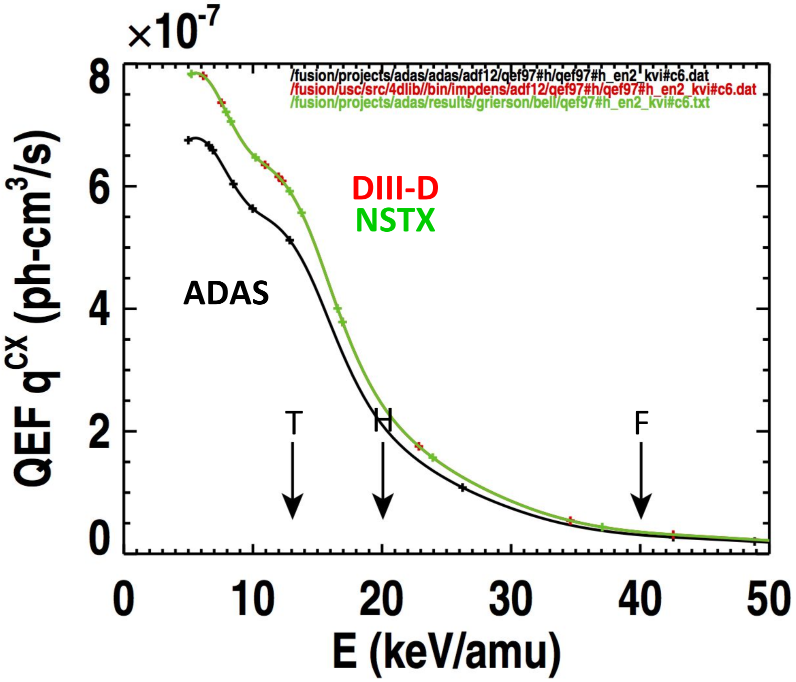
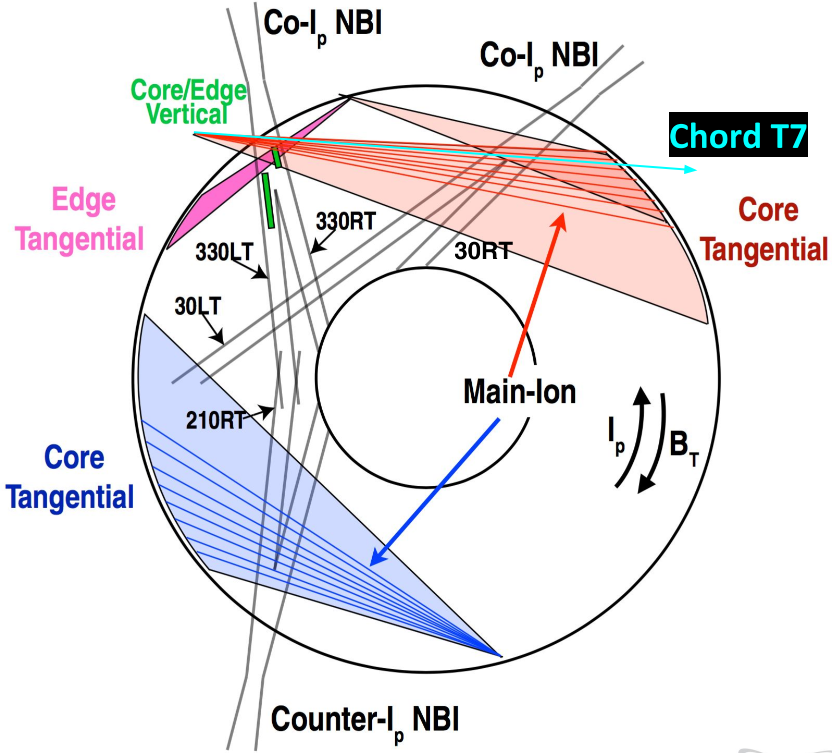


However Operation Away From Nominal Conditions Can Reveal Large Discrepancies Between Impurity Density Measured by CXRS

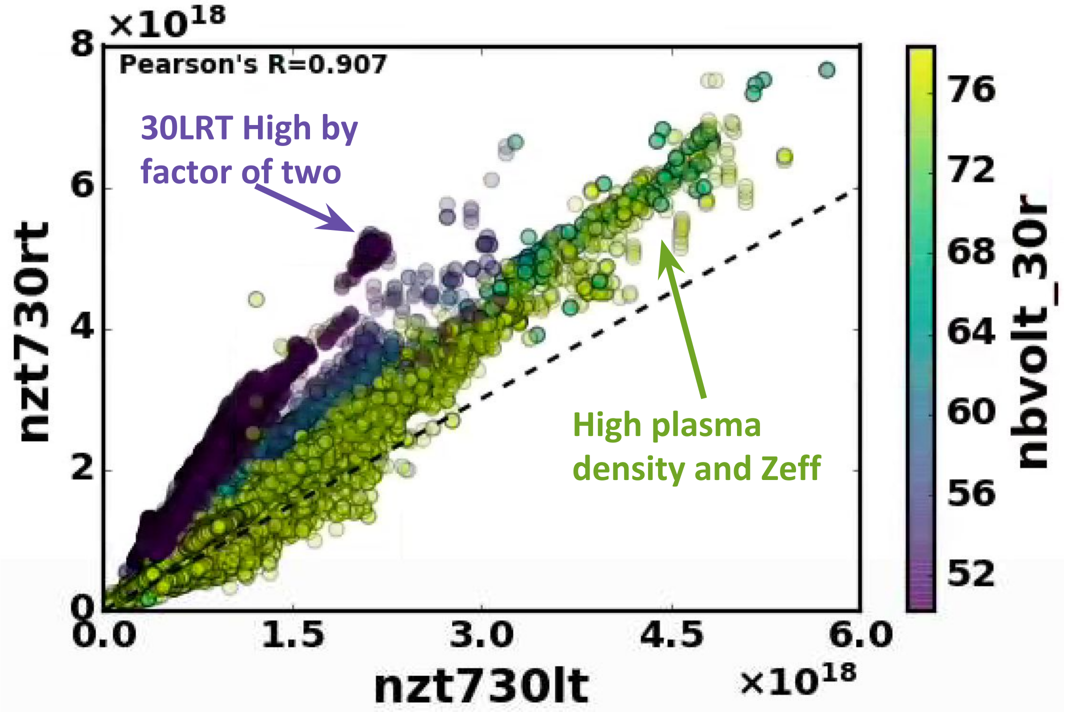
- Sightlines that cross two neutral beams provide opportunity to explore rate coefficients
- Consider one core tangential sightline *T7* viewing *30LT* and *30RT*
  - Same plasma flux surface
- We inject 30LT at its nominal voltage of 81 kV
  - Same voltage as absolute and relative calibrations
- Vary the voltage of 3RT
  - Move down from nominal 75 kV to 50 kV

Should measure same impurity density!



However Operation Away From Nominal Conditions Can Reveal Large Discrepancies Between Impurity Density Measured by CXRS

- Carbon density from T7 viewing 30LT at 81 kV is reference
- Carbon density computed from T7 viewing 30RT becomes erroneously high as 30RT voltage is varied from 50-75 kV
- Indicates that rate coefficient or other process is increasing intensity at C-VI (8-7) 5290.5



A Number of Contributing Factors Could Cause the Anomalously High Calculated Impurity Density

- Rate coefficient could be incorrect at low energy F/H/T of 25/12.5/8.3 keV/amu
  - Ground state n=1 rate small, n=2,... rates become large at low keV/amu
- Neutral beam power/species/geometry could be incorrect[1]
  - Neutral beams are calibrated with water flow calorimetry at few voltages
  - Species mix measurements only available on a few beams[2]
  - Neutral beam divergence may change with pulse as perveance is adjusted[3]
- Background emission becomes large relative to active emission and may require more careful background subtraction to remove contribution
- Other atomic processes such as plume emission, and excited halo neutral donors may become large

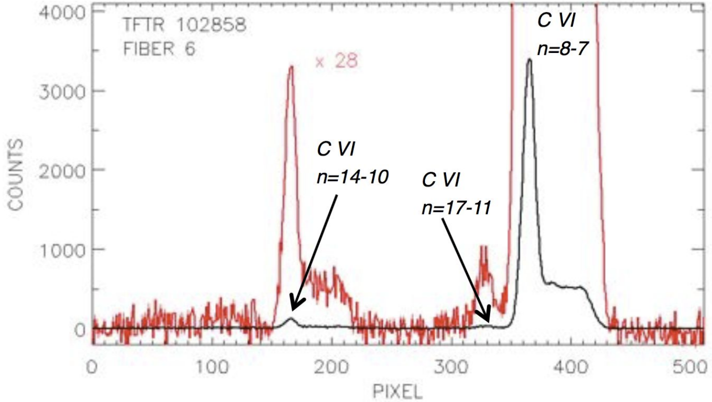
All of these processes are being considered and quantified

[1]W.W. Heidbrink NF **52** (2012)
[2]D.M. Thomas RSI **83** (2012)
[3]B.A. Grierson RSI **85** (2014)

Neither DIII-D nor NSTX Have or Use Contributions from n>2 Beam Neutrals for Determining Carbon Density

- Mentioned by D. Stotler at 2017 RCM1
- Previous work on TFTR[1] showed that emission ratios from C-VI 8-7, 14-10, 17-11 indicate population of high-n
- DIII-D has confirmed this measurement
  - More shown on later slides in this presentation on Li-III density

CX spectra obtained by subtracting pre-beam spectrum from post-beam turn-on spectrum.



- Assuming fully mixed levels, the TFTR measurements imply that the *n*=14 and *n*=17 levels are more populated by charge exchange with the neutral beams that the *n*=8 level

[1]R. Bell, APS-DPP (2014)

Neither DIII-D nor NSTX Include Photoemission from Halo Neutral CX with Impurity Ions

- Beyond direct charge-exchange [$D_b^0(n) + C^{+5}$] there can be halo neutrals as a source of CX with low energy and n>1

  $$D_{th}^0(n) + C^{+6} \rightarrow D_{th}^+ + C^{+5}(n')$$

- Conditions most sensitive to this process will be high density plasmas with high plasma purity
  - High density → strong beam attenuation minimizes n_b
  - High purity → large population of halo neutrals
- ASDEX-Upgrade recently implemented calculations and corrections for this process → Reduces peaking of impurity density profile[1]

[1]R.M. McDermott PPCF **60** (2018)

Interim Summary

- Both NSTX and DIII-D use the same rate coefficients for n=1 and n=2 donors for CX onto fully stripped carbon
- This procedure produces reasonable data consistency checks for nominal tokamak operation
  - Carbon is overwhelmingly dominant impurity in most conditions
  - Neutron rates and stored energy in reasonable agreement
  - Bremsstrahlug emission consistent[1]
- There are known shortcomings in existing analysis of unquantified impact
  - Higher n-level donors for CX, multi-step halo neutrals

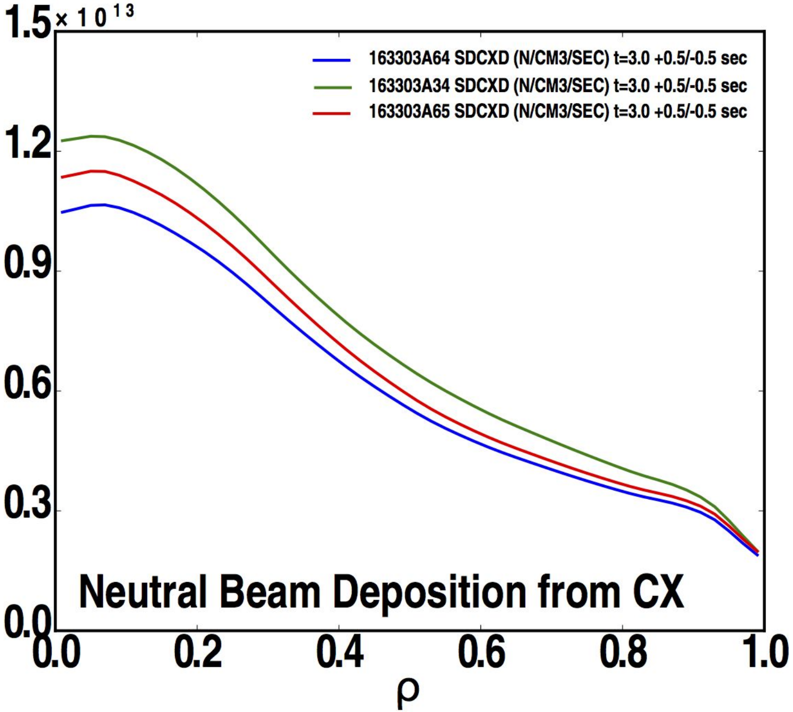
[1]K. Callahan APS-DPP (2018), ECPD (2019)

TRANSP/NUBEAM and FIDASIM

Recommended Settings for NUBEAM Atomic Data Usage

- Tokamaks are now suggested to use full ADAS atomic data for NUBEAM in TRANSP
  - `LEV_NBIDEP = 2` $\longrightarrow$ All ADAS atomic physics
  - `NSIGEXC = 3` $\longrightarrow$ Excited states, stopping cross-sections from ADAS 310 (in appendix of D.P. Stotler RCM1)
- In high density plasmas the enhancement to the stopping cross-section from excited states can be significant
- For typical operating voltages and densities the impact on beam heating appears relatively minor

Comparison of Simple and ADAS Excited States Shows 10-15 % Differences for Moderate DIII-D Density



- DIII-D daily reference shot with $\langle n_e \rangle$ 5.7 e19
- Compare three TRANSP runs
  - LEV_NBIDEP=1 (ground), NSIGEXC=1 (simple)
  - LEV_NBIDEP=2 (ADAS), NSIGEXC=1 (simple)
  - LEV_NBIDEP=2 (ADAS), NSIGEXC=3 (ADAS)
- Ground state with simple excitation is the weakest stopping from CX
- All three give comparable total stopping, power flows and neutrons for this moderate density

FIDASIM Proton CX Data Includes Higher-n Levels

- FIDASIM is fully documented [online]

- Use “equivalence principle” to obtain reverse reactions for data available in ADAS

$$\sigma(n_f \rightarrow n_i) = \frac{E_i}{E_f}\frac{n_i^2}{n_f^2}\sigma(n_i \rightarrow n_f)$$

- Data from JRS-4105 used to fill out table
- Cross sections summed over m → “spread” out assuming exponential variation with energy difference

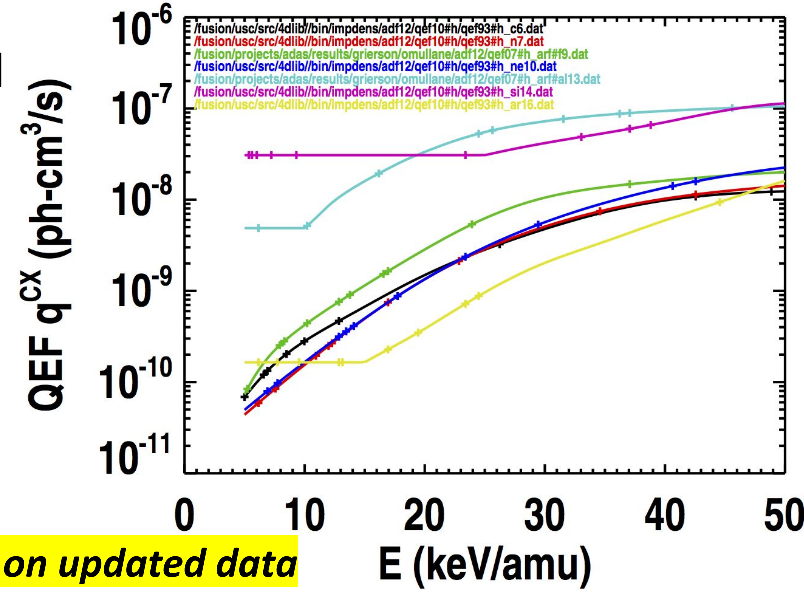
H-H Charge Exchange Data Source

n \ m	1	2	3	4	5	6	Total
1	ADAS	ADAS	ADAS	ADAS	Spread	Spread	Janev(n=1)
2	Equivalence	ADAS	ADAS	Spread	Spread	Spread	Janev(n=2)
3	Equivalence	ADAS	ADAS	ADAS	ADAS	Spread	ADAS/Janev(n=3)
4	Equivalence	Equivalence	Equivalence	Spread	Spread	Spread	Janev(n=4)
5	Spread	Equivalence	Equivalence	Spread	Spread	Spread	Janev(n=4)
6	Spread	Equivalence	Equivalence	Spread	Spread	Spread	Janev(n=4)

Other Impurities

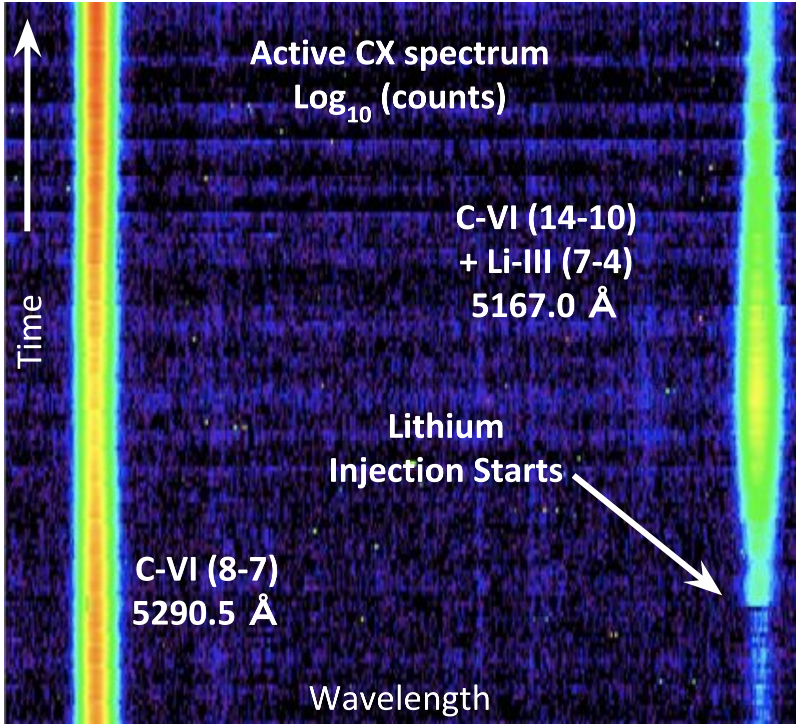
DIII-D is Expanding the Use of a Range of Impurities for Charge-Exchange

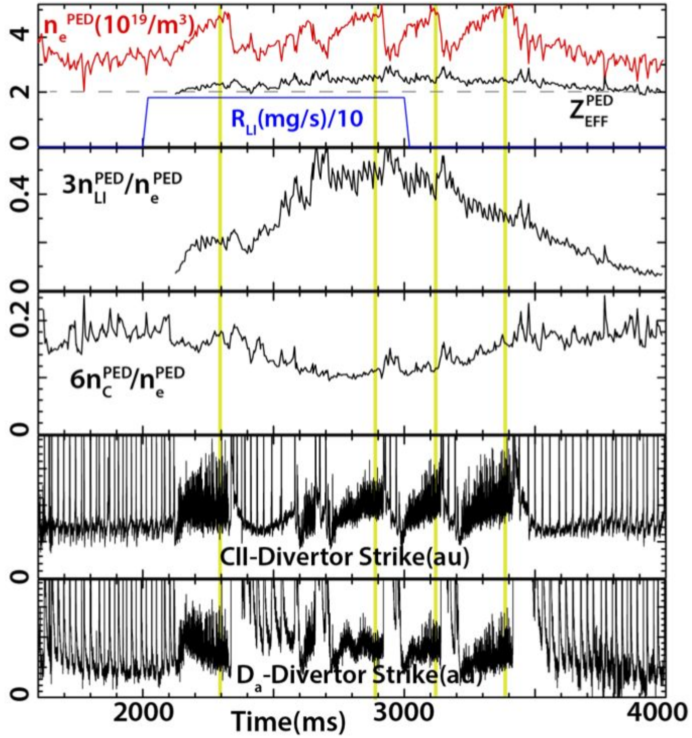
- Recent increased emphasis on impurity transport including installation of laser blow-off by MIT
- Some recent impurities that have been used
  - Nitrogen (Z=7) N-VII(9-8) 5669.0
    - Rate from ADAS, updated by J.M. Munoz-Burgos
  - Fluorine (Z=9) F-IX(10-9) 4796.0
    - Rate from M. O'Mullane July 12 2013
  - Neon (Z=10) Ne-X(11-10) 5249.2
    - Rate from ADAS, updated by J.M. Munoz-Burgos
  - Aluminum (Z=13) Al-XIII (12-11) 4083.8
    - Rate from M. O'Mullane Feb. 23 2018
  - Silicon (Z=14) Si-XIV (12-11) 3521.1
    - Rate from ADAS
  - Argon (Z=18) Ar-XVI (14-13)
    - Rate from ADAS



Need guidance on updated data

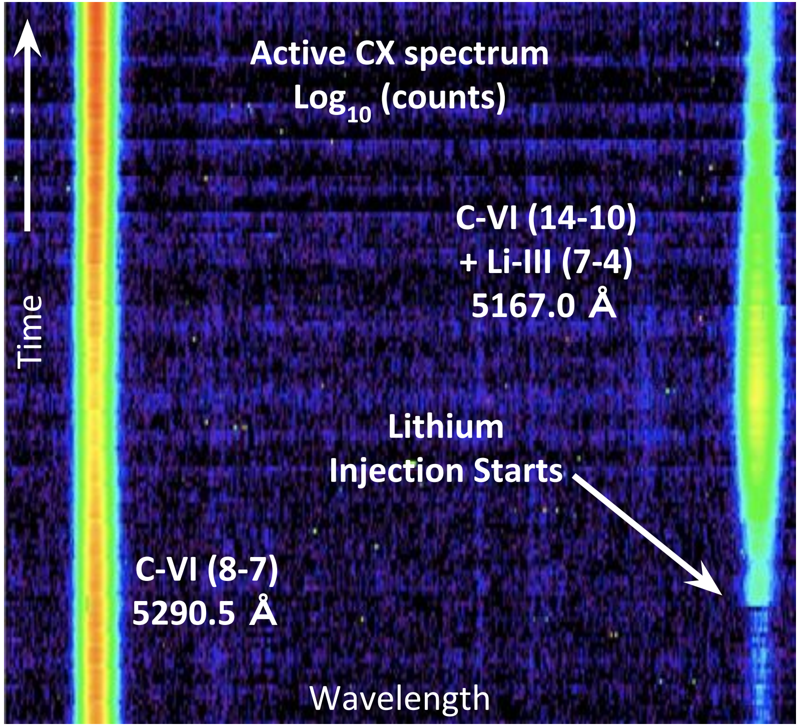
Combined C-VI(8-7) C-VI(14-10) and Li-III (7-5) Being Used with Wide Wavelength Spectrometer





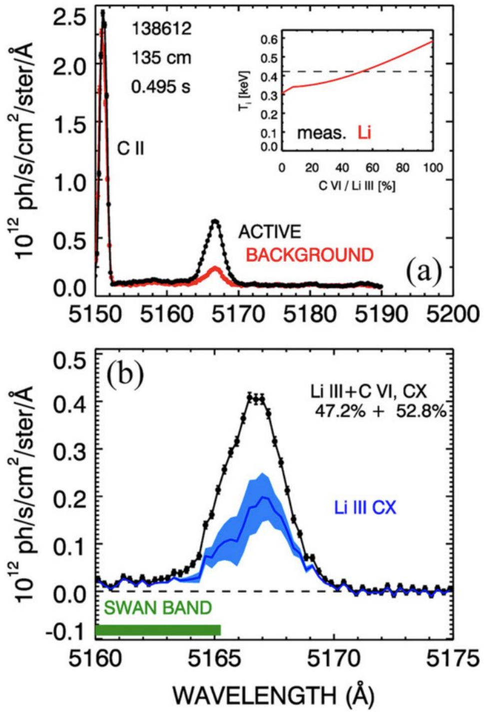
Osborne, et. al. Nucl. Fusion **55** (2015)

Combined C-VI(8-7) C-VI(14-10) and Li-III (7-5) Being Used with Wide Wavelength Spectrometer



- By measuring both C-VI (8-7) and C-VI (14-10) on same sightline/spectrometer/CCD we can remove the C-VI contribution to emission at Li-III(14-10)
- Enables measurement of absolute lithium density
- This ratio $B_{14\text{-}10}/B_{8\text{-}7} \approx 1/30$
  - Close to R. Bell 1/28 and is higher than expected using only n=1,2 donors

NSTX Uses Dual Systems to Determine Li Density[1]

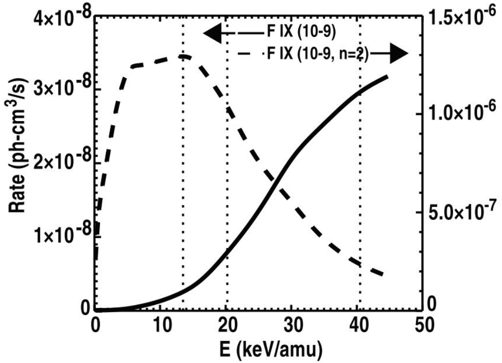


- The lithium-poloidal-CHERS (Li-pCHERS) spectrometers measure wavelength range 5145–5180 Å
- Second set of pCHERS view C-VI emission interleaved with the Li-pCHERS views
  - Views looking at the same portion of the plasma share the same optics
- 25% uncertainty in Li brightness
  - Major source of uncertainty is caused by the C-VI(14-10) transition

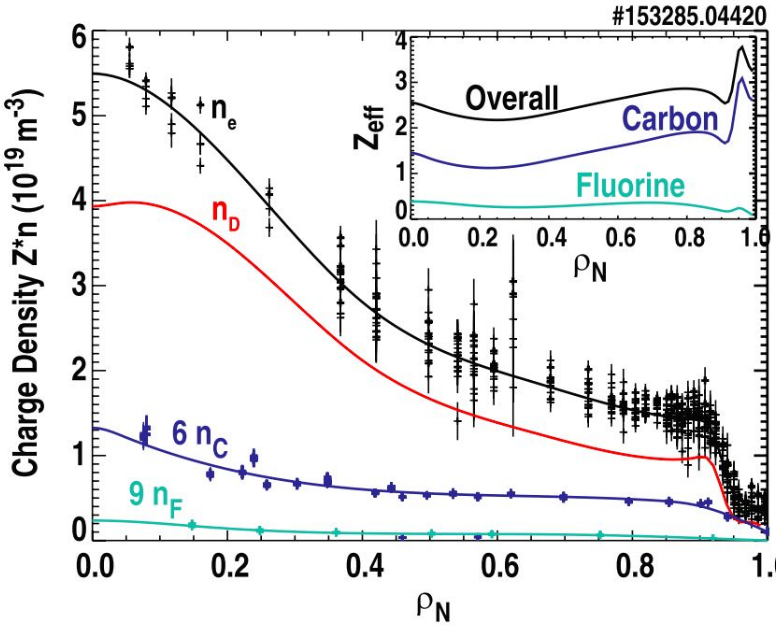
[1]M. Podesta Nucl. Fusion **52** (2012)

Fluorine Has/Will be used for Impurity Confinement and Transport Studies

- Carbon tetraflouride (CF_4) gas has been used for non-intrinsic non-recycling impurity
- LBO now injecting F from CaF2



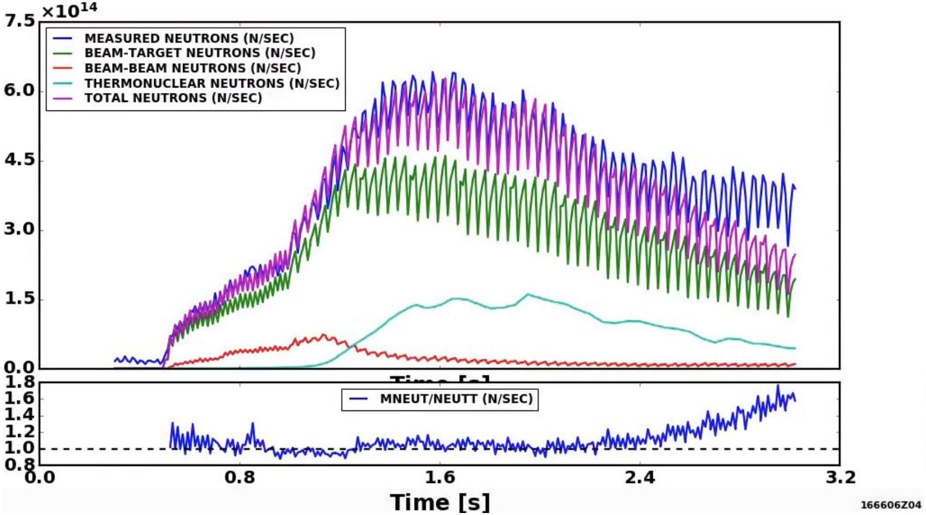
- Rate coefficients from M O'Mullane

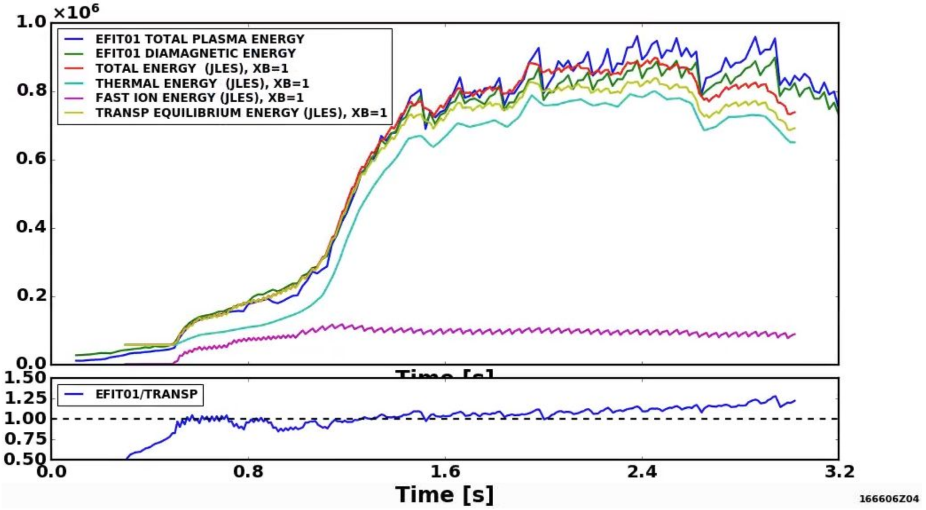


Grierson, et. al. Nucl. Fusion **54** (2014)

When Nitrogen is Injected into DIII-D the Deduced Nitron Density Appears Too High by Factor of Two

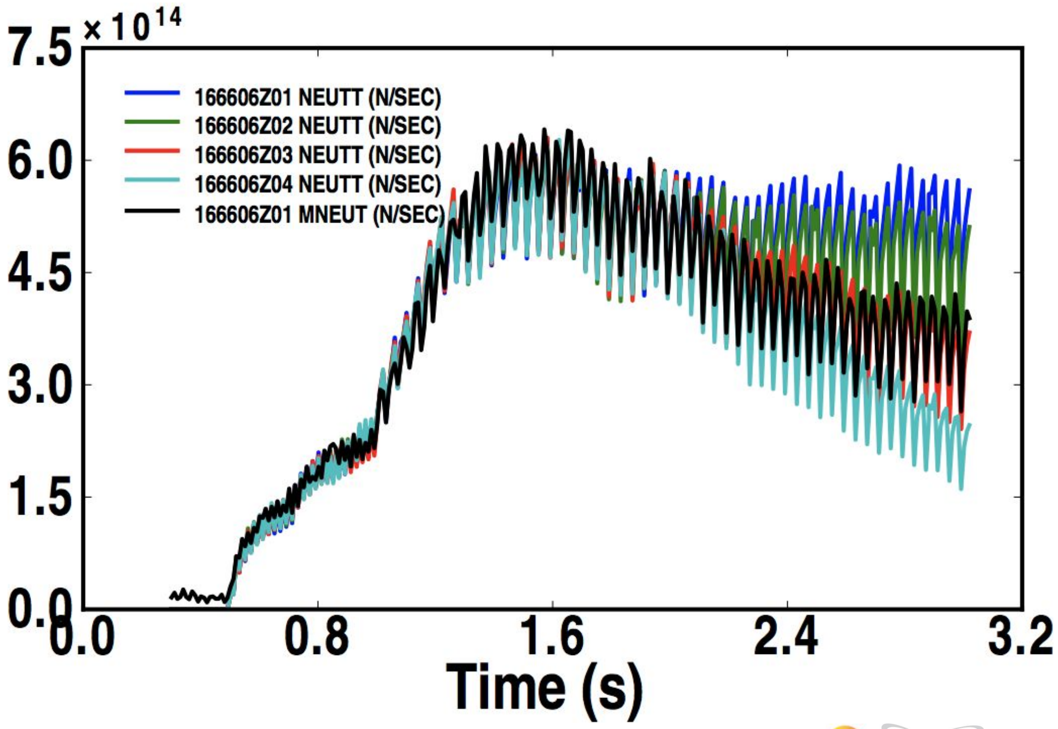
- N-VII(9-8) line at 5669.0 used, impurity profile measured and put into TRANSP runs for neutrons and stored energy





By Scaling the Measured Nitrogen Density Before Running TRANSP we Estimate Density Error

- TRANSP first run with measured n_N profile shape
- Re-run with scale factors to determine best match
- When CER determined n_N profile is cut in half then neutron rate agrees
- Careful analysis by T. Osbrone matching neutrons and stored energy indicates this is generally true for Nitrogen
  - Is there something different about nitrogen than C, Ne?



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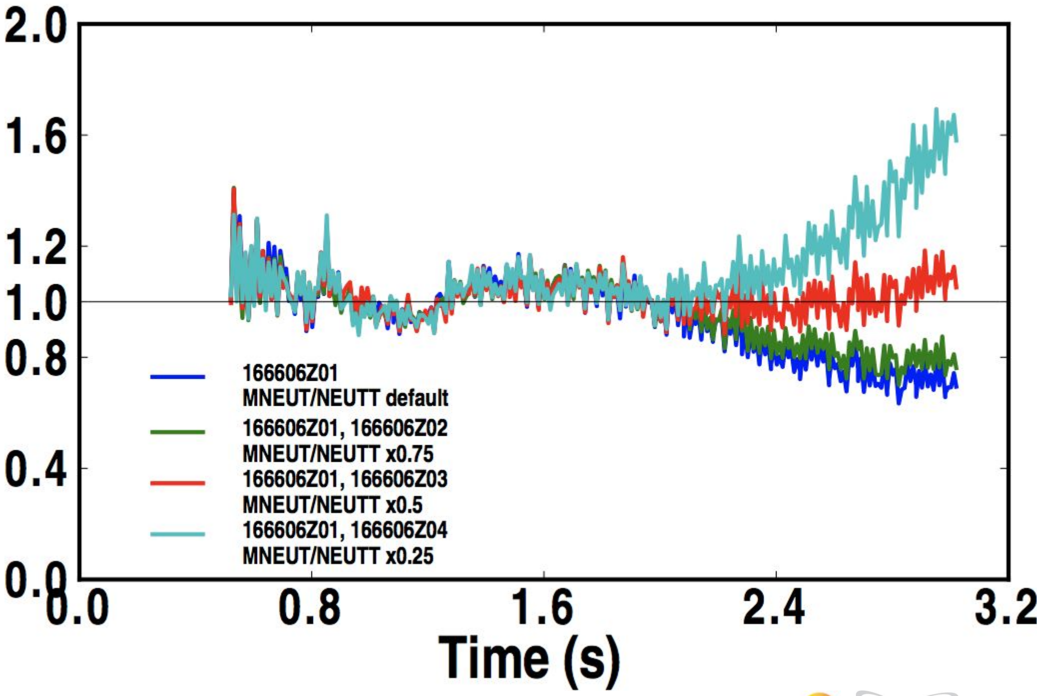
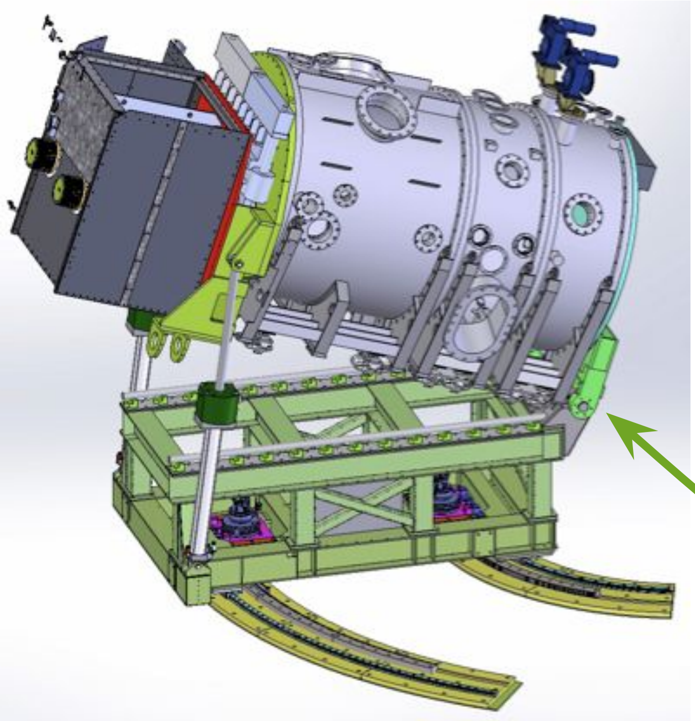


Future/Conclusions

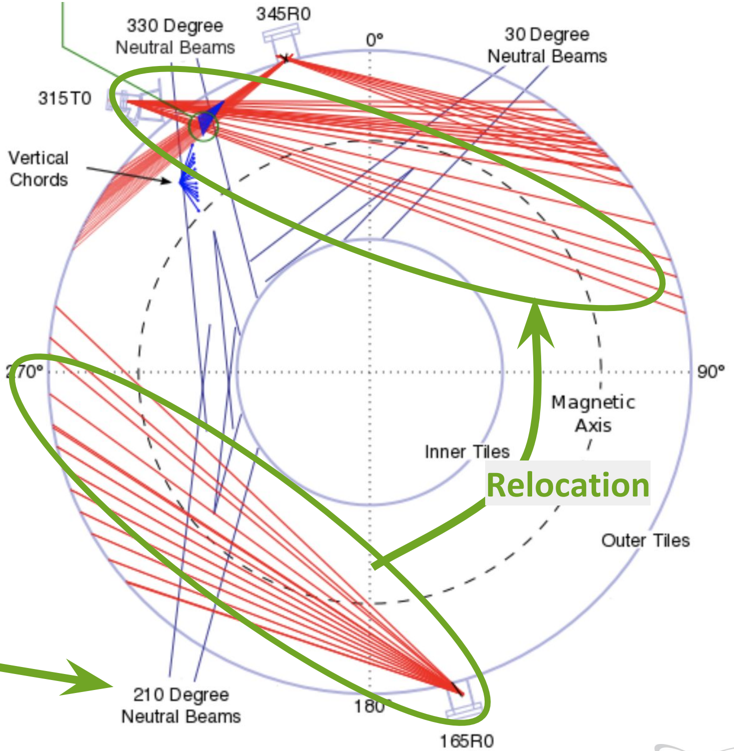
DIII-D is Upgrading CER for High-field Side Measurements



210 degree neutral beam being elevated off-axis and now steerable for co/ctr injection

CER system channels for main-ion and impurity systems being relocated for HFS measurements

Enables beam emission over longer path length



Conclusions

- NSTX and DIII-D are using the same n=1 and n=2 rate coefficients for C-VI(8-7)
- Both TFTR and DIII-D have determined ratio of C-VI $B_{14\text{-}10}/B_{8\text{-}7} \approx 1/28$
  - Knowledge being used when determining Li density
- Concern over low energy NBI operation, n>2 processes, and inconsistencies with nitrogen data
- We expect to discuss these issues and make progress through this NB CRP in future RCMs

Acknowledgement

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