Measuring the Ion Temperature, Rotation, and Density: Impurity and Main-Ion Charge Exchange Recombination Spectroscopy

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PRINCETON PLASMA PHYSICS LABORATORY

Introduction to charge exchange recombination spectroscopy (CER/CHERS/CXRS/…)

Typical Physics Applications

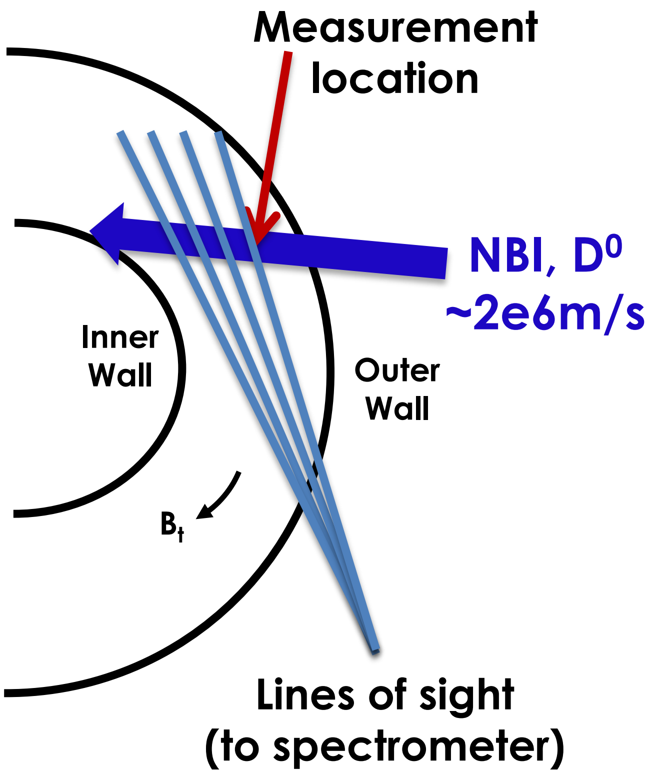
Some finer details: Cross section distortions

Main-ion CER (MICER)

Example main-ion measurements

Charge Exchange Recombination Spectroscopy (CER) is Used to Measure Ion Properties on Most Magnetic Confinement Experiments[1,2]

- Neutral beam injector atom exchanges an electron with an ion species (charge exchange), electron may be in an excited state:
  - $D^0 + A^{+Z} \rightarrow D^+ + A^{+(Z-1)}(n_H)$
- Species emits spectral light through spontaneous emission
  - $A^{+(Z-1)}(n_H) \rightarrow A^{+(Z-1)}(n_L) + \Upsilon$
- Light is collected and analyzed with a spectrometer and camera (counts vs wavelength [pixel])



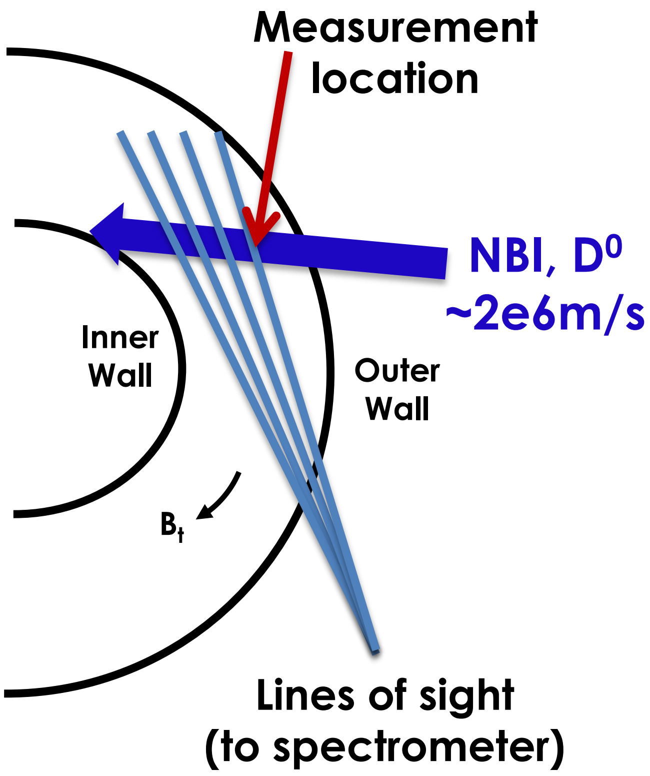
[1] R.J. Fonck, *Phys. Rev. A*,1984
[2] R. Isler, *Plas. Phys. Cont. Fus.*, 1994

Charge Exchange Recombination Spectroscopy (CER) is Used to Measure Ion Properties on Most Magnetic Confinement Experiments[1,2]

- **The collected light is Doppler shifted by the velocity of the emitting atom/ion**
  - Information about the ion distribution function is encoded onto the spectral line "carrier"

- **Allows spectral emission from hotter regions of the plasma by donating an e- to low Z ions which would otherwise be fully stripped**
  - Can use intrinsic impurity (i.e C6+ in C wall machines), introduced impurities, or main ions (D+)

- **Measurement for each line of sight/chord is radially localized to beam-chord intersection**
  - Profiles without tomographic inversion



[1] R.J. Fonck, *Phys. Rev. A*,1984
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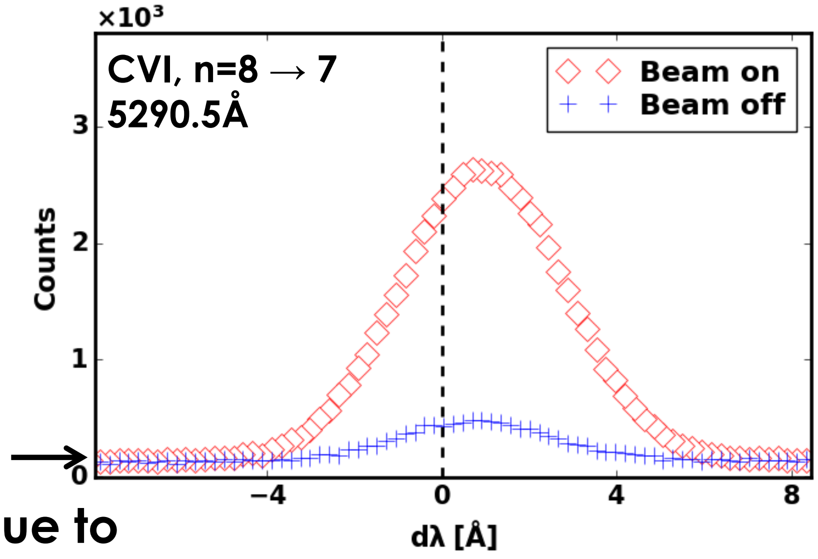
Impurity Ions Have Been Used For CER since the 80s Providing Accurate Local Impurity Ion Temperature, Rotation, and Density Measurements

- **Time slice subtraction isolates active emission**
- **A Gaussian is fit to the active emission**
  - Doppler shift: Velocity/Rotation
  - Doppler broadening: Temperature
  - Radiance: Impurity density
- **Essentially imaging the distribution function at a specific location, and in a certain direction (along LOS)**



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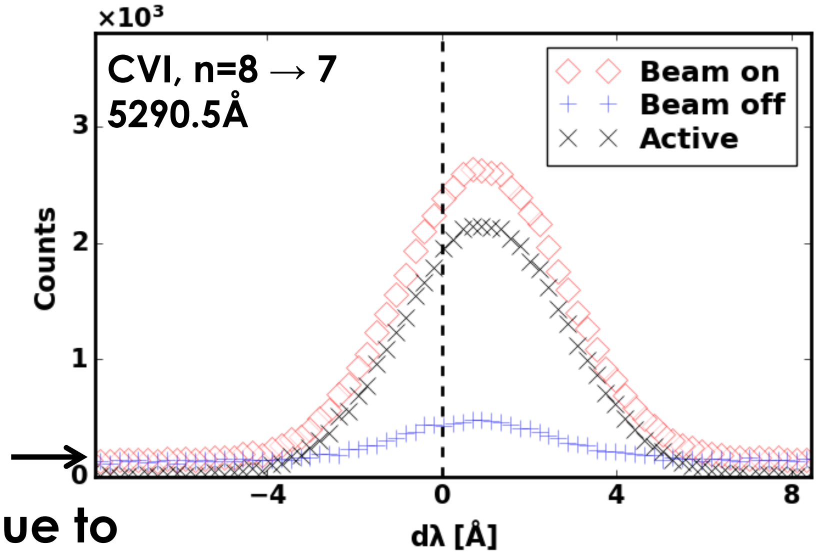

Offset due to Bremsstrahlung

∝ ion vel along LOS

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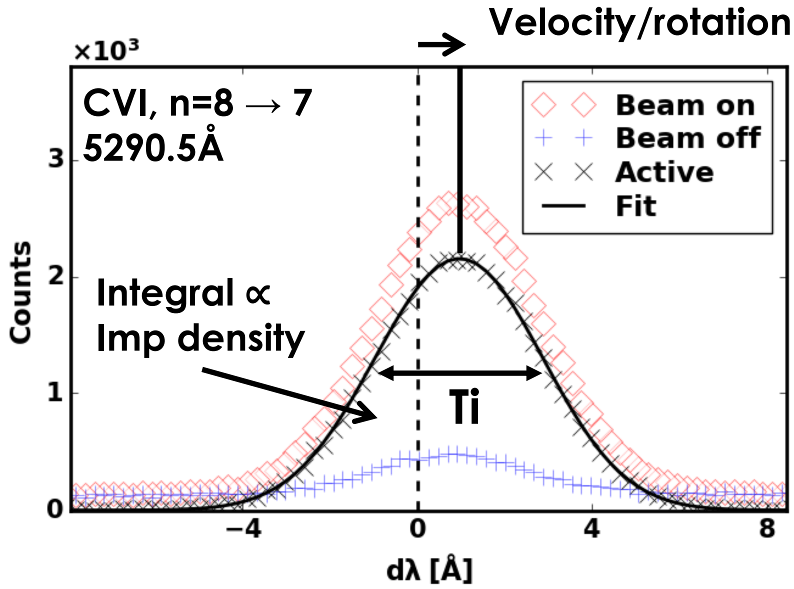
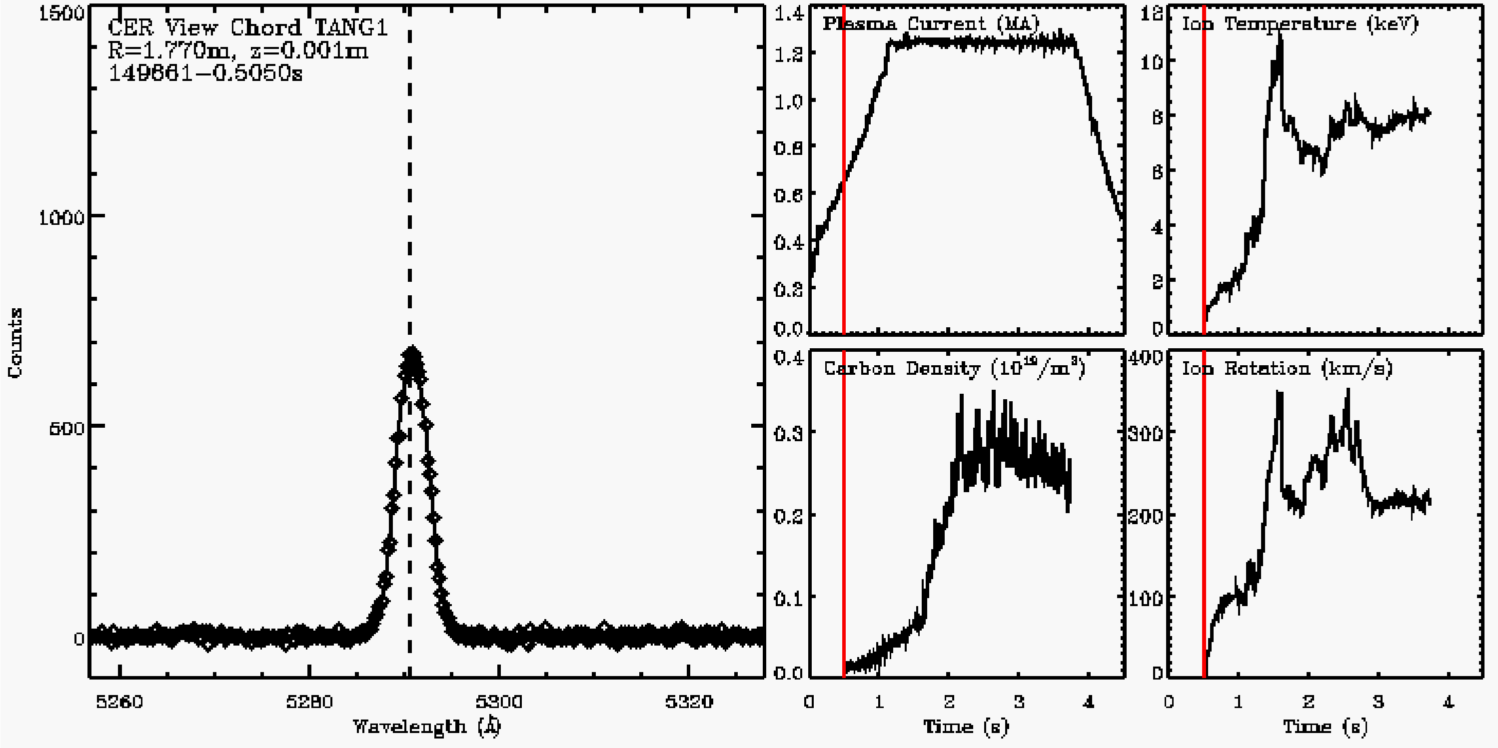


∝ ion vel along LOS

1Å=0.1nm [~diam of H atom]
(1Å/5290Å) c ~= 60km/s

Example Spectrum from a Single Channel During a Typical Discharge



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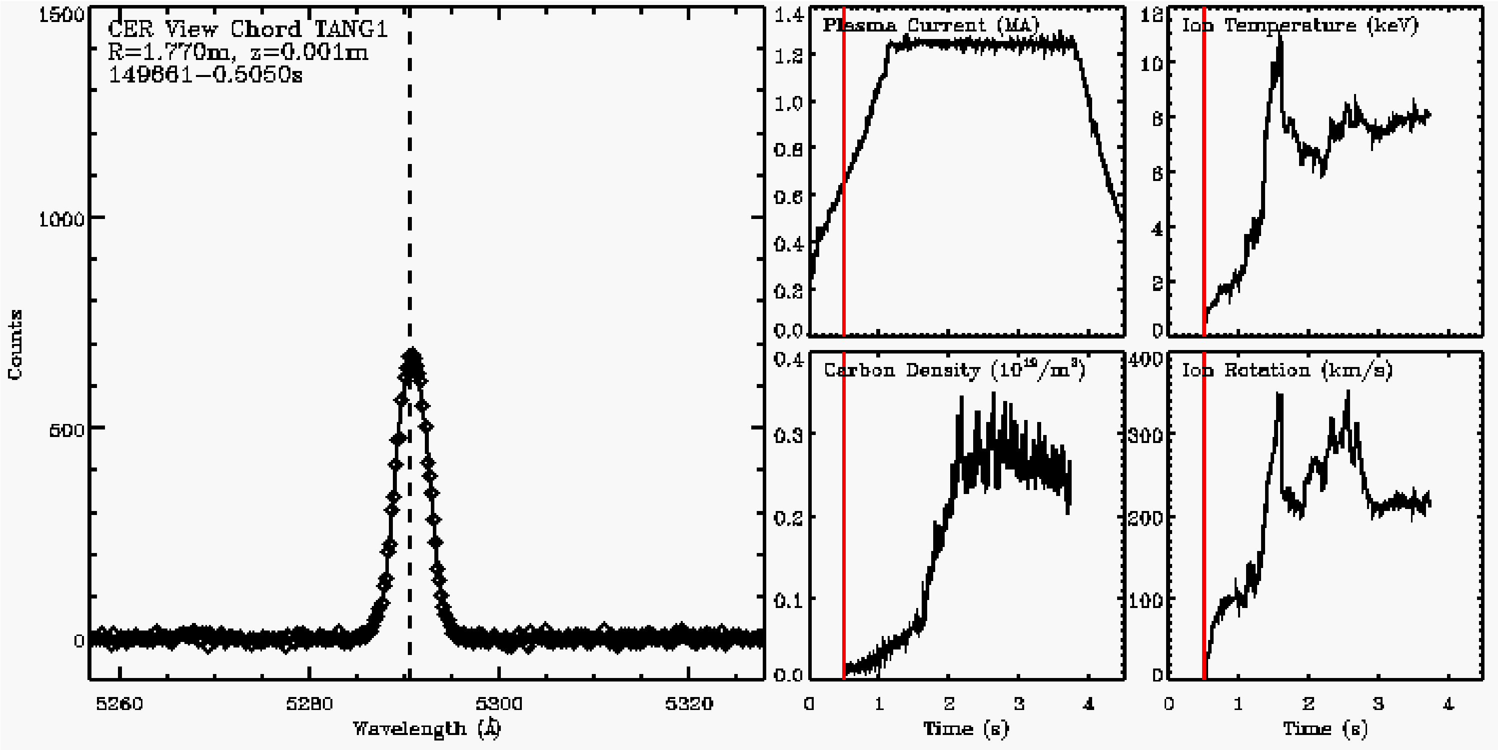
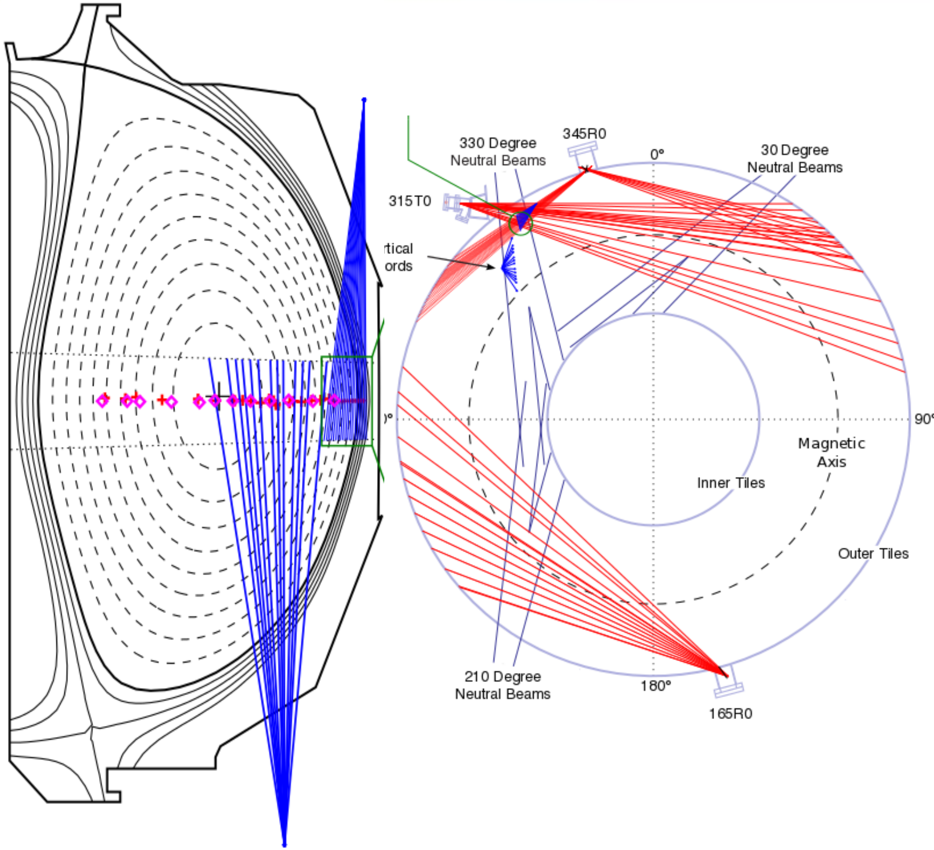


CER Systems are Extensive on Most Magnetic Confinement Machines

- **For example on DIII-D**
  - 16 scanning spectrometers (350-800nm)
  - 32 cameras
  - 112 channels: 48 impurity tangential, 32 impurity vertical, 32 main-ion
- **One of the 'always on' diagnostics**
  - Variable integration time down to 0.2ms, 5ms typical
  - 4 levels of analysis depending on speed/accuracy tradeoff: realtime (control), between shots, over night, manual



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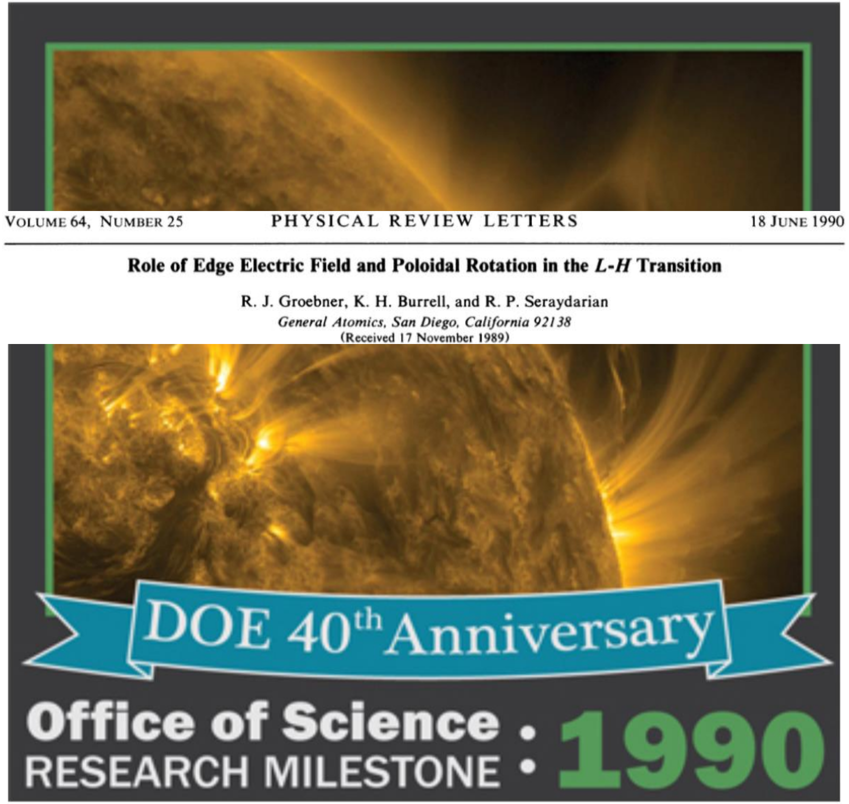
CER Measurements are a Cornerstone of many Physics Research Areas

- **Transport model validation**
- **Impurity transport**
- **Rotation**
  - Momentum transport
  - Poloidal rotation
  - Intrinsic rotation
- **Radial electric field – ExB shear suppression of turbulence**
  - L-H transition, internal transport barriers
- **…**



The Radial Electric Field can be Inferred using CER Measurements

- **Momentum conservation equation for a species 'a' (i.e C6+)**

$$m_a n_a \frac{d\vec{V}_a}{dt} = -\nabla p_a - \nabla \cdot \vec{\pi}_a + Z_a e_a n_a (\vec{E} + \vec{V}_a \times \vec{B}) + \vec{R}_a$$

- **Take the radial component, neglect convective derivative, interspecies friction, and divergence of viscosity tensor. Radial pressure gradient is balanced by the radial component of the EM forces on a fluid element of the species:**

$$\frac{\partial p_a}{\partial r} = Z_a e n_a [E_r + (\vec{v}_a \times \vec{B})_r]$$

- **We can rearrange to get an equation that tells us how to measure Er:**

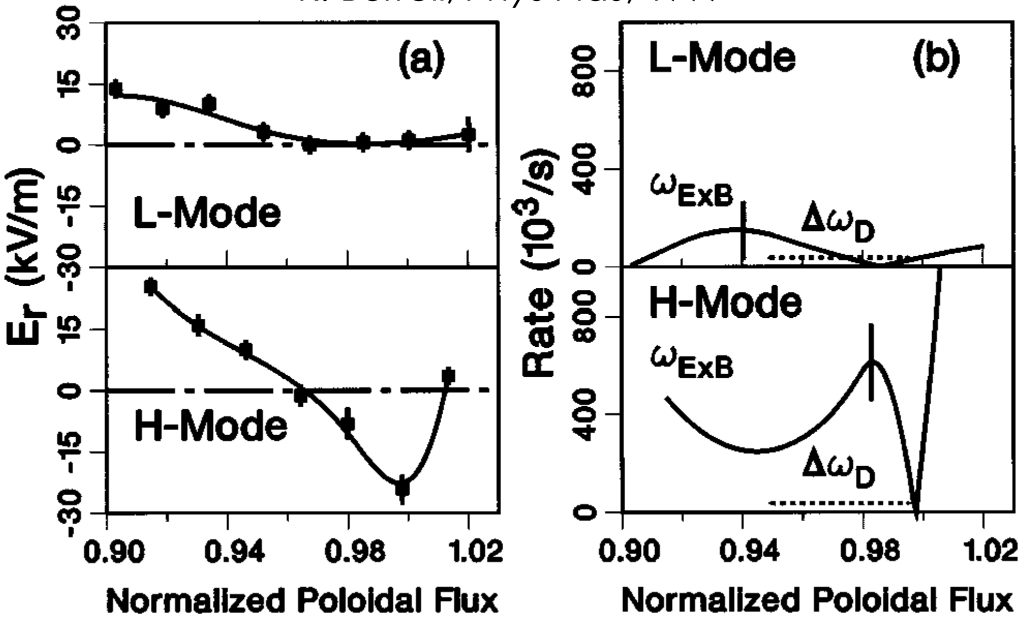
$$E_r = \frac{1}{Z_a e n_a} \frac{\partial p_a}{\partial r} - v_{\theta,a} B_\phi + v_{\phi,a} B_\theta$$

- **CER measures density and temperature profiles, and poloidal and toroidal rotation for a single species at the outboard midplane, can infer Er**

Large Changes in the Radial Electric Field Shear are Associated with Enhanced Confinement Regimes, H-mode, ITBs, etc..

- **ExB drift velocity is special – same for all species**
  - Turbulence is advected with this velocity
- **Radial shearing in Er leads to a sheared ExB velocity**
  - Decorrelation and suppression of certain types of turbulence (i.e ITG), eddys are 'torn apart'
  - Large improvement in confinement
- **Exact mechanism behind the triggering of the L-H transition is still not fully understood**
  - Ion orbit loss, poloidal rotation, Reynolds stress, predator-prey – see review articles[1,2]

K. Burrell, *Phys Plas*, 1997



[1] J. Connor, *Plas. Phys. Cont. Fus.*, 2000
[2] L. Schmitz, *Nuc. Fus.*, 2017

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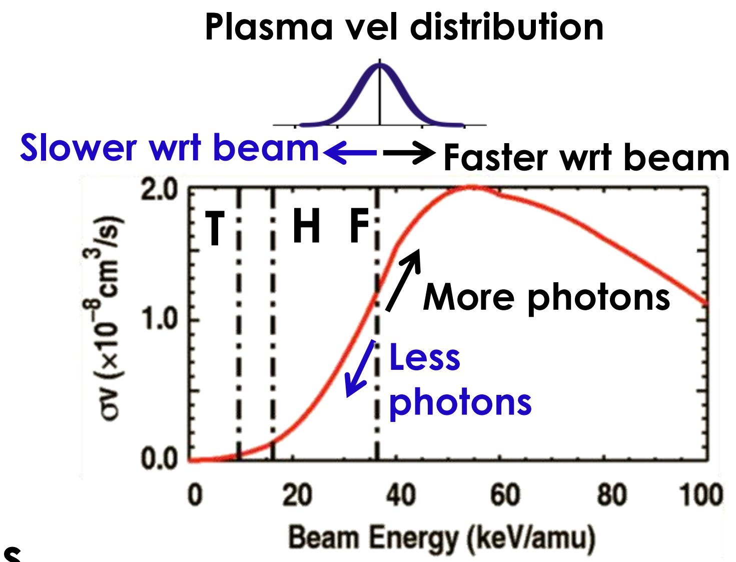
Cross Section Effects or "One of the Ways the Plasma Likes to Trick Us"

- **So far we have assumed there is a direct linear mapping between the ion distribution function and the spectrum**

- **However, probability of charge exchange depends on the relative speed of the 2 interacting species**
  - Cross section: $\sigma(v')$, $v' = |\mathbf{v_1} - \mathbf{v_2}|$
  - Source for excited particles [/s/m^3] $n_1 n_2 \langle\sigma(v')\, v'\rangle$

- **This can lead to incorrectly inferred velocities (and temperatures) due to distortion of the C5+ distribution relative to the C6+ distribution**

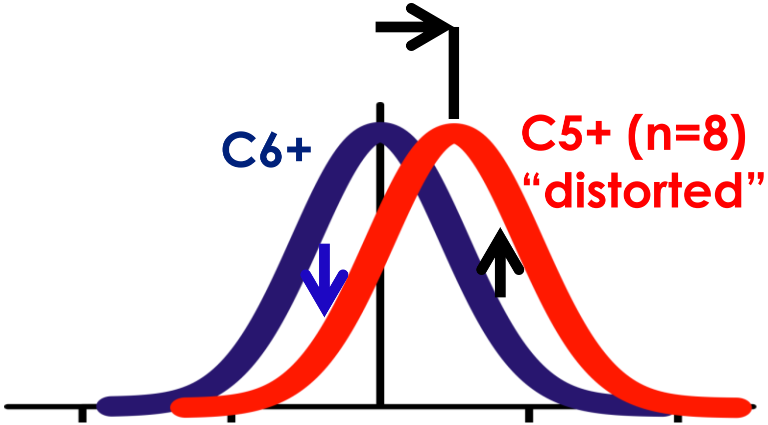


$D^0(n=1) + C^{+6} \rightarrow D^+ + C^{+5}\ (n=8)$

Cross Section Effects or "One of the Ways the Plasma Likes to Trick Us"

- **In reality more complex because of multiple beam energies**
- **Worse at higher temperatures, sampling more of the cross section curve**
- **Can correct using measurements on beams injecting in opposite directions**
  - Cross section effect cancels when combined
- **Typically corrected using a lookup table**

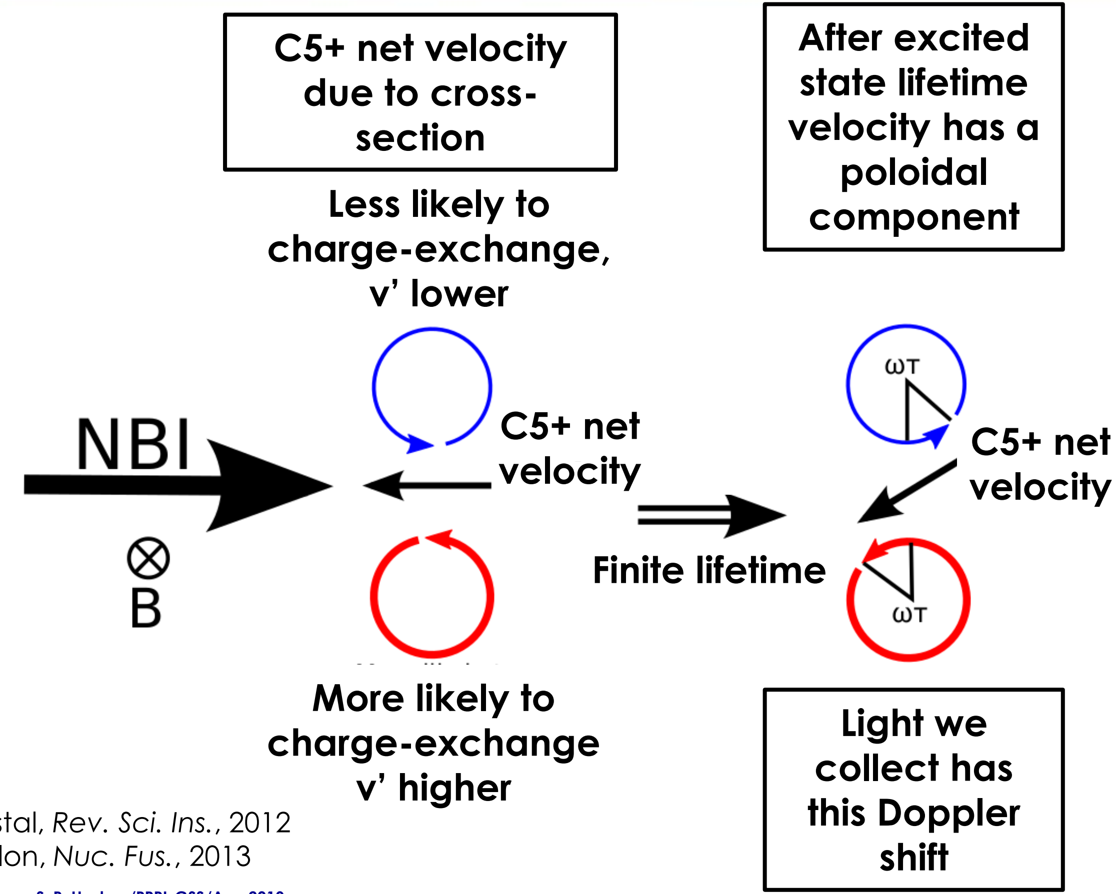
Velocity error due to combination of thermal motion and cross section gradient



Poloidal Rotation Corrections - Cross Section + Finite Lifetime + Gyro-orbit

- **Poloidal rotation measurements are very tough**
  - Trying to measure a few km/s
- **Rotation can couple into the poloidal rotation measurement**
  - Cross section
  - Gyro-orbit
  - Finite lifetime of excited state
- **Can correct using multiple views[1], modeling[2], HFS/LFS toroidal measurements[3,4]**

[1] R. E. Bell, *AIP Conf. Proc.*,2000
[2] W. Solomon, *Phys. Plas.*, 2006
[3] C. Chrystal, *Rev. Sci. Ins.*, 2012
[4] A. Bortolon, *Nuc. Fus.*, 2013



What if the Impurities have Different Properties to the Main-Ions (D+)?

- **We expect the rotation to be different where there are large pressure gradients**
  - Important for momentum transport, intrinsic rotation

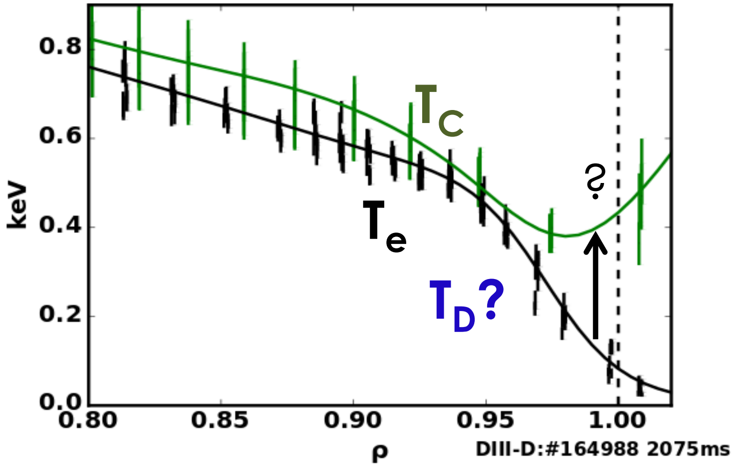
- **Temperatures can deviate in the core (weaker coupling), what about the edge?**
  - Orbit and atomic physics effects near the edge?
  - Sometimes the impurity temperature goes up near the boundary – does this represent the main-ions?

Species independent

Species dependent

$$\boxed{E_r} = \boxed{\frac{\nabla P_c}{Z_c e n_c}} - \boxed{v_{\theta,c}} B_\phi + \boxed{v_{\phi,c}} B_\theta$$

$$v_\phi^D - v_\phi^C = \frac{1}{B_\theta}\left(\frac{\nabla P_C}{6 e n_C} - \frac{\nabla P_D}{1 e n_D} + B_\phi[v_\theta^D - v_\theta^C]\right)$$



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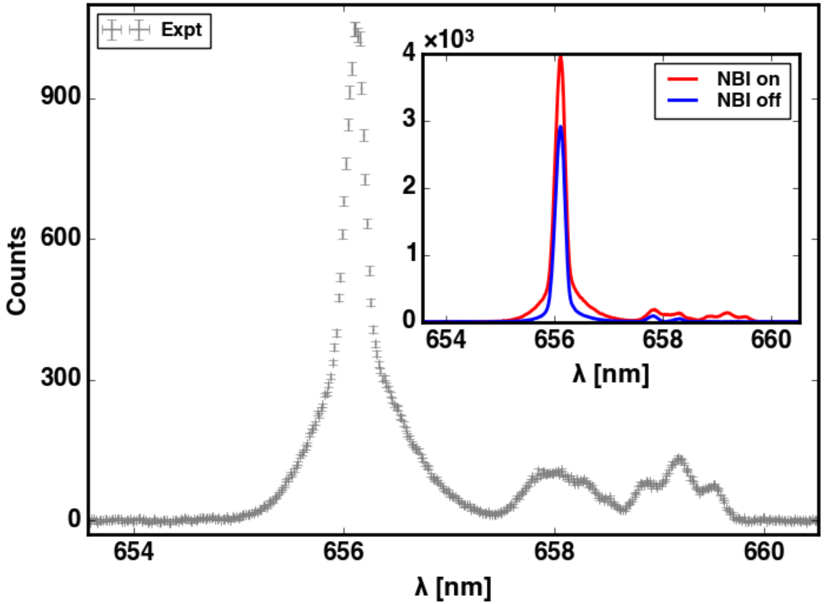
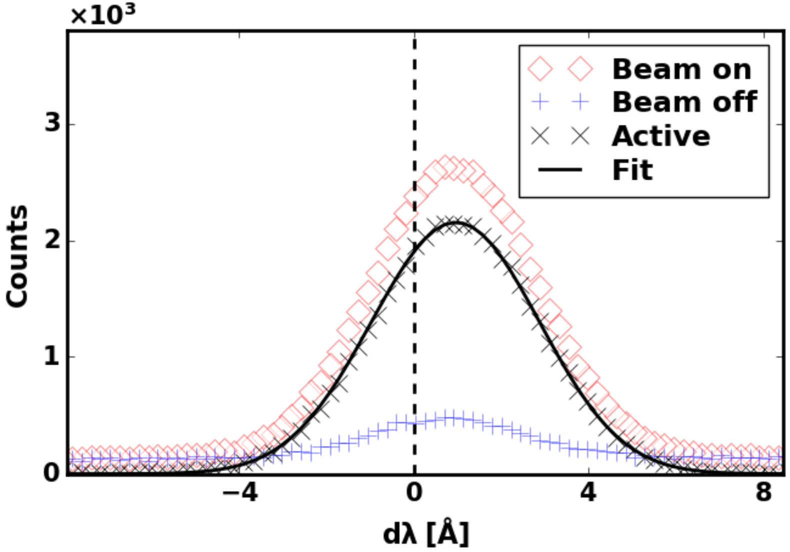
The Main Ion (Da) Spectrum Is More Complex than the Impurities, but Contains Substantially More Information

Main ion: DI, n=3→2, 6561Å (Balmer Alpha)



Impurity: CVI, n=8 → 7, 5290Å



Complexity of the Da spectrum, atomic physics corrections, and required camera performance made this an illusive measurement until recently

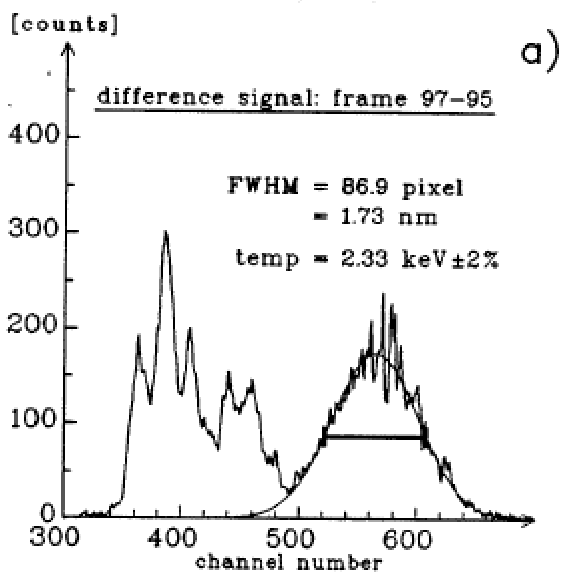
30 years of Active Spectroscopy has Achieved Many Advances Enabling Edge Main-ion (D_α) Charge Exchange Recombination Spectroscopy (CER)

- **Initial work on T-10[1], JET[2], TEXTOR[3] in the 80s and 90s**

- **Core main ion CER on DIII-D[4]**
  - Comprehensive fitting model, optimized viewing geometry, improved cameras
  - Time-dependent collisional radiative modeling (FIDASIM)

- **Edge main ion system on DIII-D[5,6,7]**
  - B. Grierson DOE early career award
  - Built on what was learned for the core main ion system
  - Iterative time dependent collisional radiative modeling[6,7]

- **Recent work also on AUG[8], T-10[9], JET**

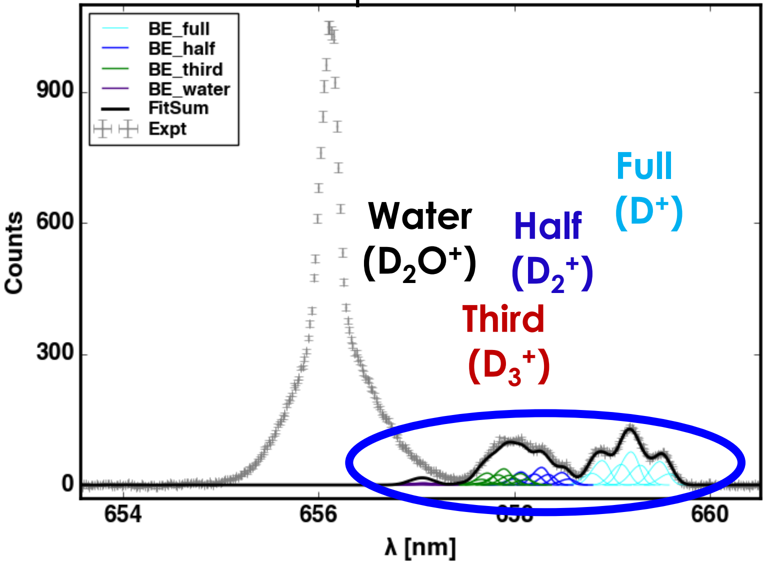


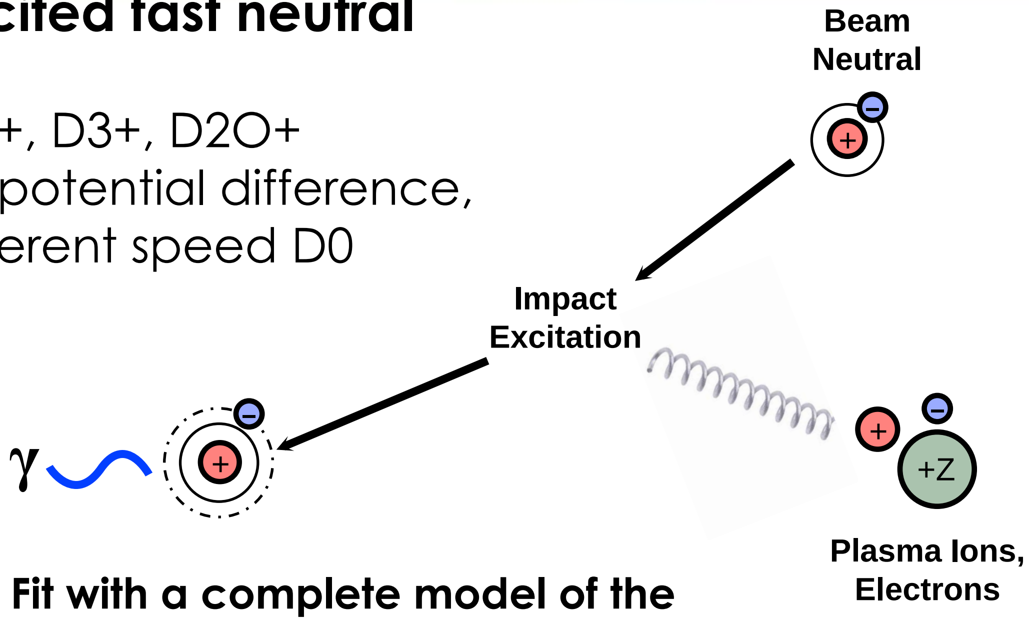
W. Mandl, JET-IR(92), 1992

[1] E. L. Berezovski, NF, 1985, [2] W. Mandl, JET-IR(92), 1992, [3] E. Busche 1997, PPCF, 1997
[4] B. A. Grierson, RSI, 2012, [5] B. A. Grierson, RSI, 2016, [6] S. R. Haskey, RSI, 2016
[7] S. R. Haskey, RSI, 2018, [8] M. Salewski, NF, 2018, [9] V.A. Krupin, Plas Phys Reports, 2013

Active D_α Photoemission Occurs from Three Fundamentally Different Processes

- **Beam emission is from an excited fast neutral**
  - MSE[1,2], BES[3]
  - NBI source produces D+, D2+, D3+, D2O+
  - Accelerated through same potential difference, breakup in neutralizer -> different speed D0



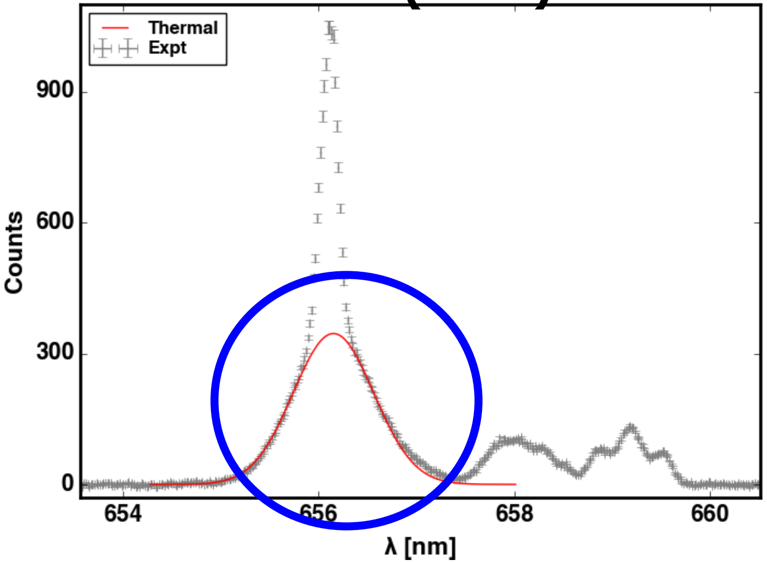


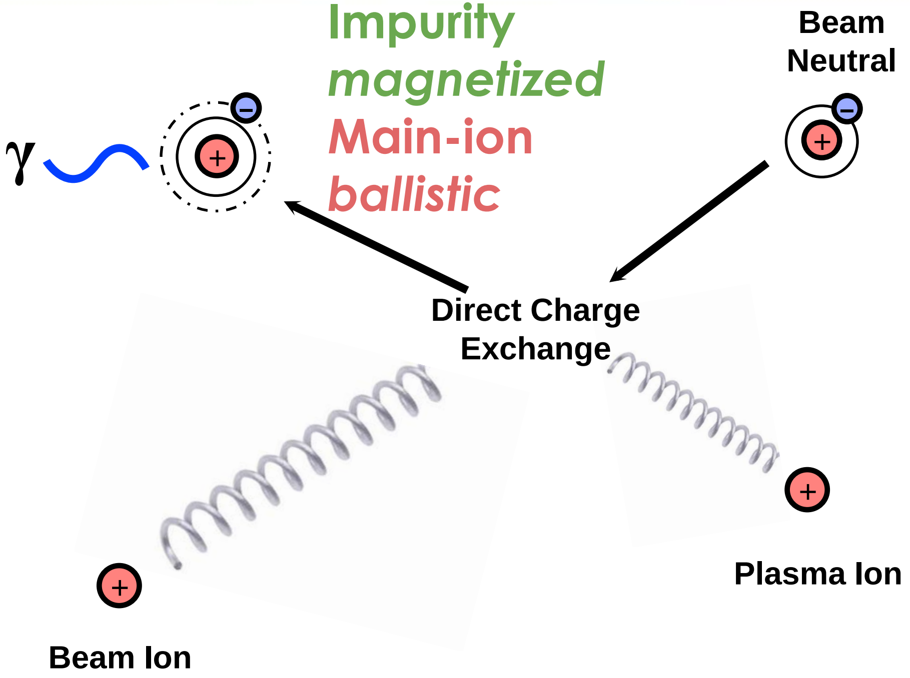
- **Fit with a complete model of the stark split beam emission**
  - Beam velocity, energy fractions, excited state populations

[1]F. Levinton, *Phys. Rev. Lett.*, 1989
[2]N.A. Pablant, *Rev. Sci. Instrum.*, 2010
[3]R. J. Fonck, *Rev. Sci. Instrum.*, 1990

Active D_α Photoemission Occurs from Three Fundamentally Different Processes

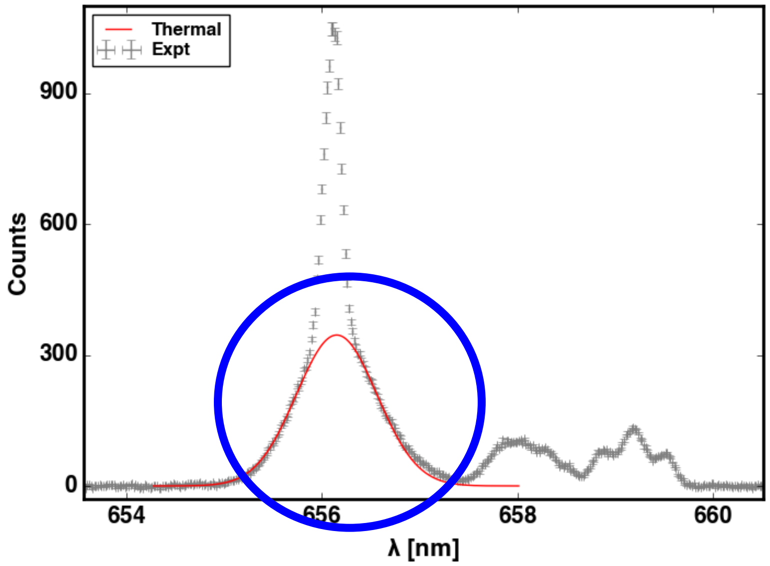
- **Direct charge-exchange is from a beam neutral to a thermal ion (D+, C6+) or fast ion (FIDA)**

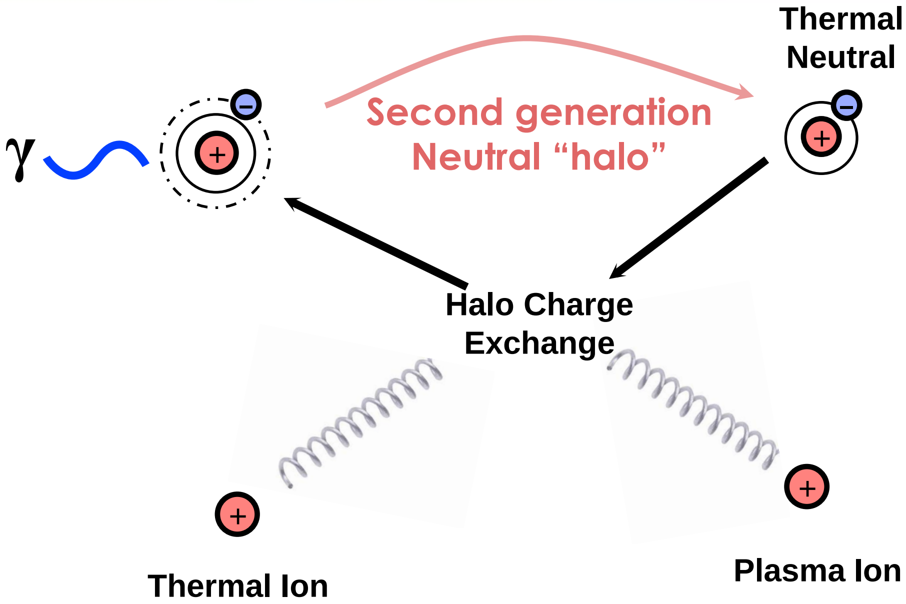




Active D_α Photoemission Occurs from Three Fundamentally Different Processes

- **Halo charge-exchange is from a thermal neutral to a thermal ion[1]**



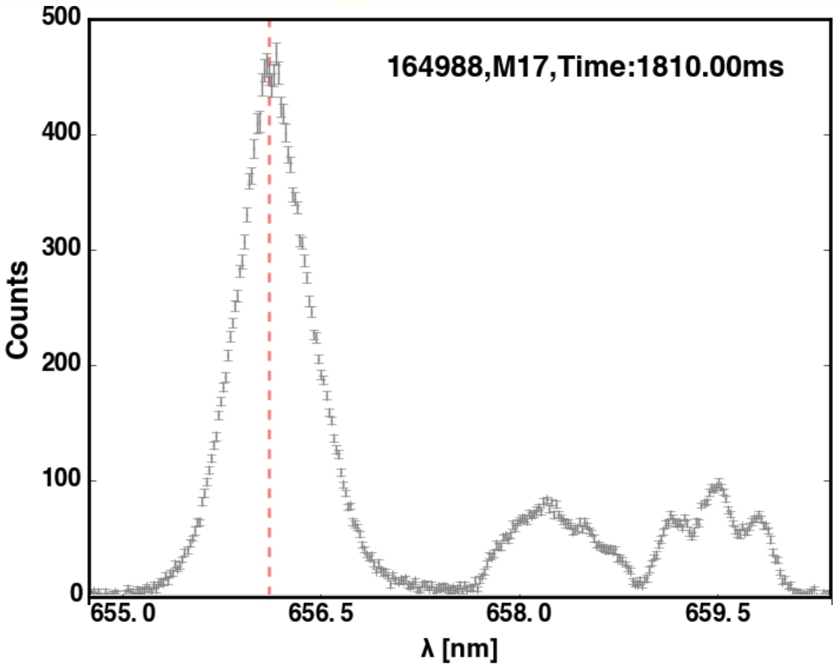


Fit with a single Gaussian

- Radiance, apparent deuterium temperature (Doppler broadening) and velocity (Doppler shift)

[1]J. Hogan *J. Nucl. Mat.*,1982

Qualitative Changes in the D_α Spectrum Can be Seen Across an L-H Transition



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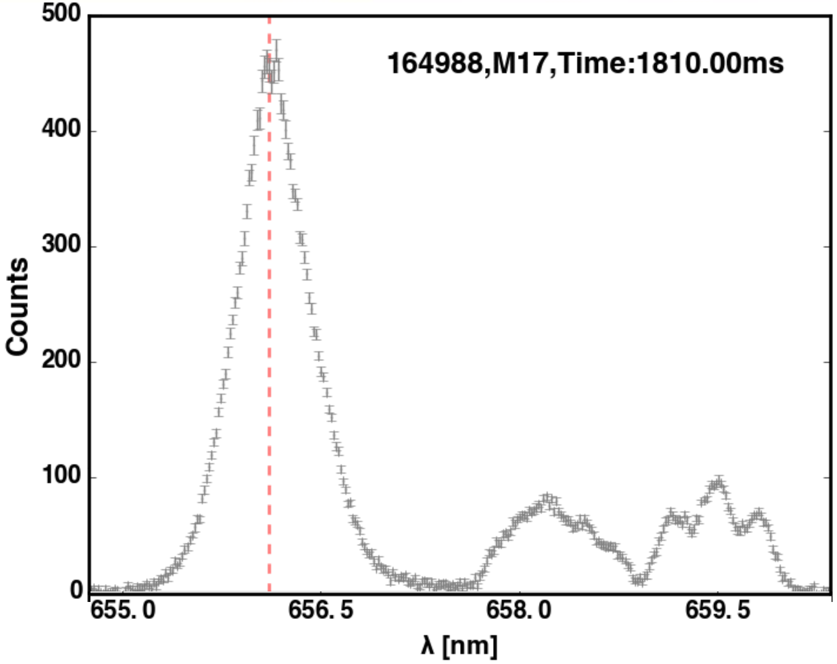
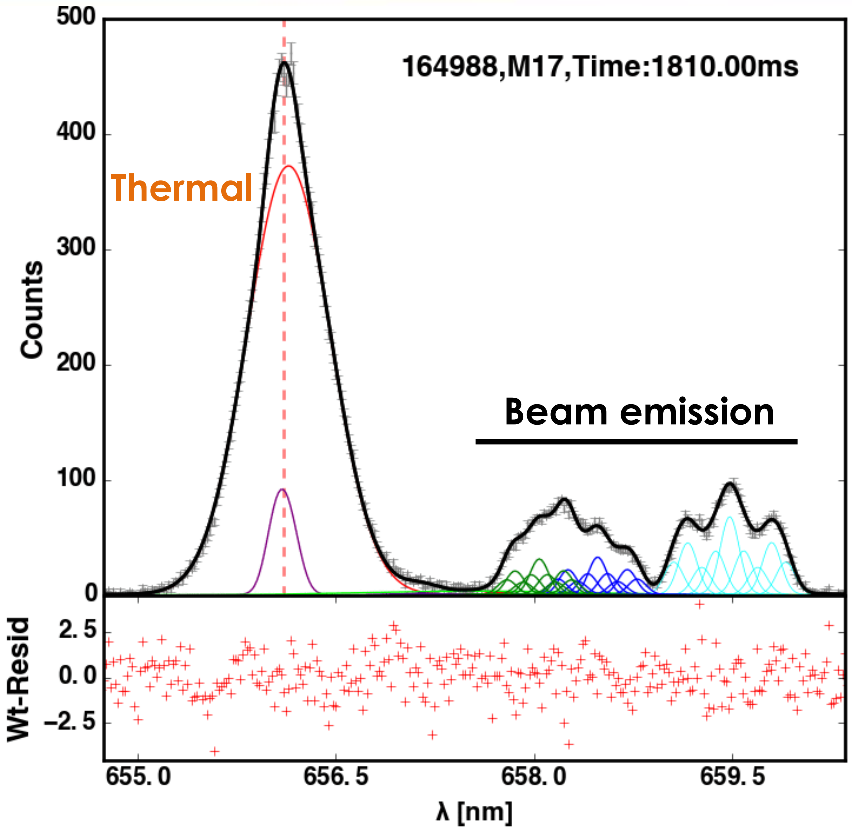
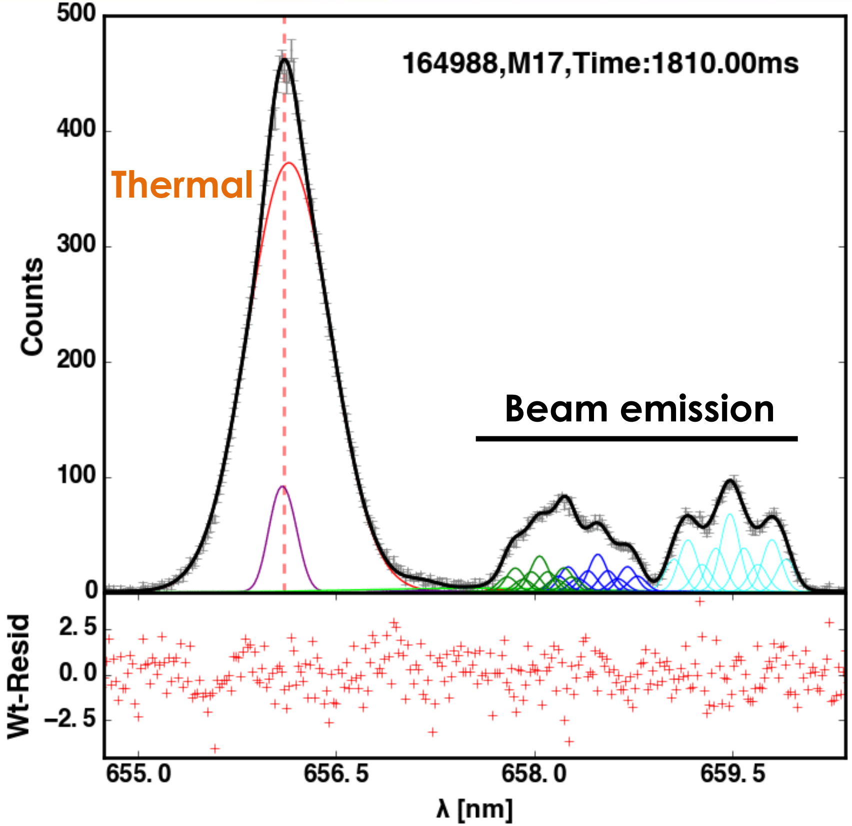
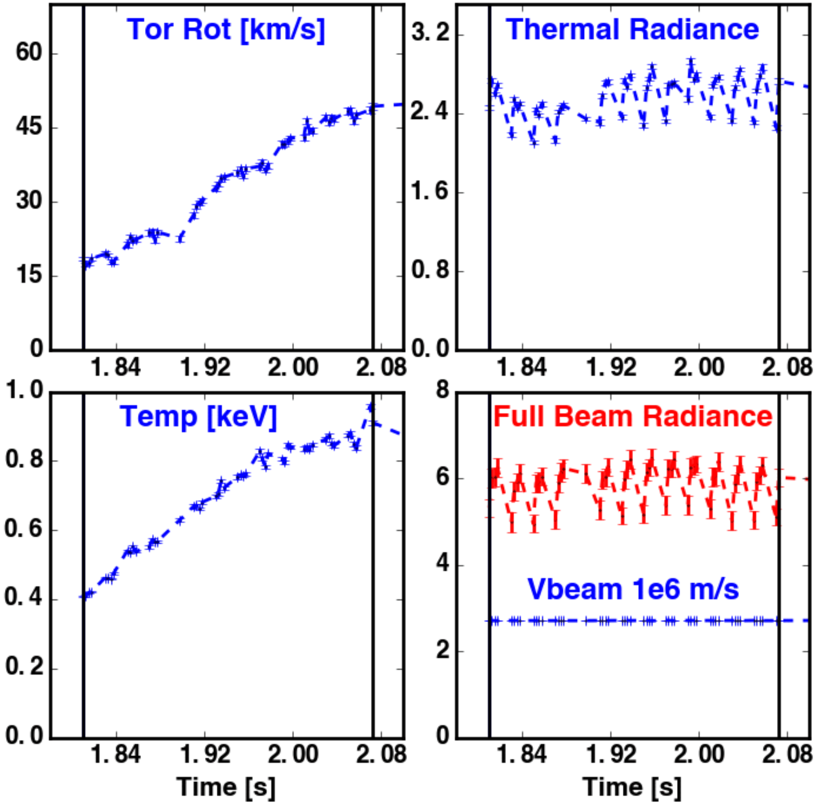


Fitting the Spectrum Allows the Changes to be Quantified



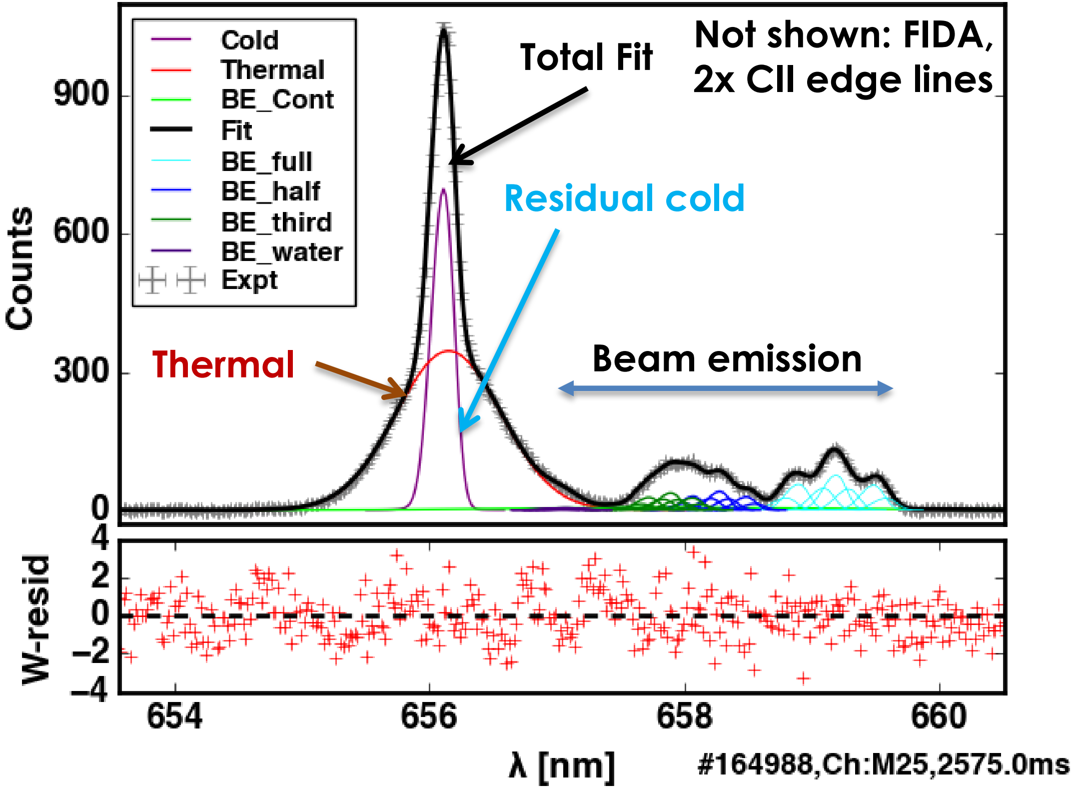
Fitting the Spectrum the Allows Changes to be Quantified





Comprehensive Fit Model Accurately Represents the Data, Allows Many Parameters to be Extracted from Da Spectrum

- Low weighted residual with minimal structure shows that the model fits the data very well
- Apparent deuterium ion temperature, rotation, density
- Also: Beam injection energy, beam full half, third components radiance (can infer ne from these), |B|, FIDA radiance

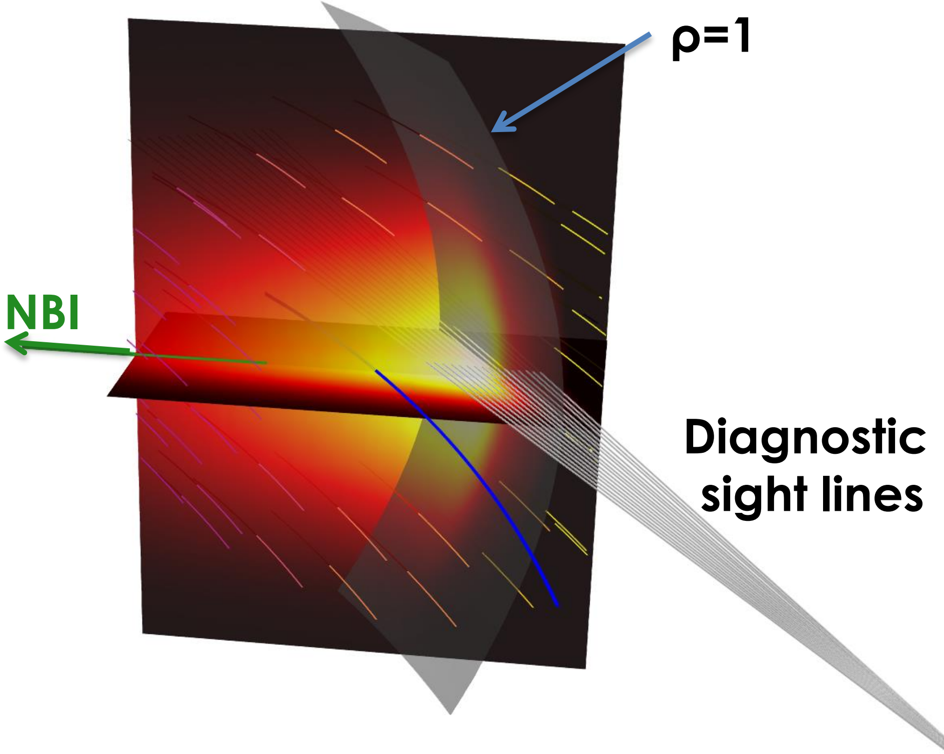


The Spectral Photoemission is Modeled with an Iterative Time-Dependent Collisional-Radiative Model (FIDASIM)[1,2]

- **Monte-Carlo neutrals tracked through spatially varying plasma and spectra simulated[1,2]**
  - Charge exchange, collisional excitation, ionization, multiple halo generations, simulated sightline spectrum

- **Given the D+ properties FIDASIM can simulate the spectrum MICER should observe**

- **FIDASIM is used in an iterative loop to correct the D+ measurements in the H-mode pedestal region[3,4]**



[1] W. W. Heidbrink, *Commun. Comput. Phys.*, 2011
[2] L. Stagner, http://d3denergetic.github.io/FIDASIM, 2016
[3] S. R. Haskey, *JINST*, 2018 [4] S. R. Haskey, *RSI*, 2018

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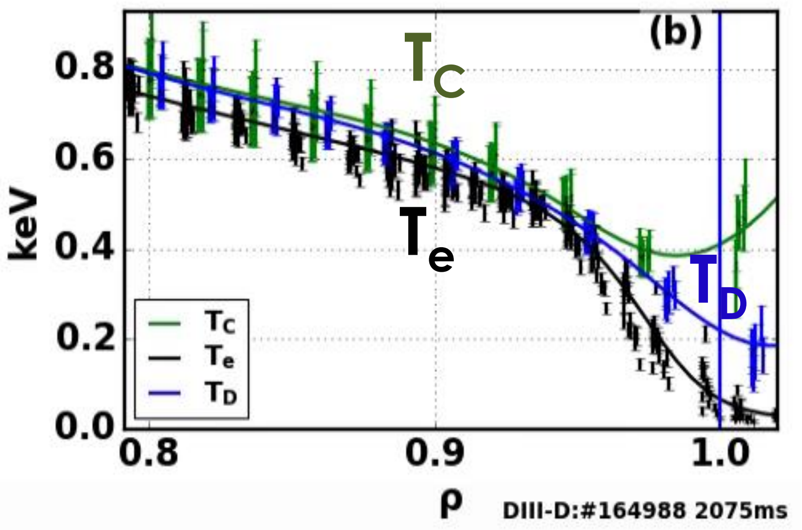
In Some Cases Main-Ion and Impurity Temperatures Diverge Approaching the Separatrix

- **D+ temperature can be 1/2 of C6+ value at separatrix on DIII-D[1]**
  - Unexpected given rapid eq time:

$$\tau_{\alpha\beta} = \frac{1}{1.8\times 10^{-19}} \frac{(m_\alpha T_\beta + m_\beta T_\alpha)^{3/2}}{\sqrt{m_\alpha m_\beta}(Z_\alpha Z_\beta)^2 n_\beta \ln\Lambda}$$

- **Possible reasons**
  - Local C^{6+} population may be dominated by non-local higher energy C^{6+} from pedestal top[2,3]
  - HFS impurity density accumulation[4] with constant pressure -> high impurity LFS temperature
  - Only the D+ is cooled by charge exchange with edge cold D neutrals – additional sink



[1] S. R. Haskey, *PPCF*, 2018
[2] D. Battaglia, *PoP*, 2014
[3] S. R. Haskey, *EPS proceedings*, 2019
[4] T. Putterich, *Nuc. Fus.*, 2012

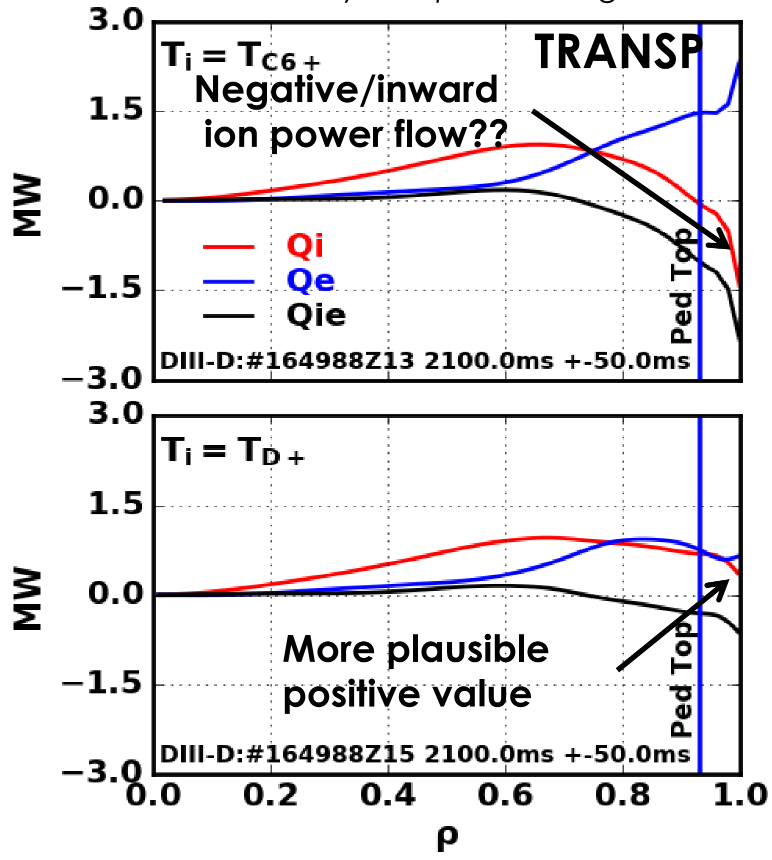
Using T_{D+} Measurement Resolves Historical Issue of Negative Inferred Ion Heat Flux

- **Minimal work on ion thermal transport in the pedestal has been done on DIII-D**
  - Largely due to issues like negative Qi

- **The ion-electron collisional exchange term ($\sim n_e n_i (\Delta T)/T_e^{3/2}$) affects both the inferred ion and electron heat fluxes**

- **Needed in several research areas**
  - Species dependent fluxes for comparison with theories of different modes ('fingerprints')
  - Qi role in L-H[1]
  - Power flow into the SOL

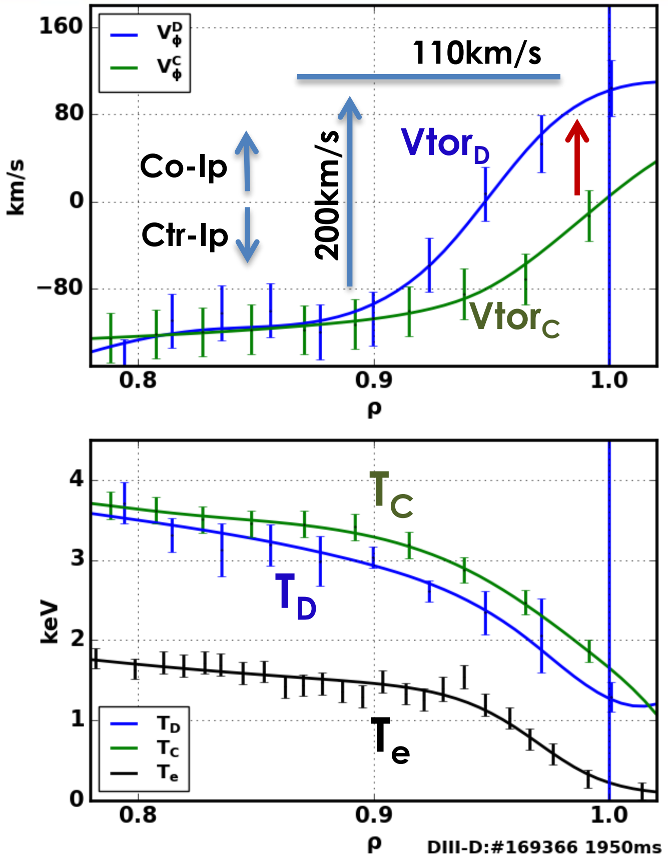
S. R. Haskey, *EPS proceedings*, 2019



[1] F. Ryter, *NF*, 2014

A High Power, Low Collisionality QH-Mode Shows Rapid Co-Ip Intrinsic Rotation at Separatrix on Low Field Side Midplane

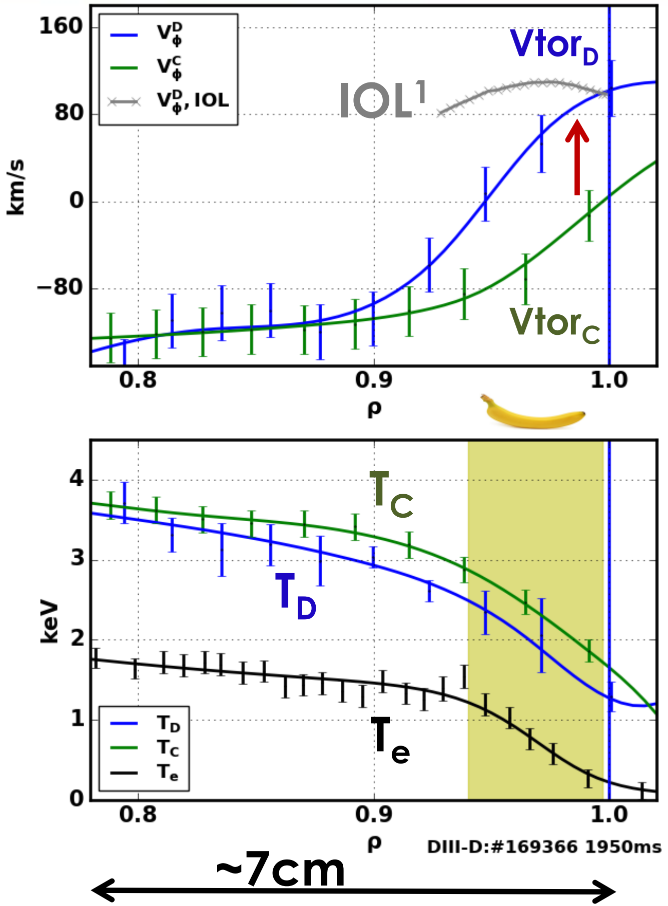
- **Large orbit widths – non local and non-Maxwellian effects are important**
  - β_N~2.2, $\bar{n}_e$~2.5e13cm^{-3}, P_{NBI}~8MW,
  - T_{NBI}~-5Nm, v*< 0.01
- **Deuterium toroidal rotation 110km/s Co-Ip at LFS separatrix even though 5Nm injected beam torque in opposite direction**
  - Co-Ip bulk rotation at separatrix has been studied at lower temperatures with Mach probes[1]



[1] Boedo, J., *Phys. Plas.*, 2016

D+ Toroidal Rotation in Close Agreement With Collisionless Ion Orbit Loss Calculation at Separatrix

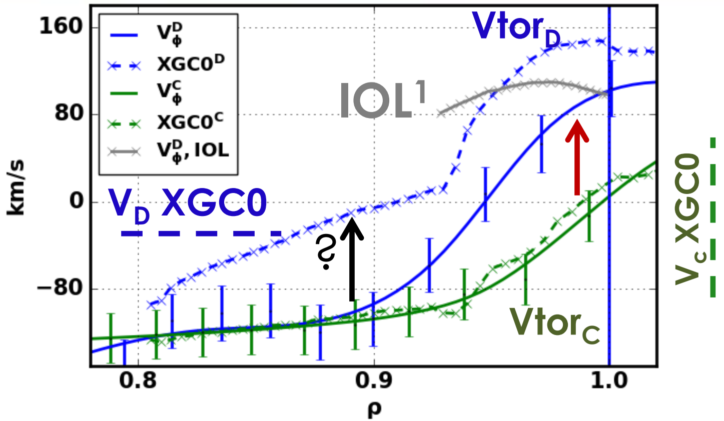
- **Highly non-local in the steep gradient region**
  - Banana orbit widths are large enough to sample the SOL and pedestal top
  - Low collisionality (0.01) - orbits completed many times before a collision
- **Ion orbit loss model[1] predicts the rapid Co-Ip D+ rotation at the sepataratrix**
  - 10-20% D+ orbits in a Maxwellian with this T_D are loss orbits @ LFS midplane for rho>0.92
  - Possible source of intrinsic rotation
  - How does the distribution function respond to this loss cone?

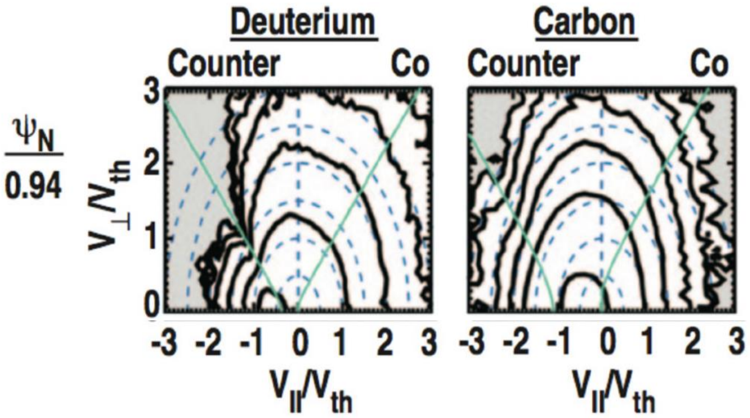


[1] J. deGrassie, *Nuc. Fus.*, 2009

Previous XGC0 Simulations of a Similar QH-Mode [D. J. Battaglia, 2014] Provides an Opportunity For Comparisons With the D+ Properties

- **XGC0[1]: Neoclassical drift kinetic, 5D full-f code (run as 4D)**
  - Impurities, neutral model, and anomalous transport model (random walk)
- **D+ toroidal rotation in good qualitative agreement although more co-Ip inside pedestal top**
  - XGC0 simulation predicted non-Maxwellians all the way to the pedestal top, non-isotropic temperatures, interaction with neutrals



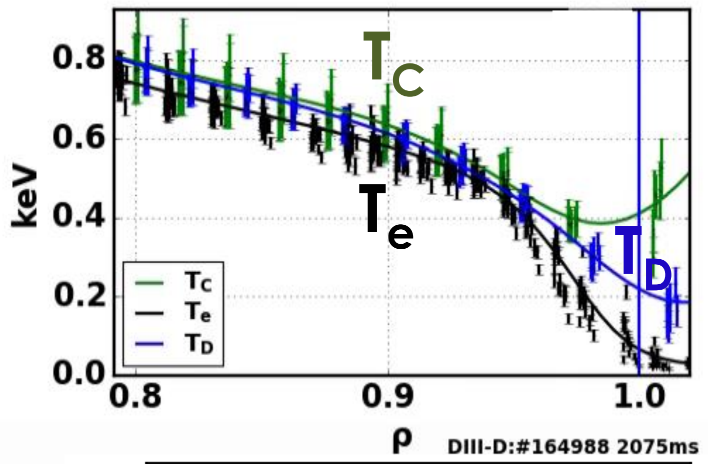


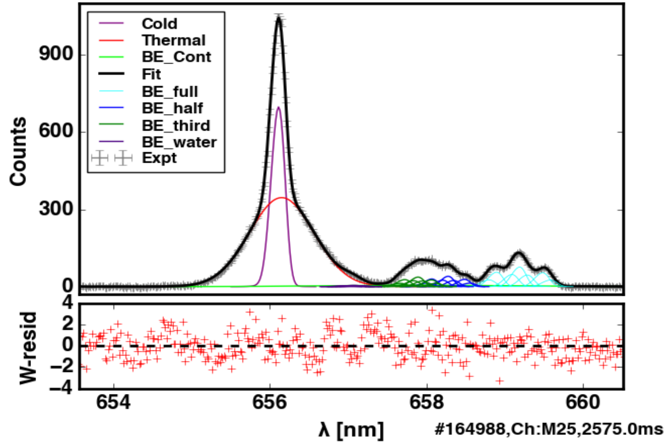
D. Battaglia, *PPCF*, 2016

Summary

- **CER provides spatially resolved measurements of ion temperature, rotation, density, and Er**
  - Based on Doppler broadening, shifting, brightness of a spectral line
  - Relies on charge exchange between an injected neutral beam and the plasma ions (spatially localizes and enables line emission)
  - Work horse diagnostic, cornerstone of experimental validation in many Physics areas

- **Recent advances have led to full profile measurements of the main-ions (D+)**
  - Differences with the impurities in the pedestal region and are being explored

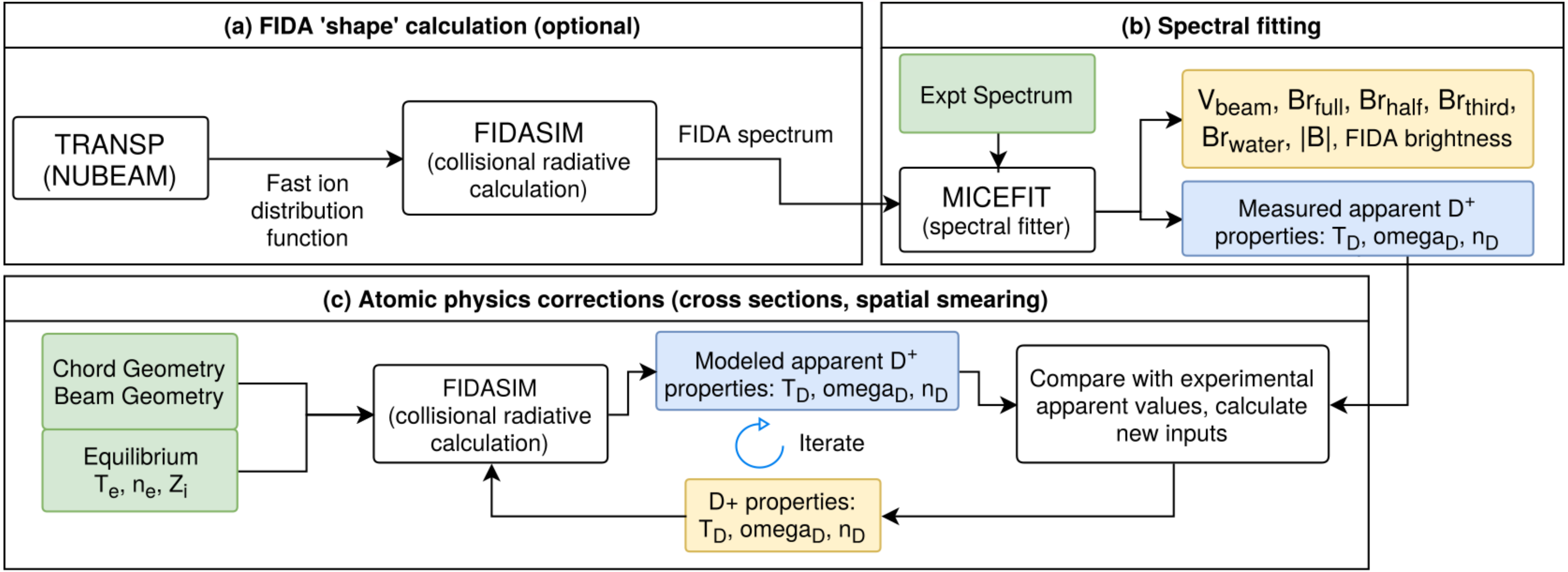




PRINCETON PLASMA PHYSICS LABORATORY

BONUS SLIDES

MICER Analysis Consists of Three Main Steps: FIDA Calculation, Spectral Fitting, Atomic Physics Corrections



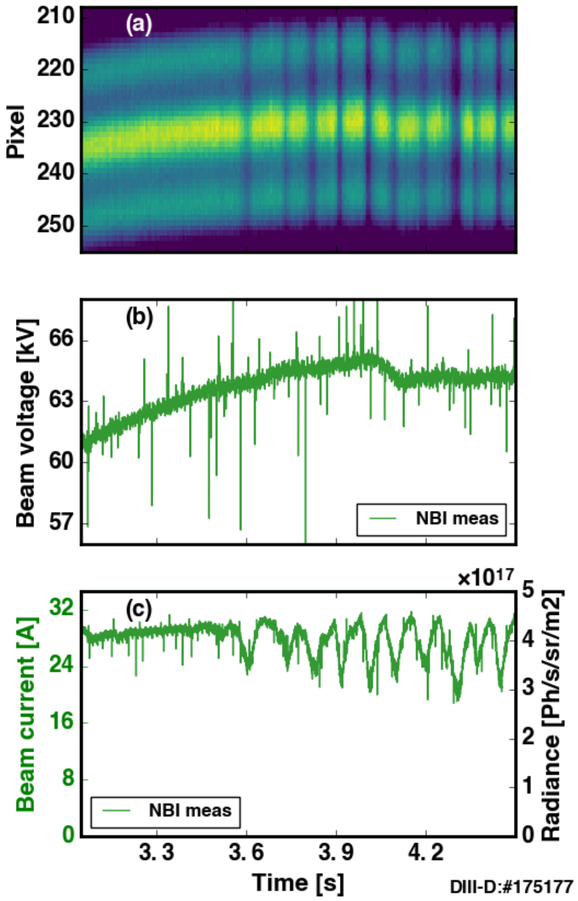
Workflow implemented in OMFIT[1]

[1]O. Meneghini, Nuc. Fus., 2015

NBI Control Experiment Demonstrates MICER NBI Parameter Measuring Capabilities, Validates Beam Emission Fit

- **Recent upgrades allow the beam voltage and perveance[1] to be controlled in real time**
  - Simultaneous toroidal rotation and stored energy control[2]

- **Main ion CER system can measure the parameters of the neutral beams as they travel through the plasma**



[1] D. Pace, *Nuc. Fus.*, 2017
[2] D. Boyer, *Nuc. Fus.*, 2019

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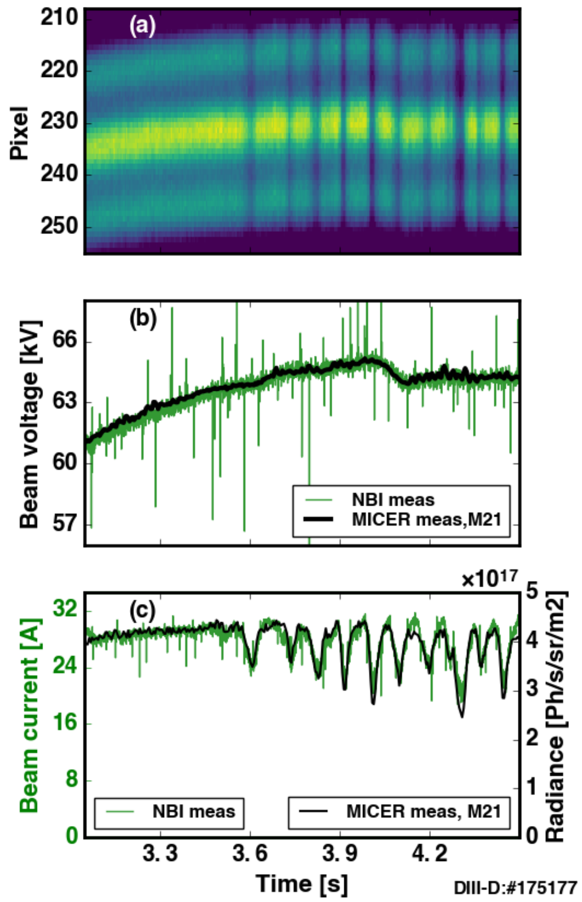
  - Simultaneous toroidal rotation and stored energy control[2]

- **Main ion CER system can measure the parameters of the neutral beams as they travel through the plasma**

- **Excellent agreement with the parameters measured by the beam group**

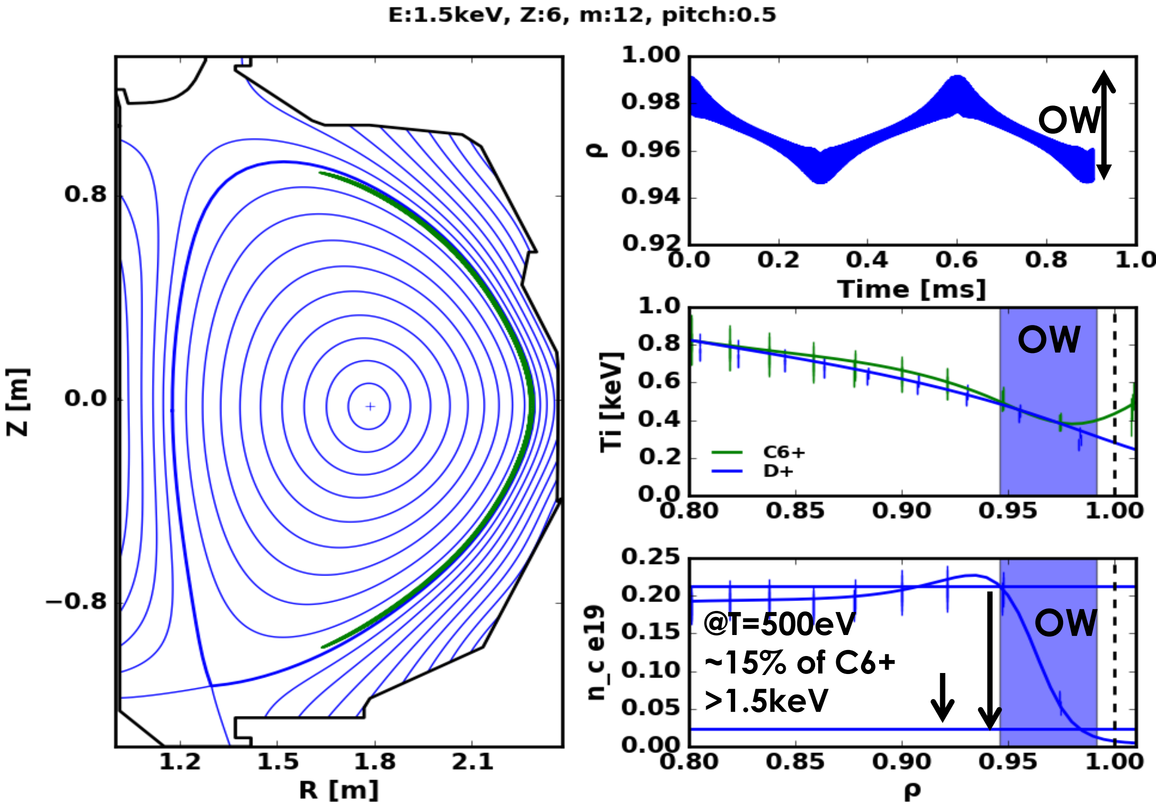
- **Demonstrates that we are accurately fitting the beam emission**



[1] D. Pace, *Nuc. Fus.*, 2017
[2] D. Boyer, *Nuc. Fus.*, 2019

Hot Tail C6+ Orbit Widths (OW) May Explain Elevated Impurity Temperature at Plasma Edge

- Orbit following shows OW of tail C6+ can cover the whole pedestal
- Reduced time scale ~300μs << radial transport, similar to KE collision time (increased w energy)
- Expected number of tail ions is consistent with drop in impurity density
- D+ orbit width is ~2x larger, but 'local' population will also be larger…
- Previous work with XGC0 showed similar effects in a QH-mode shot[1]



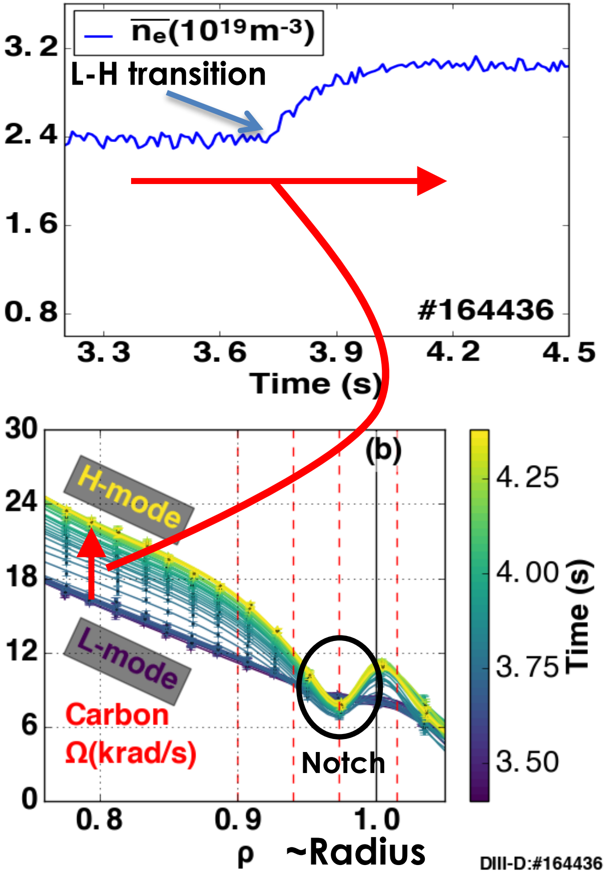
[1] D. Battaglia, *PoP*, 2014

A Spontaneous L-H Transition in Low Zeff Plasma Illustrates the Need for Main-ion Measurements

- **Constant beam power and input torque across L-H transition**

- **Carbon rotation shows spin-up and notch feature**
  - Gradient steepens before reversing
  - Often seen on DIII-D[1], AUG[2,3], and CMOD[4] – thought to be due to impurity density asymmetry

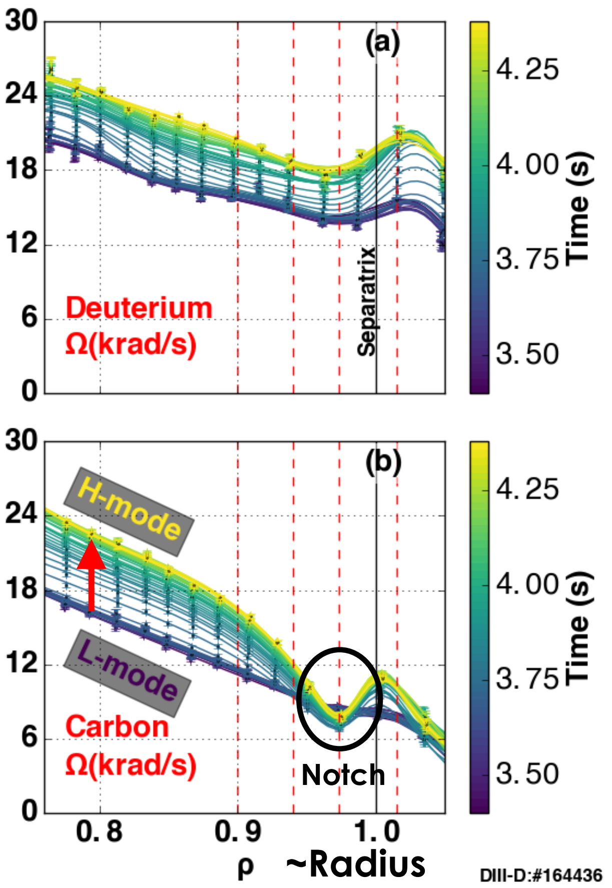
- **Is this representative of the main-ion toroidal rotation?**



[1] J. S. deGrassie, Phys. Plasmas, 2004
[2] T. Pütterich, Nuc. Fus., 2012
[3] E. Viezzer, PPCF, 2013
[4] R. Churchill, Nuc. Fus., 2014

A Spontaneous L-H Transition in Low Zeff Plasma Illustrates the Need for Main-ion Measurements

- Large velocity notch feature not present in the D^+ rotation
- Slight edge peaking seen in D^+ rotation
- Clear main-ion toroidal spin up following L-H transition



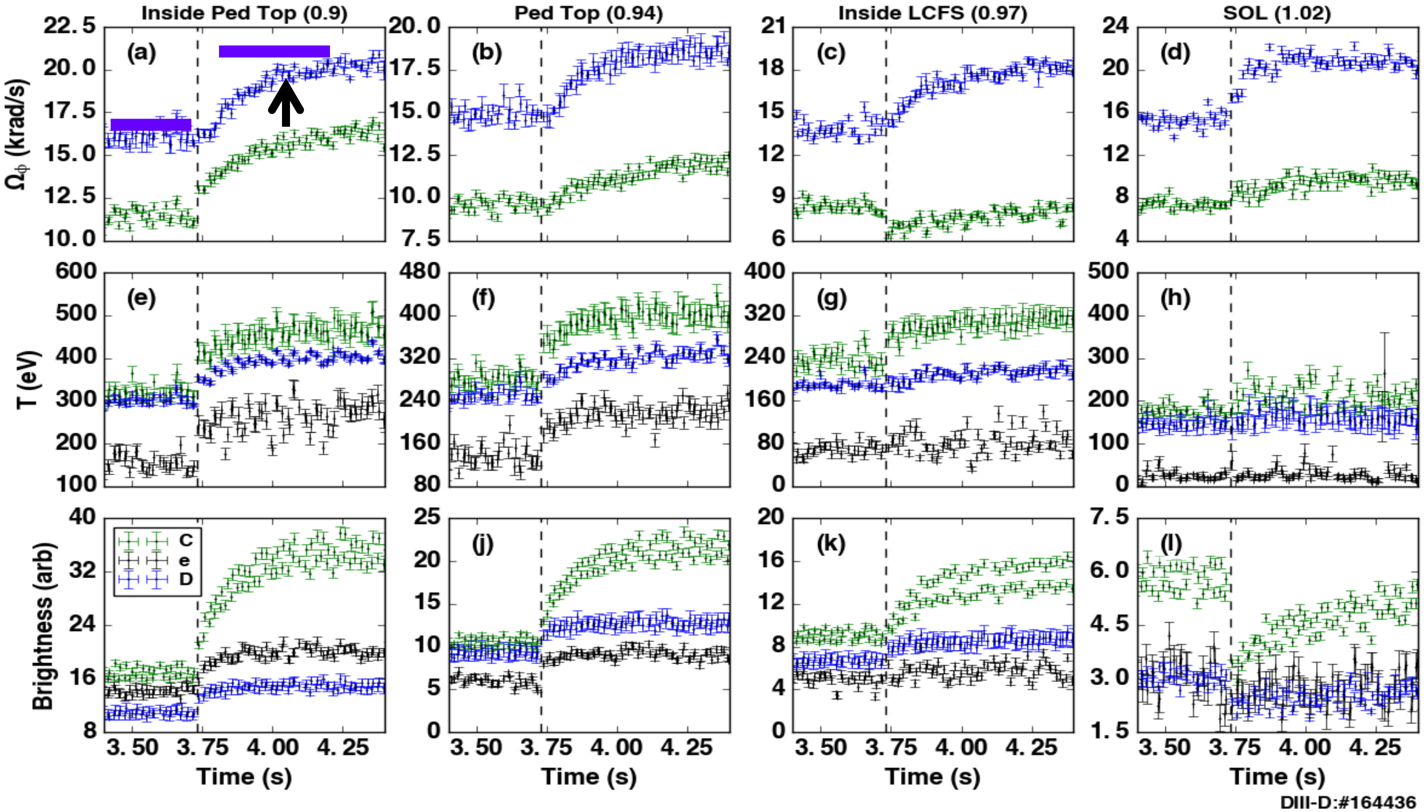
S. R. Haskey, submitted to PPCF

Large increase in SOL D+ rotation compared with C6+, Rapid reduction in C6+ density in SOL

Deuterium and carbon gradually spin up

Deuterium and carbon temperature significantly higher than electrons

Rapid decrease of carbon in SOL



S. R. Haskey, *PPCF*, 2018

Hollowing of Intrinsic Rotation Profile Shows Change In Momentum Transport Going from LOC to SOC

B. A. Grierson, *Phys. Plas.*, 2019