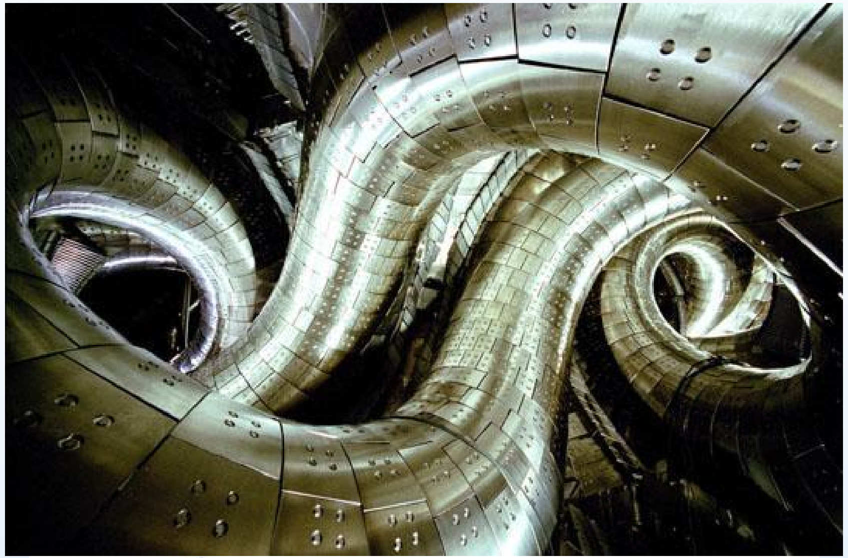
Charge-Exchange Recombination Spectroscopy:

A technique for spatially localized diagnosis of a magnetized fusion plasma

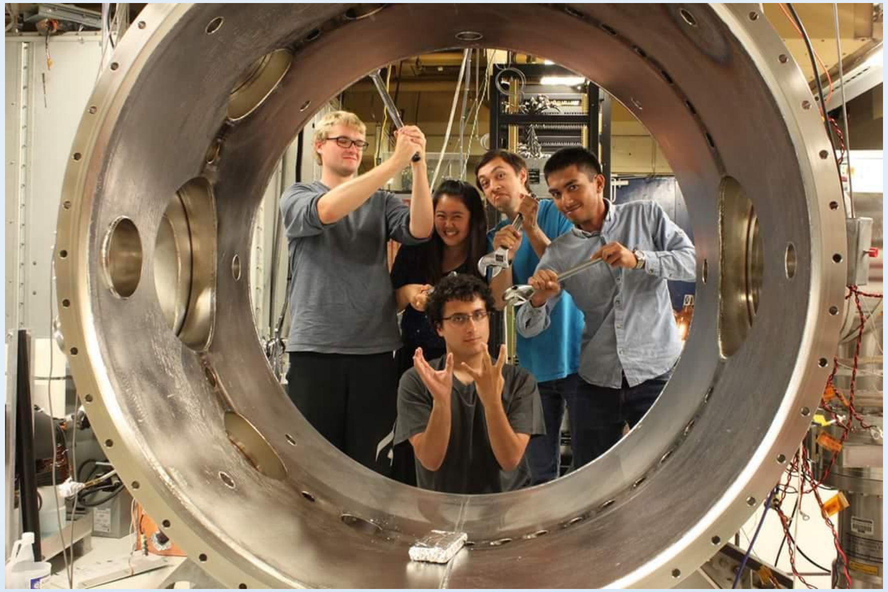
Rian Chandra, PHYS 485

Who Cares?

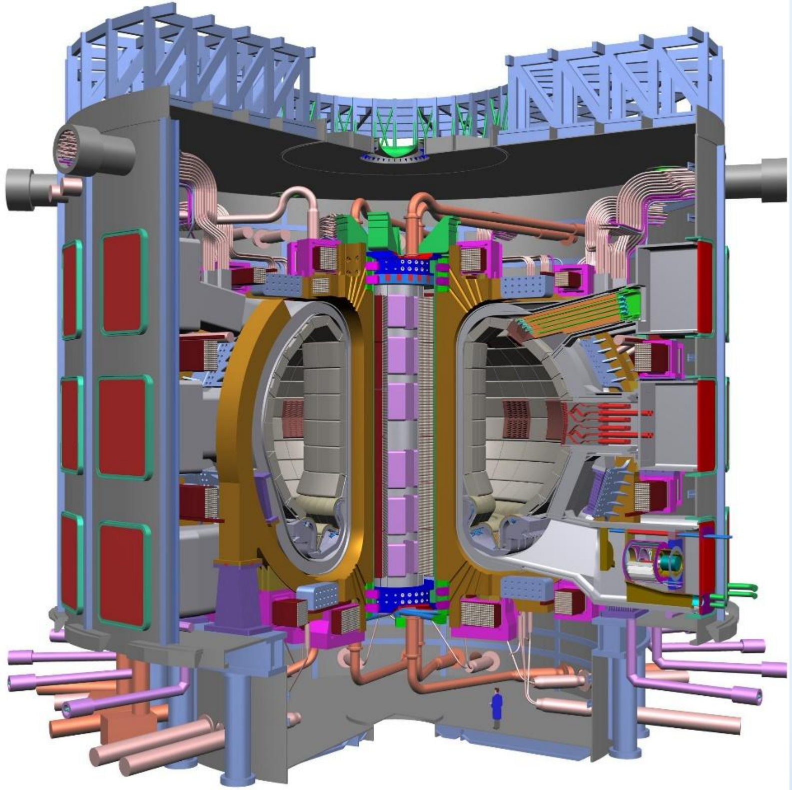
NSTX-U, Princeton NJ



LHD, Japan



HIT-SI3, UW



ITER, France

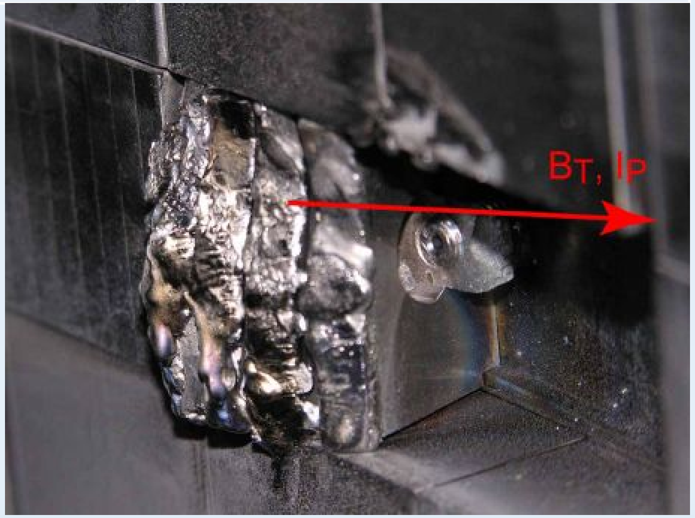
http://www.pppl.gov/sites/pppl/files/styles/insert-default/public/basic-pages/associated-images/WorkersNSTX-U.jpeg?itok=zXnhI8AP

http://www.japantimes.co.jp/wp-content/uploads/2013/06/nc20100929a1a.jpg
http://tempest.das.ucdavis.edu/pdg/ITER_Website/ITER01.jpg

Plasma parameters

Temperature	10eV-10keV	Energy	1KW-50MW
Density	1E16 - 1E22 m^{-3}	B-Field	1mT-5.3T
Mean Free Path	1cm-1m	Instability timescale	1µS -10S
Length Scale	1µm -1m	Discharge timescale	5ms – 500s

- Harsh + Complex + Delicate environment demands localized, noninvasive measurements



Divertor tungsten tile, Alcator C-Mod

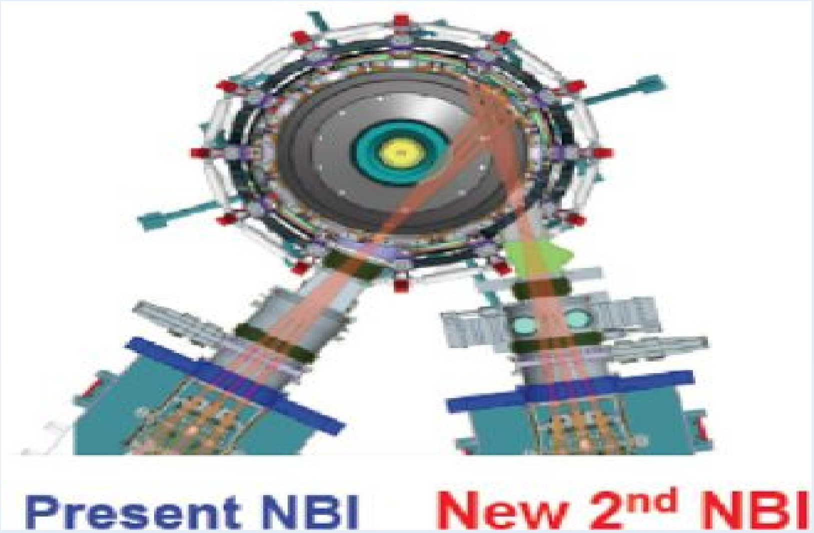
B. Lipshultz et al., 2012 Nucl. Fusion 52 123002

Overview

- CHERS Hardware/History
- Diagnostic Goals
- Interaction Cross-Sections: why and how
- Diagnostic Theory:
  - Doppler Brodening for T_i
  - Doppler Shift for v_i
  - Motional Stark Effect for B Mag, Direction
  - Spectral Intensity for n_i/ Potentially T_e, N_e

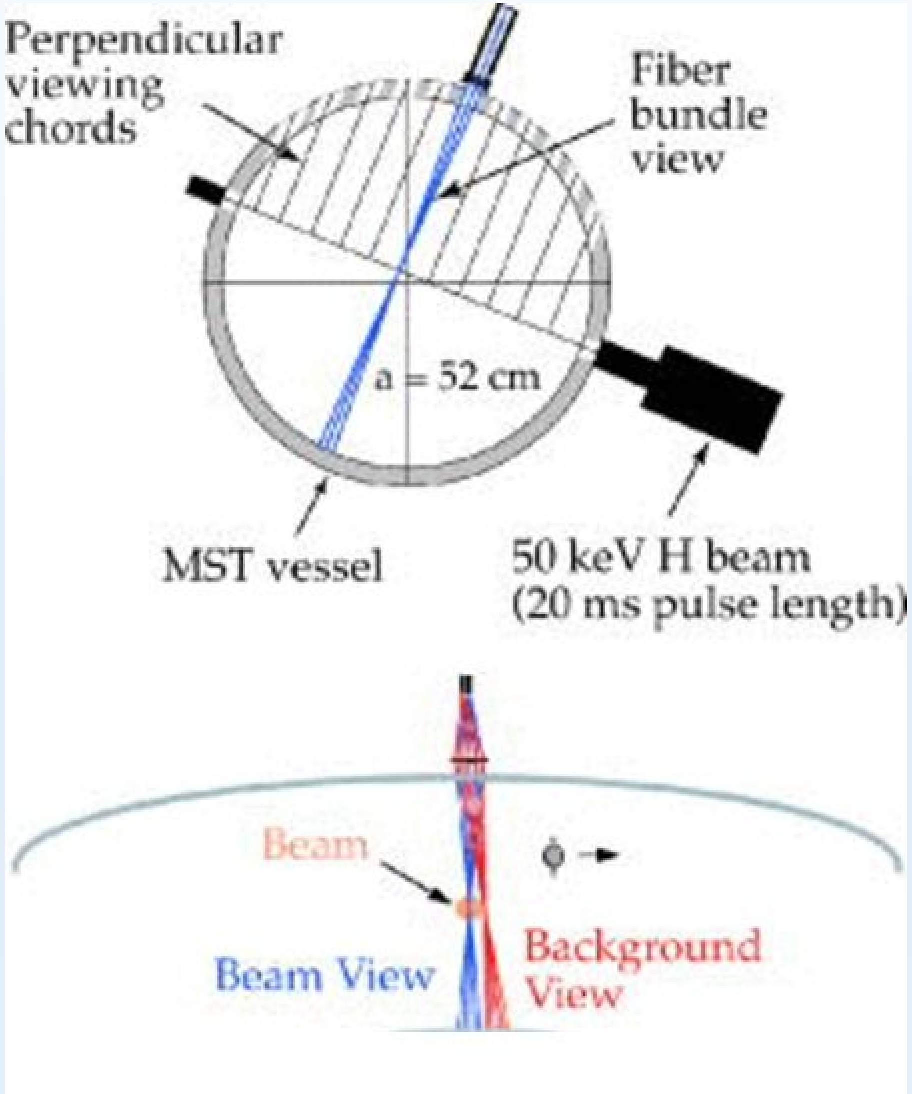
Harness Neutral Beams

- Inject high velocity neutral atoms (H_0) for fueling/drive ion current
- Radiation from the beam necessarily spatially localized
- Research began in the 1980’s to re-apply standard optical diagnostics:
    - Ion Doppler Spectrometry: Measure Doppler shift and broadening
    - Motional Stark Effect: E=vxB splits J degeneracy
    - Spectral Intensity/Collisional Radiative Modeling



Neutral Beams Installed on NSTX-U

M. Ono Et Al, Nucl. Fusion 55 (2015) 073007 (11pp)



Neutral Beam and Spectrometer on MST

S. Gangadhara,Rev. Sci. Instrum. 77, 10F109 "2006

Determining spectral lines of interest

- CHERS Process: $H^0 + A^q \Rightarrow H^+ + A^{(q+1)^*} \Rightarrow H^+ + A^{(q+1)} + \gamma_\lambda$
- Need to make sure that spectra only produced by charge exchange
  - Intensity/surrounding line intensity can be modified by ion-ion impact excitation, electron-ion impact excitation
  - Consideration of fine-splitting may be necessary to determine spectral broadening
  - Use Convergent Close Coupling/other perturbative methods
- Intensity of line λ due solely to charge exchange:

$$B_\lambda^{CX} = \frac{1}{4\pi} \sum_{j=1}^{M} \langle \sigma v \rangle_j^\lambda \int N_Z N_j dl$$

Where: N_z is the impurity ion density, N_j is the beam density at j^{th} velocity component, and $\langle \sigma v \rangle_j^\lambda$ is the reaction cross section at that velocity.

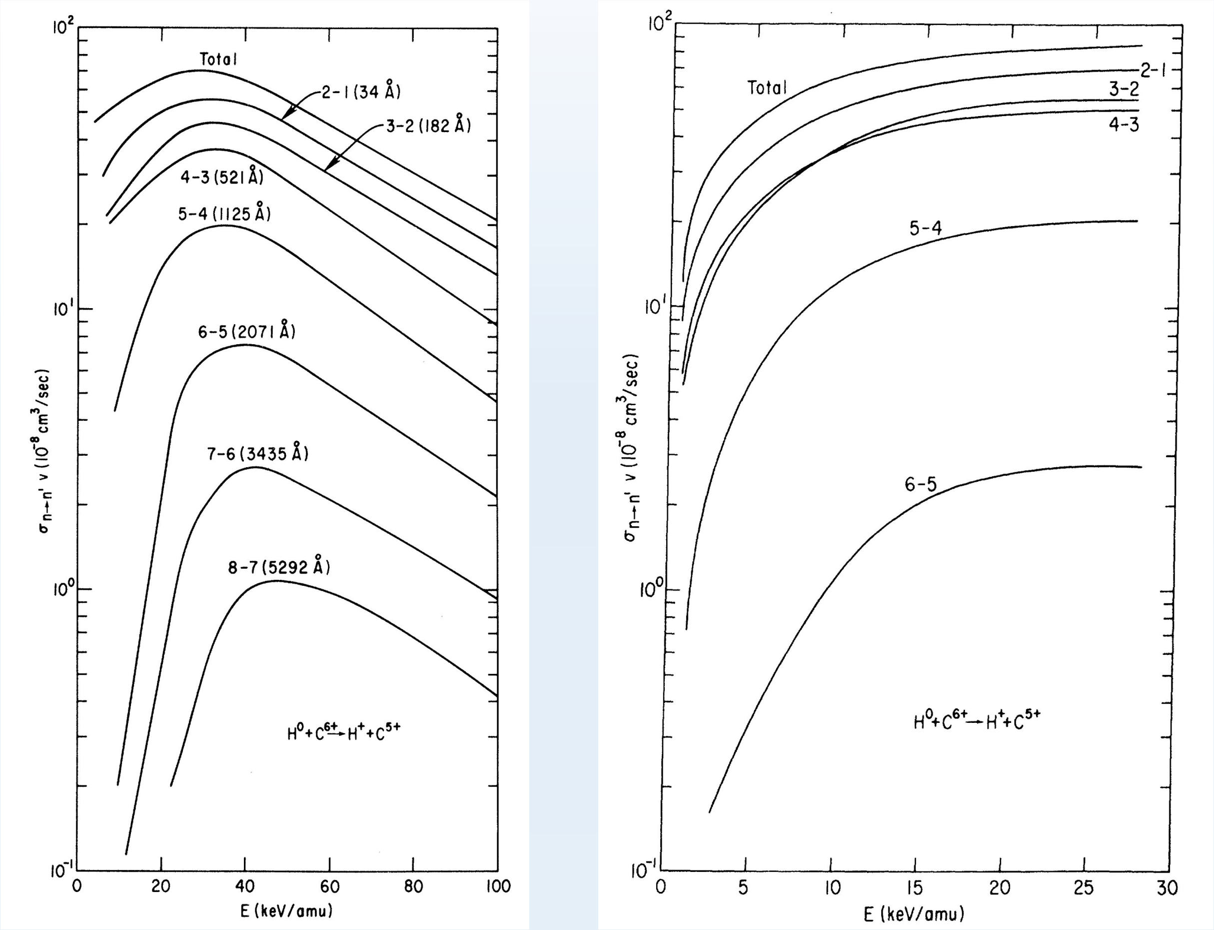
- $\sigma_D(\mathrm{n}, \mathrm{l})$ gives cross-section for direct charge-exchange transfer into state n
- Need to account for branching ratios (n’l’=>nl), the spectral line wont just be from the transferred state to ground

Calculation of cross sections

- Use perturbation theory to find σ_D: Perturbed stationary state/Unified Distorted Wave Approximation
- Example from e-He: two electrons, require that one is in s1.
- $H_T \approx H_1 + H_2 + V_{1,2}$ Where $H_\alpha = R_\alpha + V_\alpha$, α=1,2 designates electrons, R_α,V_α are the radial wave functions and single electron He potential of the standard form
- The He wave function will diagonalize the Hamiltonian as so $\left\langle \Phi_i(x_1, x_2) \middle| H_T \middle| \Phi_f(x_1, x_2) \right\rangle$
- $H_e \approx H_0 + V_{0,1} + V_{0,2}$ Where H_0 is the electron Hamiltonian, and $V_{0,\alpha}$ is the electron-electron potential.
- $\left\langle k_f \phi_f \middle| T \middle| \phi_f k_i \right\rangle = \left\langle k_f \phi_f \middle| V \middle| \phi_f k_i \right\rangle + \sum_n \int d^3k \, \frac{\langle k_f \phi_f | T | \phi_f k_i \rangle \langle k_f \phi_f | V | \phi_f k_i \rangle}{E - \epsilon_n - k^2/2}$
- Where $V = V_0 + 2V_{0,1} + 2P_{0,1}(E - H_T - H_0 - V_{0,1} - V_{0,2})$

Results from PSS and UDWA

- Comparison of UDWA (left) and PSS (right) for C-V
- PSS more accurate at low energy
- UDWA gives global picture

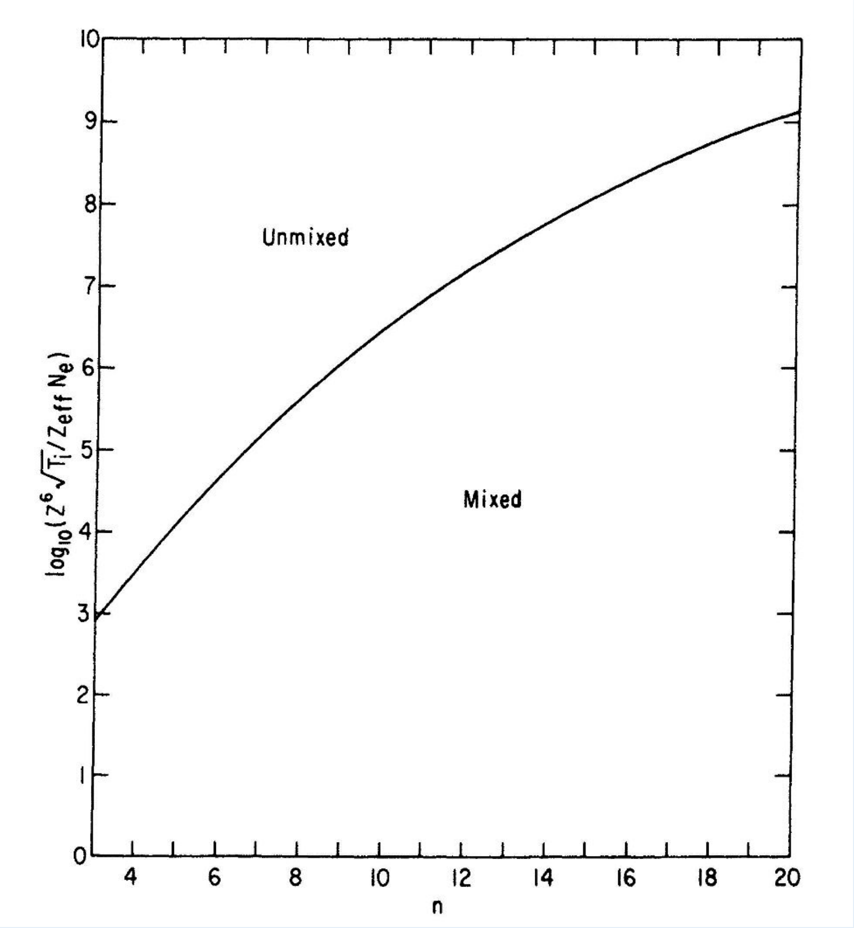


UDWA vs PSS emission cross sections for C-V

Fonck, R. J., D. S. Darrow, and K. P. Jaehnig. *Physical Review A* 29.6 (1984): 3288.

Predicting L-Mixing: Collisional and Stark

- Electron may not immediately radiate to ground: l-mixing may occur
- Ion-Ion Impact: $q_{nl}^{Z,z} = 9.93 \times 10^{-6} \left[\frac{\mu}{m}\right]^{\frac{1}{2}} \left[\frac{D_{nl}}{T_i^{\frac{1}{2}}}\right] \left[11.54 + \log_{10}\left[\frac{T_i m}{D_{nl}\mu}\right] + 2\log_{10} R_c\right] \quad [cm^3 s^{-1}]$
- If $\mathrm{A}_{\mathrm{nl}}^{\mathrm{Z}} \tau_{nl}^{Z} \gtrsim 1$ the l-levels are collisionally mixed (collisional excitation rate exceeds spontaneous emission)

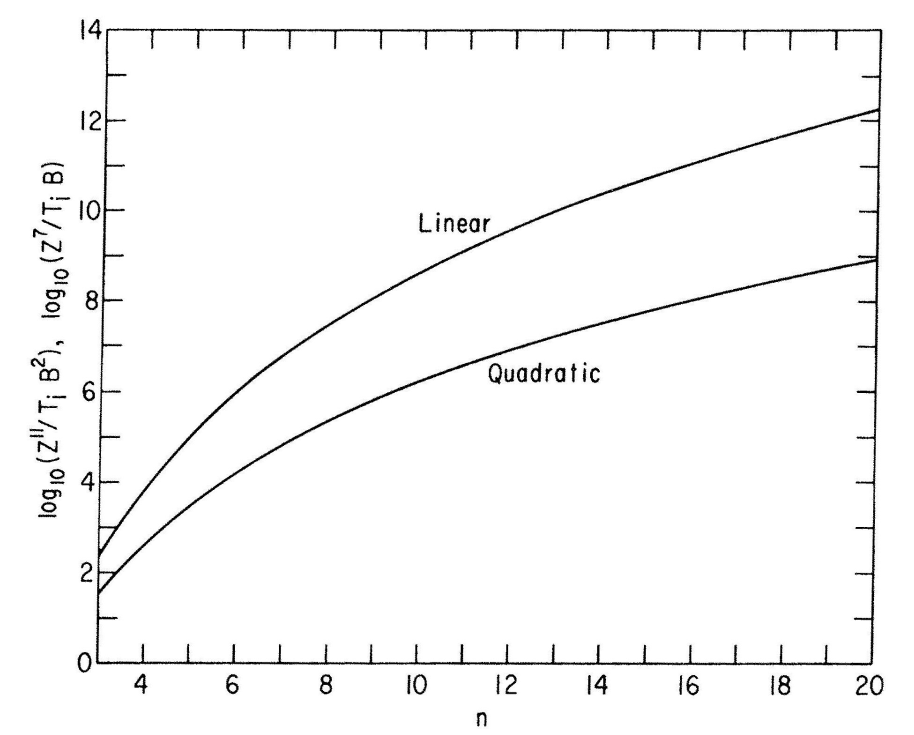


Collisional l-mixing onset level n

Fonck, R. J., D. S. Darrow, and K. P. Jaehnig. *Physical Review A* 29.6 (1984): 3288.

Motional Stark Effect Mixing

- Ions moving through a magnetic field will "see" E=vxB in their rest frame.
- Estimate perturbation to Hamiltonian:
- $V' = -(v \times B) \cdot \mu$
- $E^1 = -(v \times B) \cdot \langle \psi_k^0 | \mu | \psi_l^0 \rangle$ to 1^{st} order.
- Equate E^2 with fine-structure energy spacing to find Stark onset level n:
- $n_s = 2.04 \left[\frac{Z^7}{T_i B} \right]^{1/9}$

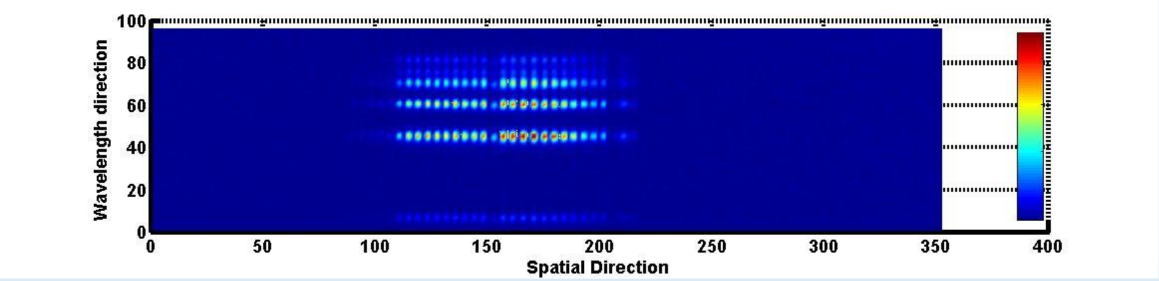


Stark l-mixing onset level n

Fonck, R. J., D. S. Darrow, and K. P. Jaehnig. *Physical Review A* 29.6 (1984): 3288.

Diagnostic Possibilities: DopplerStuff

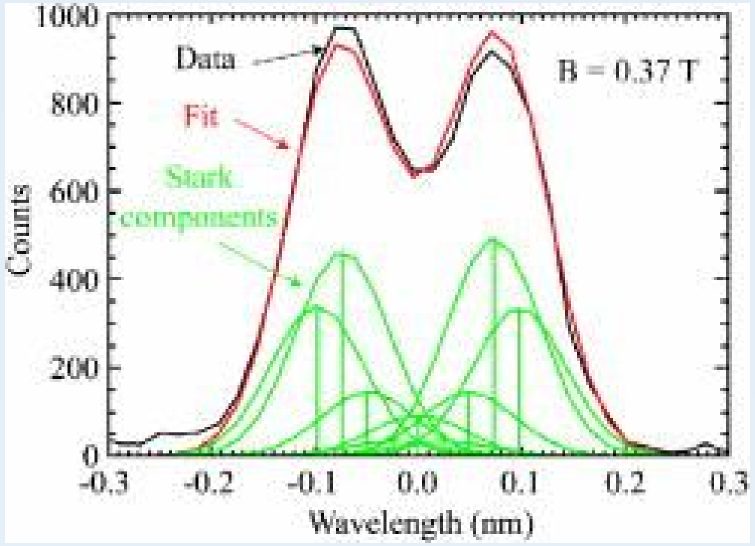
- Photons emitted by excited plasma ions will be shifted, broadened:
- $v_i = \frac{c(\Delta\lambda)}{\lambda}$ solves for ion velocity
- Given Maxwellian ion velocity distribution in 1D:
- $f(v_i) = \sqrt{\frac{m_i}{2\pi k_b T}}\, exp\left[\frac{-m_i v_i^2}{2k_b T}\right]$, then:
- $T_i(eV) = \frac{\sigma^2 c^2 m_i}{\lambda_0^2 k_b}$ solves ion temperature, where σ is the Gaussian width



Light-Gaussians on IDS CCD, center at 464.9nm

Motional Stark Effect

- Level splitting can diagnose $\left\|\vec{B}\right\|$
- Emitted light will be polarized at a pitch angle in the direction of $\vec{B}$
- Deviations from the expected pitch angle can diagnose $\vec{E}$
- Data pictured is from MST, using a 30keV neutral beam, with spectra from CIII

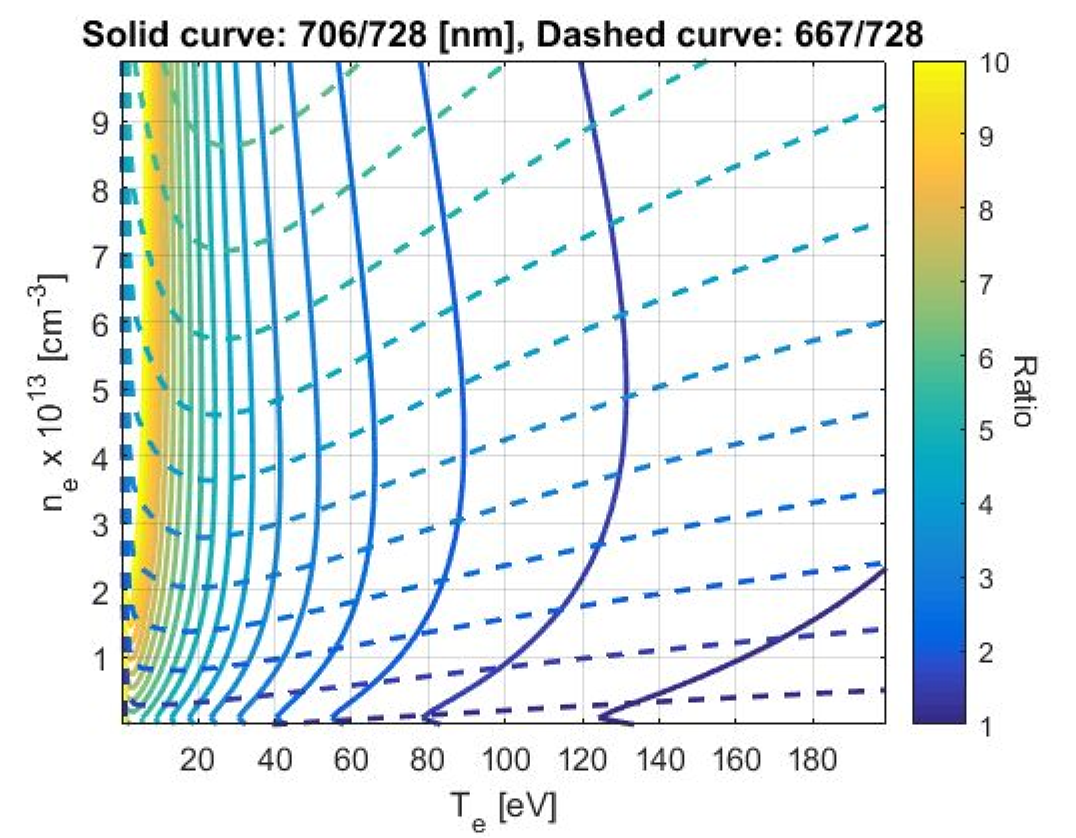


Raw data and fit for MSE from MST

D. Hartog, Rev. Sci. Instrum. **77**, 10F122 (2006)

Extended Diagnostic: $N_i, T_e + N_e$

- If the spectrometer is absolutely calibrated, can relate $\gamma \Rightarrow n_i$
- Requires complete knowledge of state population/depopulation.
- Theoretically, can run diagnostic backwards: Collisional-Radiative Modeling:
    - $e^{-,*} + H^0 \Rightarrow e^- + H^{0,*} \Rightarrow e^- + H^0 + \gamma_\lambda$ with sufficiently accurate modeling, can extract T_e, N_e.



Collisional-Radiative Matrix for He-II line ratios

Conclusions

- CHERS is a powerful diagnostic tool
- Many diagnostic possibilities are unlocked (IDS/MSE/CRM)
- Common theme: wavefunction modeling precision
- Indispensable on large-scale experiments

Primary Sources:

B. Lipshultz et al., “Divertor tungsten tile melting and its effect on core plasma performance “, 2012 Nucl. Fusion 52 123002

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Advances in neutral-beam-based diagnostics on the Madison Symmetric Torus reversed-field pinch (invited)

Den Hartog, D. J. and Craig, D. and Ennis, D. A. and Fiksel, G. and Gangadhara, S. and Holly, D. J. and Reardon, J. C. and Davydenko, V. I. and Ivanov, A. A. and Lizunov, A. A. and O’Mullane, M. G. and Summers, H. P., Review of Scientific Instruments, 77, 10F122 (2006), DOI:http://dx.doi.org/10.1063/1.2217920