An Overview of Possible Auburn University Support for NSTX-Upgrade Spectroscopy and Diagnostics

David Ennis, Stuart Loch, Connor Ballance
& Curtis Johnson

Auburn University

PPPL Seminar
July 22nd, 2015

High-Z Material Erosion is a Critical Research Priority

- **NSTX-U Five Year Plan:** *"Recent papers have pointed out that wall erosion could result in thousands of kilograms per year of circulating material in a power reactor [P. Stangeby, J. Nucl. Mater. 2011]. The eventual fate of the eroded wall material is unknown at this point and requires further study."*
- **NSTX-U Program Letter:** *"To interpret the measurements, knowledge of accurate atomic physics factors, such as ionizations per photon and photon emission coefficients, is needed for common NSTX-U impurities originating from plasma-facing component materials, surface contamination, or those seeded externally."*

High-Z Material Erosion is a Critical Research Priority

- NSTX-U will have an impressive suite of spectroscopic diagnostics for measuring edge plasma characteristics (NIR, VIS, UV, VUV, EUV)
- However, many of the atomic calculations needed for correct interpretation of spectroscopic measurements are known to be inaccurate or don't exist
- Example: PISCES B experiment measured Mo I SXB ratios to be different from calculated values by as much as a factor of 5 [Nishijima *et al.* J. Phys. B: At. Mol. Opt. Phys. 2010]
- Impacts line identification, measurements of wall erosion and re-depostion rates

Auburn Proposed Work to Extend NSTX-U Spectroscopy Capabilities

- **Proposed work:** Calculate and benchmark (using CTH experiment at Auburn) SXB ratios for various ionization states of Mo, W, O & Ar for NSTX-U plasma conditions
- **Purpose:** Determine wall erosion & re-deposition rates for high-Z elements of the NSTX-U PFC
- Identify line ratios to be used for temperature diagnostics of NSTX-U edge plasmas

Auburn Proposed Work to Extend NSTX-U Spectroscopy Capabilities

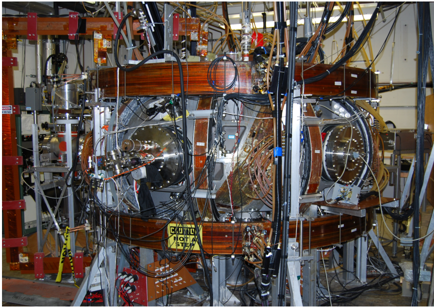
- NSTX-U spectrometers that we aim to support:
  - Two imaging spectrometers with sub-angstrom resolution (250-300 to 1100 nm)
  - VUV spectrometer SPRED with a localized view of the outer divertor leg (200-1650 Å & 100-240 Å)
  - Note: image splitter allows imaging of the same divertor regions at two wavelengths

Proposed work directly addresses NSTX-U priorities in five year plan and diagnostics FOA (Plasma Boundary Interfaces)

Outline

Benchmarking SXB Ratios Using the Compact Toroidal Hybrid (CTH)

- CTH designed to study effects of 3D magnetic shaping on disruptions & instabilities
- CTH has a number of different operating regimes:
  - Current-free vs. current-carrying plasmas
  - Significantly vary the amount of externally applied 3D field



$R_0 = 0.75$ m	$\lvert B \rvert \leq 0.7$ T	$n_e \leq 5 \times 10^{19}$ m^{-3}
$R/a \sim 4$	$I_p \leq 80$ kA	$T_e \leq 200$ eV

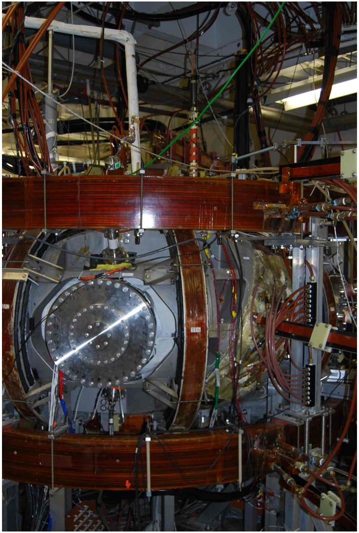
Ramping up CTH Spectroscopic Capabilities

- CTH Survey Spectrometers:
  - StellarNet BlackComet (200 to 1100 nm) *Operational*
  - StellarNet BlackComet (200 to 600 nm) *Operational*
  - StellarNet BlueWave (400 to 600 nm) *Operational*
  - StellarNet EPP2000 (200 to 300 nm) *On order* $\sim$ *2 weeks*
- CTH Higher-Dispersion Spectrometers:
  - McPherson 209 (UV-Vis-IR) *Upgrading to UV*
  - McPherson 218 (VUV-Vis-IR)

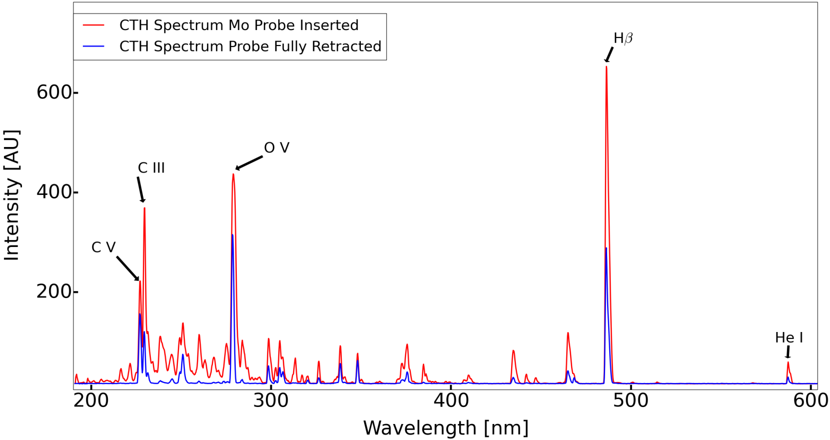
- *Emphasis on UV wavelengths to focus on high-Z elements (Mo, W)*

Molybdenum Probe Experiments Underway on CTH

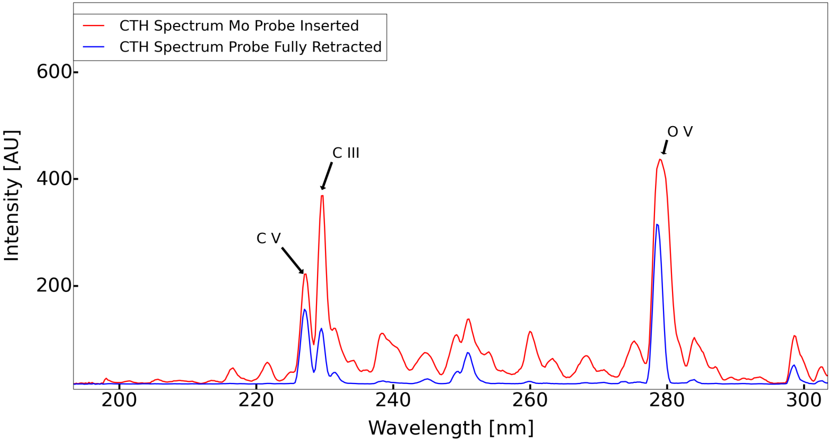
- Probe with molybdenum tip inserted from top port to just beyond last closed flux surface
- Spectrometer viewing probe from bottom viewport



Numerous Emission Lines Increase when Mo Probe Inserted into CTH Plasmas



Numerous Emission Lines Increase when Mo Probe Inserted into CTH Plasmas



- Some emission lines consistent with Mo II (*shown later*)

Ionizations per Photon - SXB Ratios

- The intensity of a spectral line can be related to its influx rate [Behringer PPCF **31** 2059 (1989)]
- The number of 'ionizations per photon' (or SXB) is directly proportional to the impurity influx (Γ)

$$\Gamma = \int_0^\infty N_e N^z S^{z \to z+1} dx$$

Ionizations per Photon - SXB Ratios

- The intensity of a spectral line can be related to its influx rate [Behringer PPCF **31** 2059 (1989)]
- The number of 'ionizations per photon' (or SXB) is directly proportional to the impurity influx (Γ)

$$\Gamma = \int_0^\infty N_e N^z S^{z\rightarrow z+1} dx = \int_0^\infty N_e \frac{S^{z\rightarrow z+1}}{A_{i\rightarrow j}\frac{N_i}{N^z}} \left(A_{i\rightarrow j} \frac{N_i}{N^z} \right) N^z dx$$

Ionizations per Photon - SXB Ratios

- The intensity of a spectral line can be related to its influx rate [Behringer PPCF **31** 2059 (1989)]
- The number of 'ionizations per photon' (or SXB) is directly proportional to the impurity influx (Γ)

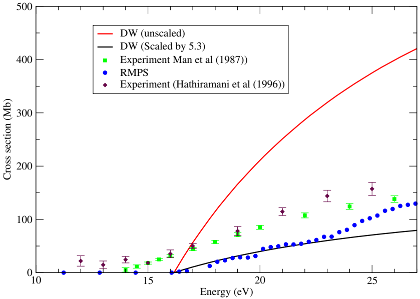
$$\Gamma = \int_0^\infty N_e N^z S^{z\to z+1} dx = \int_0^\infty N_e \frac{S^{z\to z+1}}{A_{i\to j}\frac{N_i}{N^z}} \left(A_{i\to j}\frac{N_j}{N^z} \right) N^z dx$$

$$= \int_0^\infty N_e SXB^z_{i\to j} \left(A_{i\to j}\frac{N_j}{N^z} \right) N^z dx$$

where $SXB^z_{i\to j} = \frac{S^{z\to z+1}(N_e,T_e)}{A_{i\to j}\frac{N_i}{N^z}(N_e,T_e)}$

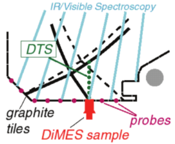
Perturbation Theory not Accurate for Low Charge States

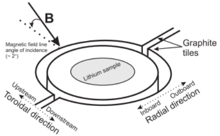
- **Electron-impact ionization ($S^{z\rightarrow z+1}$) and excitation data**
  - **Perturbation theory** works well for high charge states (> 5+)
  - Below 5+ requires **non-perturbative methods**
    - TDCC, *R*-matrix with pseudostates (RMPS), CCC
- Ionization from excited states is very important
- Non-perturbative calculations are very challenging for low charge states of high-Z systems

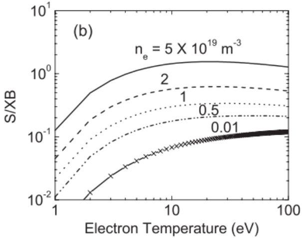


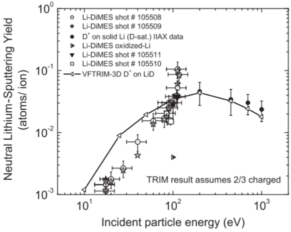
Previous PFC Erosion Studies

- SXB ratios have been used to determine influx rates for:
  - C using the C I 657.8 nm line [Field et al., Nucl. Fusion (1996)]
  - Li erosion and transport at DIII-D [Allain et al., Nucl. Fusion (2004)]
  - Mo using Mo I 386.4 nm [Lipschultz et al., Nucl. Fusion (2001)]



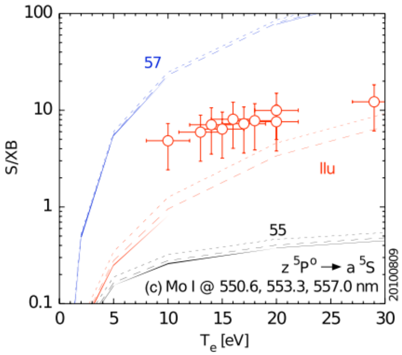






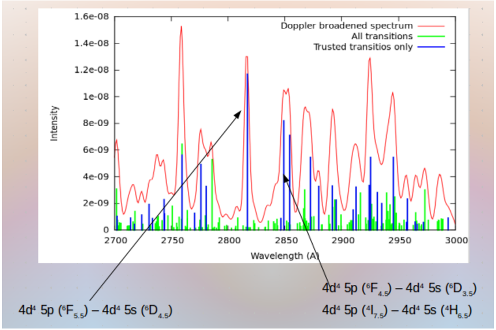
Previous Mo Erosion Studies

- Phillips et al. Nucl. Fusion (1994) used the Mo I 390.3 nm for TEXTOR studies
- Lipschultz et al., Nucl Fusion (2001)
    - Used Badnell et al. data [J. Phys. B (1996)] and Mo I 386.4 nm line
    - Determined which Mo PFCs at Alcator C-Mod were the dominant sources for Mo influx
- Recently, PISCES-B measurements [Nishijima et al., J. Phys. B (2010)] found up to factors of 2-5 difference with the SXB ratios from Badnell et al. (1996)



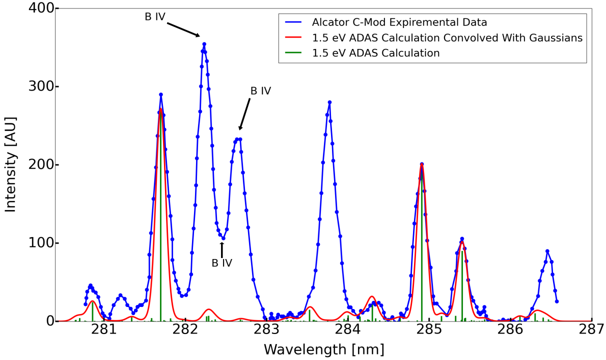
New SXBs for Mo II

- We generated new SXBs for Mo II SXBs
    - RMPS data for excitation and ionization
    - Shifted to NIST energies
- 2400 strong lines from 2000-4000 Å
- Filter on this line list, first filter produced 240 lines, **second filter produced three unblended**



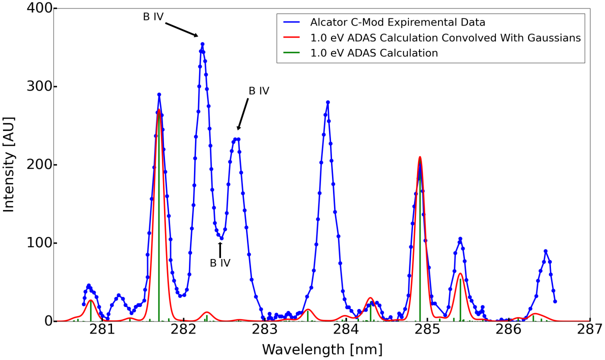
Comparison with Alcator C-Mod Spectrum

- Good match with the measured spectrum
- Relative line heights are not strongly N_e dependent, but two of the lines were strongly T_e dependent



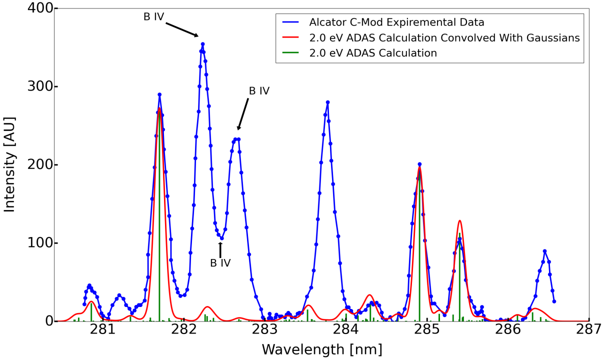
Comparison with Alcator C-Mod Spectrum

- Good match with the measured spectrum
- Relative line heights are not strongly N_e dependent, but two of the lines were strongly T_e dependent

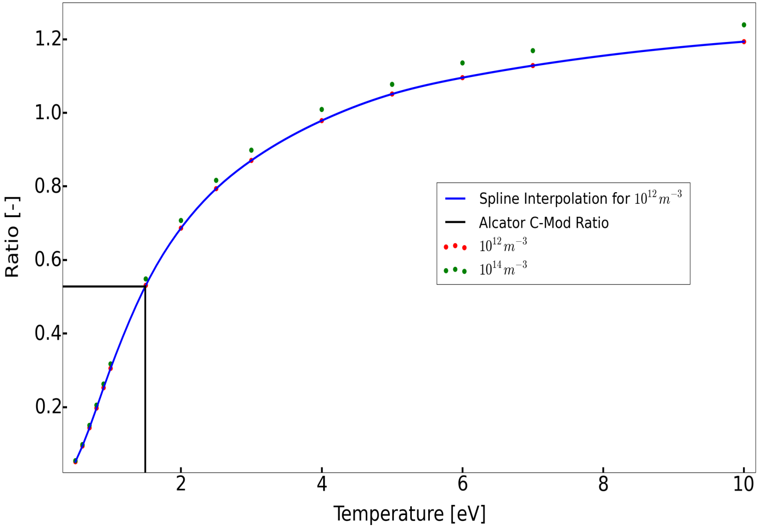


Comparison with Alcator C-Mod Spectrum

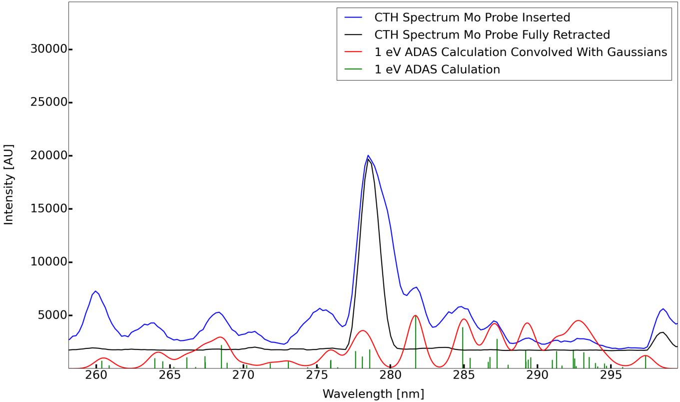
- Good match with the measured spectrum
- Relative line heights are not strongly N_e dependent, but two of the lines were strongly T_e dependent



Temperature Dependence of the Recommended Lines

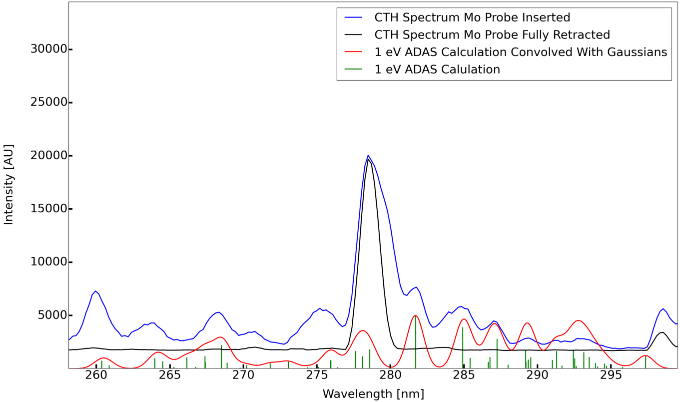


Comparison with CTH Spectrum



- Initial CTH results look promising with similar lines to Alcator C-Mod
- O V line blended with some of the features

Comparison with CTH Spectrum



- Many lines could be used from Mo II (or Mo I)
- New spectrometer should allow resolution of Mo I and Mo II features

Using Multiple Charge States for Wall Erosion Rate Measurements

- Not previously done: use multiple charge states of a high-Z material to independently measure the erosion rate
- Provides a rigorous influx diagnostic for investigating:
  - Re-deposition rates
  - Whether the Mo or W enters the plasma as a neutral
- Hence our plan to have data for the first three charge states of Mo and W

Details of Proposed Work for NSTX-U

- To determine high-Z PFC wall erosion and re-deposition rates for NSTX-U we plan to:
  - Use existing Mo II data to analyze NSTX-U spectra from granule injection experiments and Mo tiles
  - Generate ionizations per photon for:
    - Mo I & Mo III
    - W I, W II, & W III
  - Benchmark each of these calculations using CTH
- Analyze NSTX-U spectra to identify emission lines for edge temperature diagnostics
- Could also generate O II & Ar SXBs, with benchmarks on CTH

Summary

- High-Z elements for PFC present particular challenges for accurate diagnostics of erosion rates requiring accurate atomic calculations and experimental benchmarks
- We propose a set of benchmarks using the Auburn CTH experiment, coupled with new SXB calculations
  - Initial results with Mo II look promising
  - Plan to finish Mo stages (I & III)
  - Calculate and benchmark W (I, II, & III)
- Will improve the accuracy and extend the capability of high-Z PFC diagnostics for NSTX-U

Status of Current Mo I SXBs

- Distorted-wave data was used for the ground state ionization cross sections
- Semi-empirical data was used for the excited state ionization cross sections
- A term-resolved *R*-matrix calculation generated the excitation data, as big as could be done at the time
- The differences found at PISCES-B are not too surprising

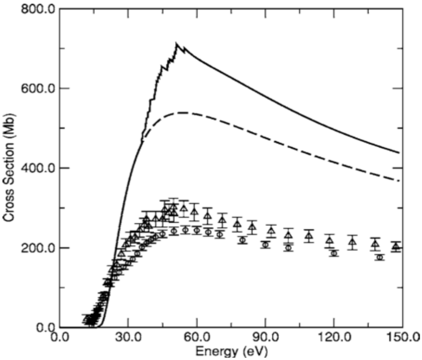


Figure taken from Ludlow et al. PRA **75** 32729 (2005)