Impurity Transport and Spectroscopy Studies on the Alcator C-Mod Tokamak

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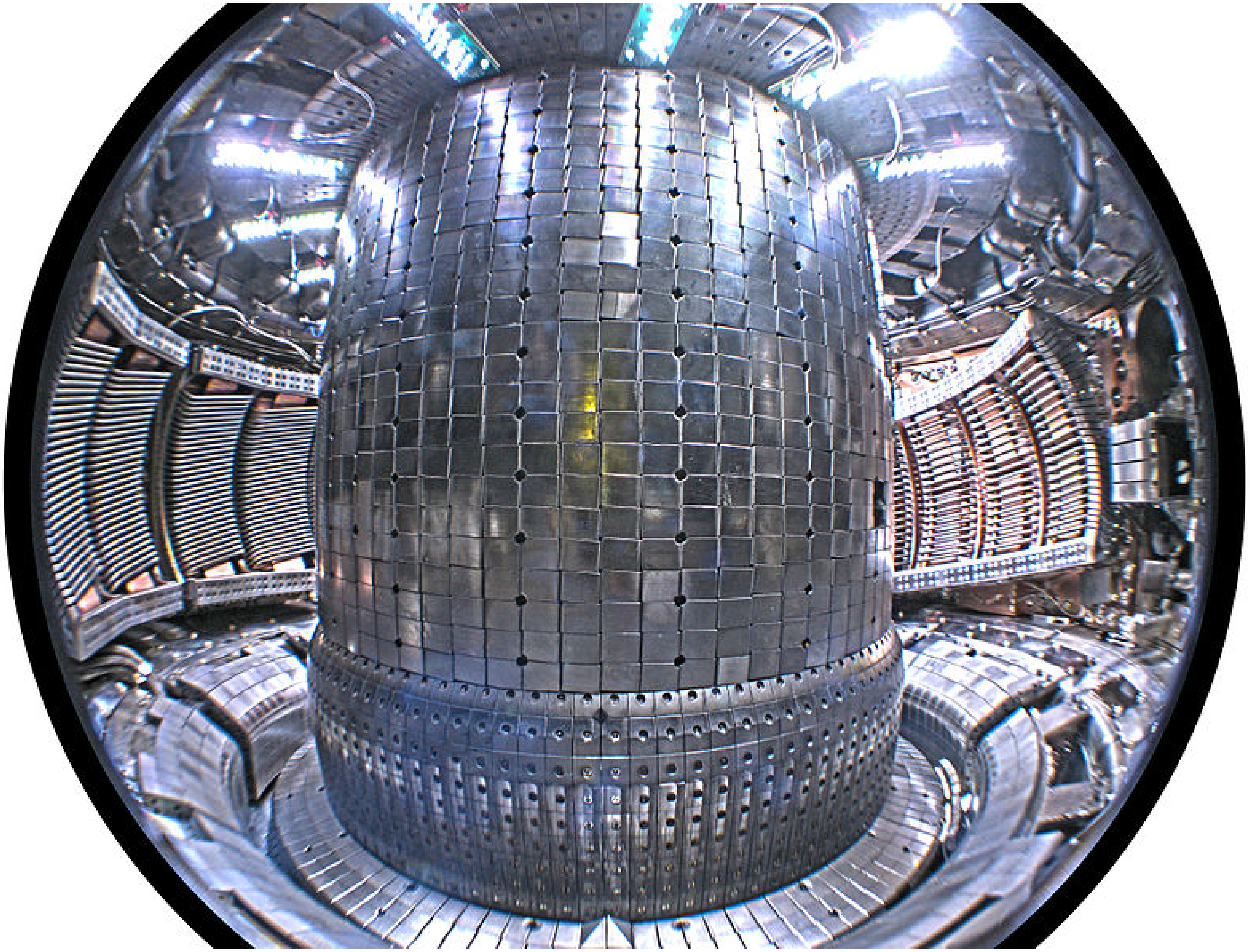
Alcator C-Mod

Topics to be Covered

- **brief introduction to Alcator C-Mod and its impurities**
- **upgrades/advancements to spectroscopy diagnostics**
- **areas where we can contribute to the community**
  - THACO – a comprehensive modeling and analysis package for X-ray imaging crystal spectroscopy (XICS)
  - cross-machine spectroscopy visualization tools
  - tests of n_e, T_e sensitivity of line-ratios for astrophysical use
- **areas where we would like some assistance**
  - charge-exchange cross-sections at low energies - gas puff CXRS
  - molecular D_2,H_2 line-emission contamination of CXRS spectra
  - S/XB data for various impurities

The Alcator C-Mod Tokamak

A high field, B_t < 8 T, compact, R_o=0.68 [m] a=0.205 [m] tokamak with all solid metal (Mo) plasma facing components



http://en.wikipedia.org/wiki/File:Alcator_C-Mod_Tokamak_Interior.jpg

$n_{e,0} < 1.0\times10^{21}$ m^{-3}
$T_{e,0}$ < 9 keV

Primary Auxiliary Heating is ICRF < 6 MW (8 MW source)

density measured using Thomson scattering and two-color interferometry

temperature measured using Thomson scattering and electron cyclotron emission

Alcator C-Mod Has a Wide Range of Impurities

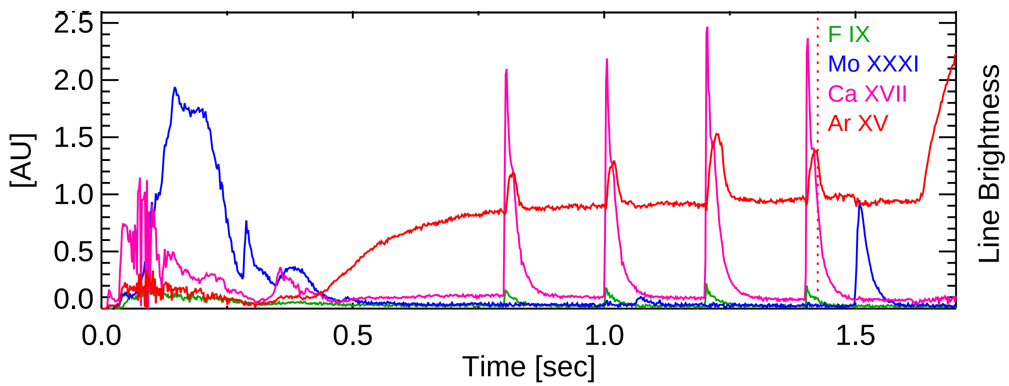
KEY: steady-state *injections* **primary** **extrinsic**

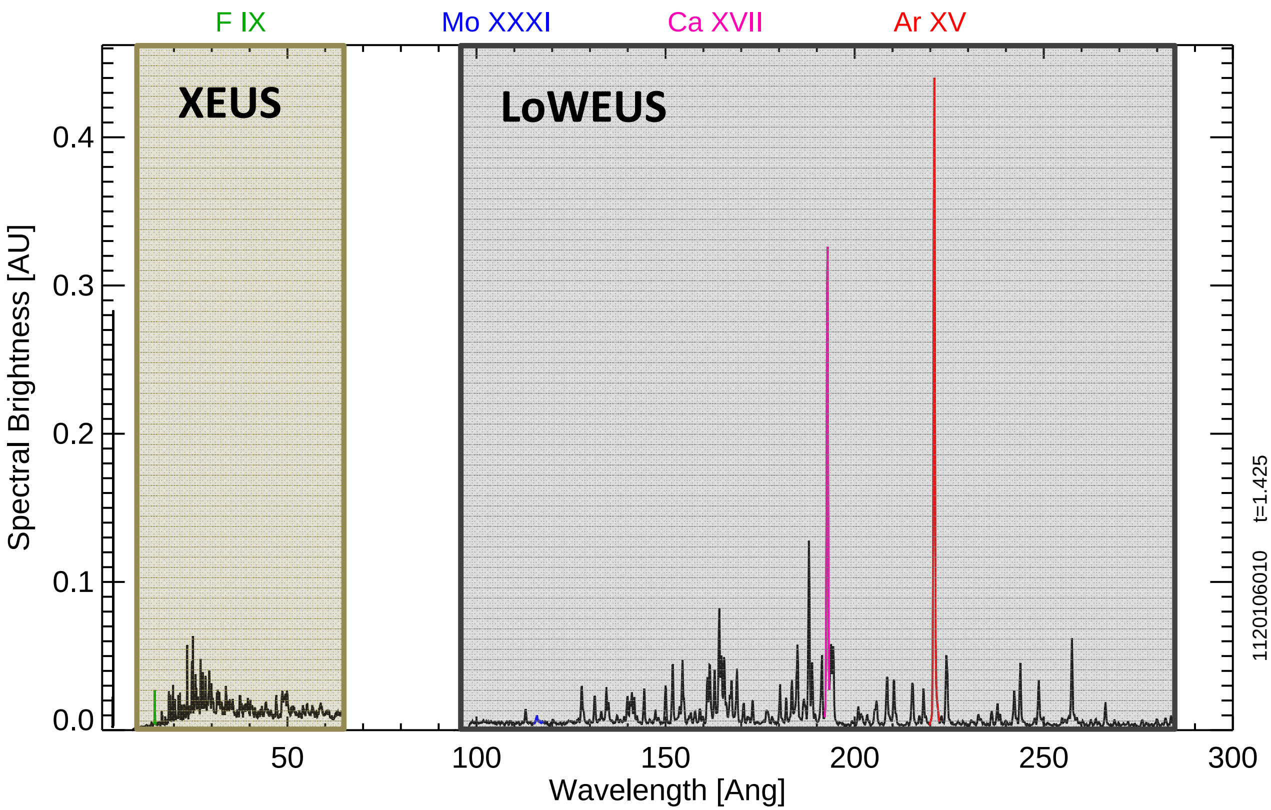
Helium	gas puff imaging of edge turbulence, D(^{3}He) heating
Boron	boron-coated tiles, periodic boronization
Carbon	seen after vessel entry, prior to first boronization
Oxygen	unknown but seems to tied to limiter
Nitrogen	seeding for heat flux mitigation and ICRF performance
Fluorine	assumed to come from teflon coated/jacketed cables
Neon	seeding for heat flux mitigation and ICRF performance
Argon	for use with X-ray imaging crystal spectroscopy (T_i, rotation)
Calcium	injected using laser blow-off for impurity transport studies
Titanium	TiC-coated rods in Faraday screen
Iron	stainless-steel* in-vessel structures
Nickel	Inconel antenna structures
Copper	copper-coated ICRF antenna straps
Molybdenum	limiters and divertors
Tungsten	Langmuir probes and remnants from melted outer divertor

(*occasionally see other traces from metal processing like S, Cl, Mn, Cr)

Expanded Coverage of VUV/SXR Spectrum

collaboration w/ LLNL, installed two flat-field VUV/SXR spec.



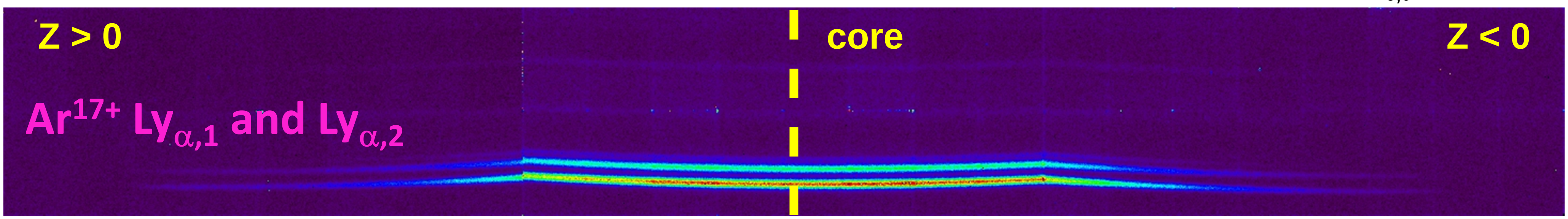


- FY10: installed a “XEUS” 1 < λ < 6 nm, for H/He-like B → Ne
- FY 11 – installed a “LoWEUS” 10 < λ < 30 nm for Li/Be-like metals, Na/Mg-like Mo and Cu/Zn-like W and He II Lyman series
- both have ~radial core views, use CCDs and operate at 500 Hz

High-T_e Operation of X-ray Imaging Spectroscopy

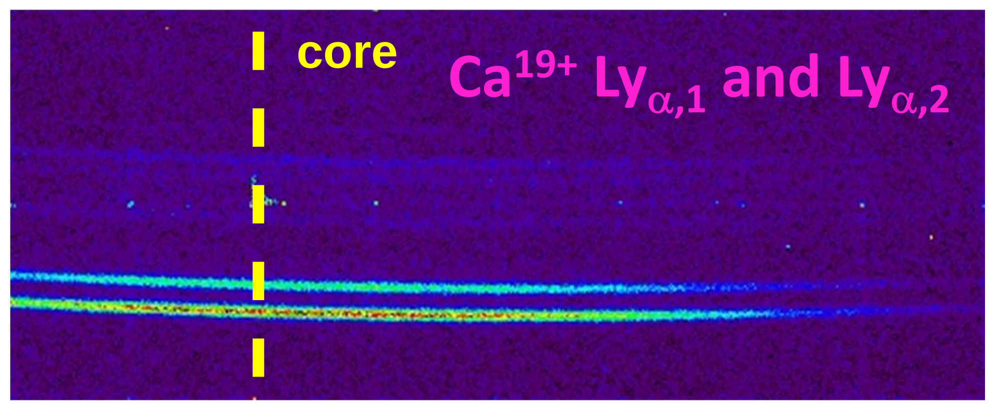
- Alcator C-Mod operates a two-branch XICS to measure **<u>local</u>** T_i, flow and impurity density profiles using H/He-like Ar
  - For T_e > 4 keV, He-like Ar burns out and H-like emission extends beyond core
- Modified Bragg angles to view full profile H-like Ar and H-like Ca in the core to be used for laser blow-off studies

1120824019 @ t =1.09 $T_{e,0}$ ~ 5+ keV



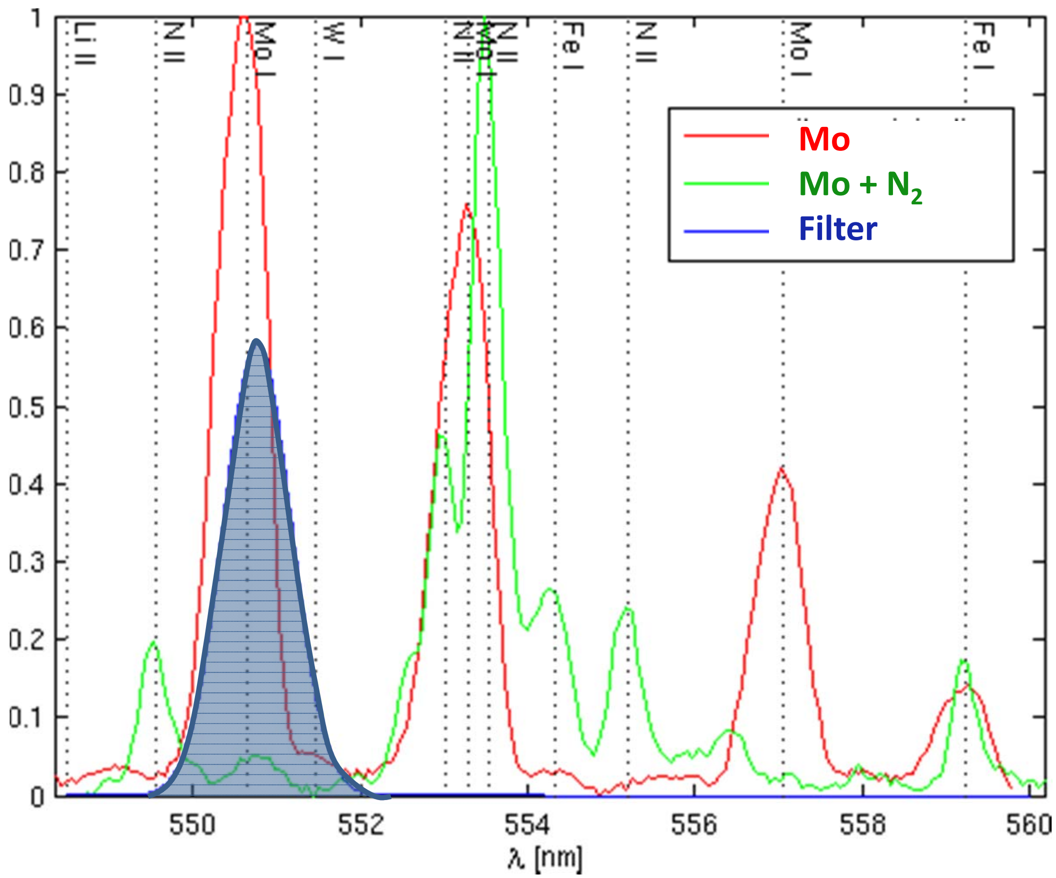
demonstration of good profile coverage for H-like Ca injections, even for T_e ~ 3 keV

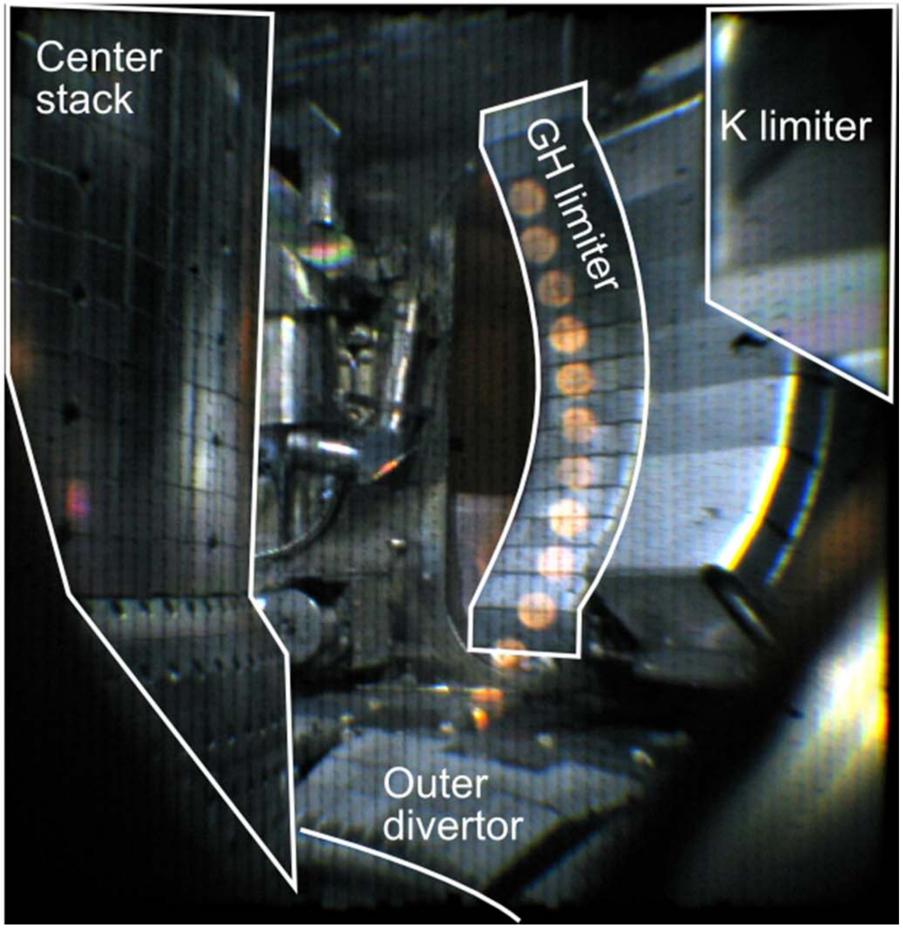
have crystals to try He-like Kr and Ne-like W, but lack experimental time due to diagnostic demand



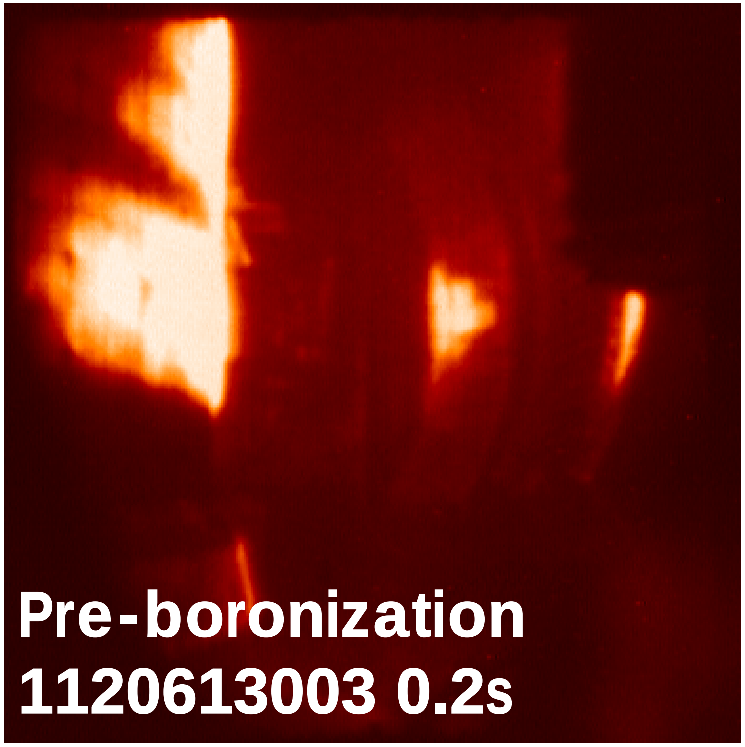
Visible Imaging of PFCs For Erosion Studies

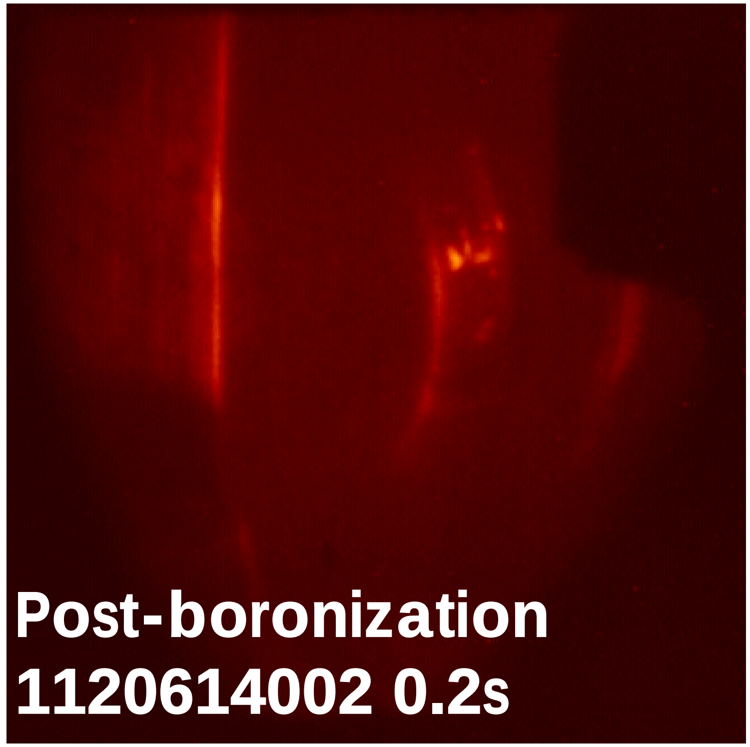
- intensified camera views time-evolving emission from a variety of molybdenum plasma facing components (PFCs)
- filter wheel enables selection of impurity or fueling studies
- use λ ~ 551 Mo I emission





Initial Results Show Promise of Technique



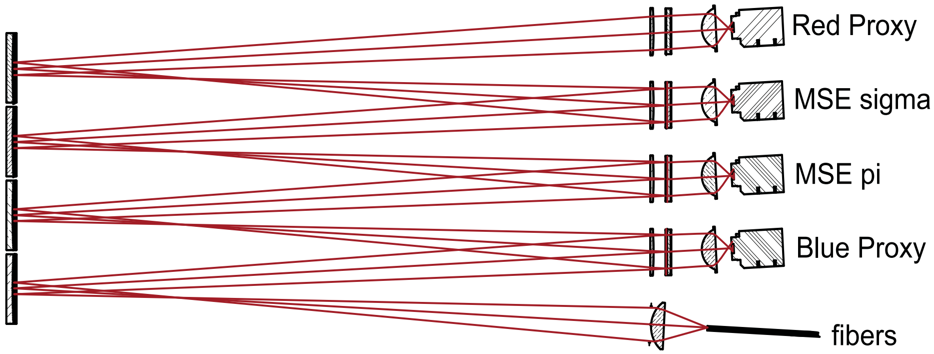


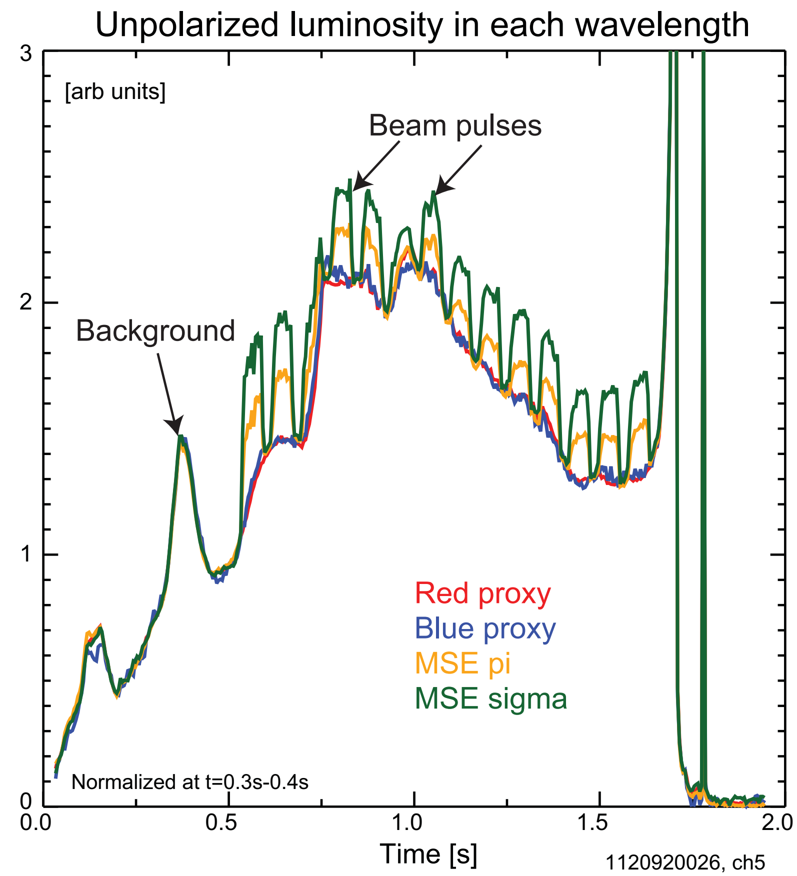
change in source across boronization clearly observed

- track Mo emission between different active ICRF antennas, power level and phasing
- quantitative analysis difficult due to continuum (Planck + brem.)
- working to demonstrate **rotating filter during discharge**

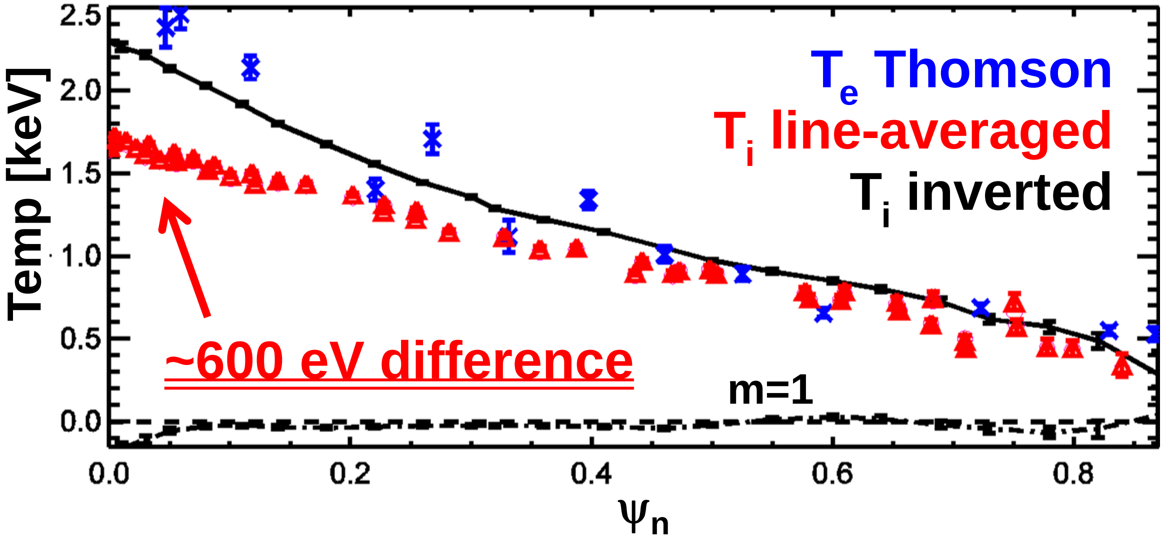
MSE Real-time Background Subtraction

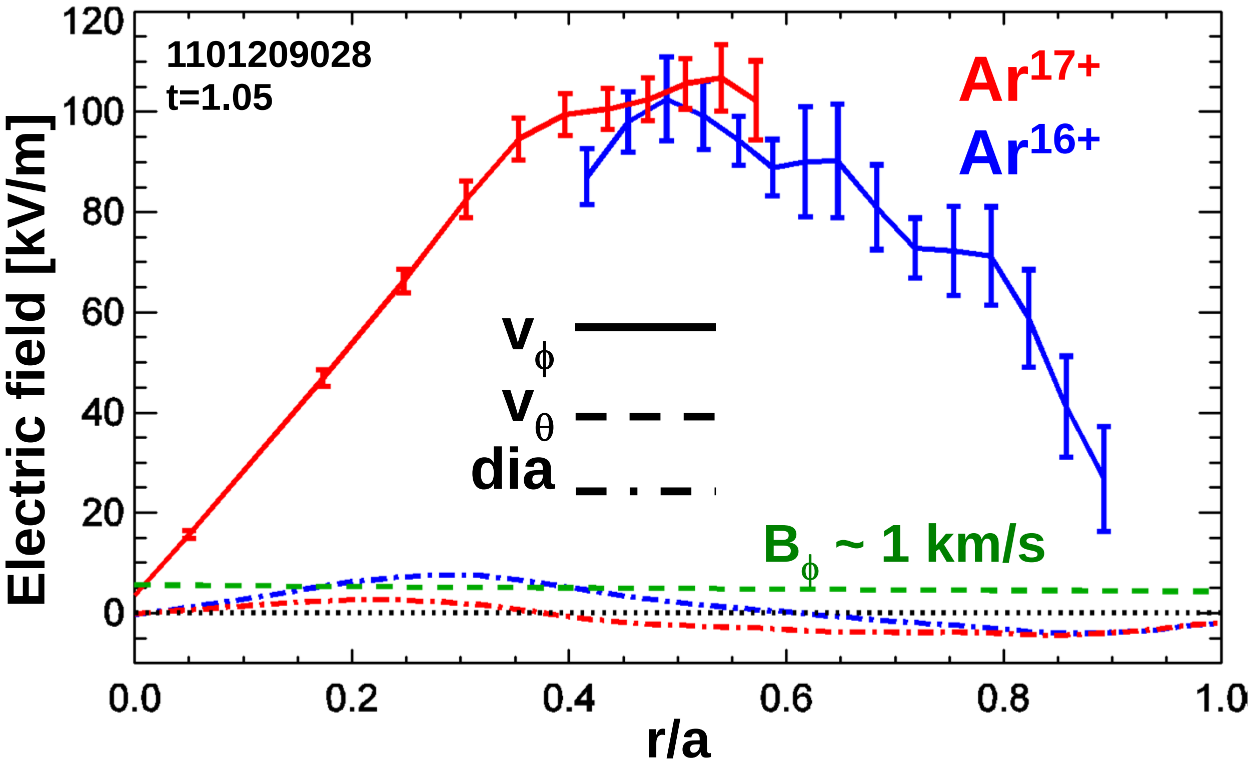
- 4 wavelength polychromator allows simultaneous measurement along the same sightline
  - MSE – pi emision
  - MSE – sigma emission
  - Lower and higher wavelengths
- enables real time interpolation of polarized background in wavelength
  - possible to forgo beam modulation?
  - critical for metal walled machines that lack proper view dumps (ITER)
- enables simultaneous polarization measurement of MSE sigma and pi components





X-ray Imaging Crystal Spectroscopy Demonstrated



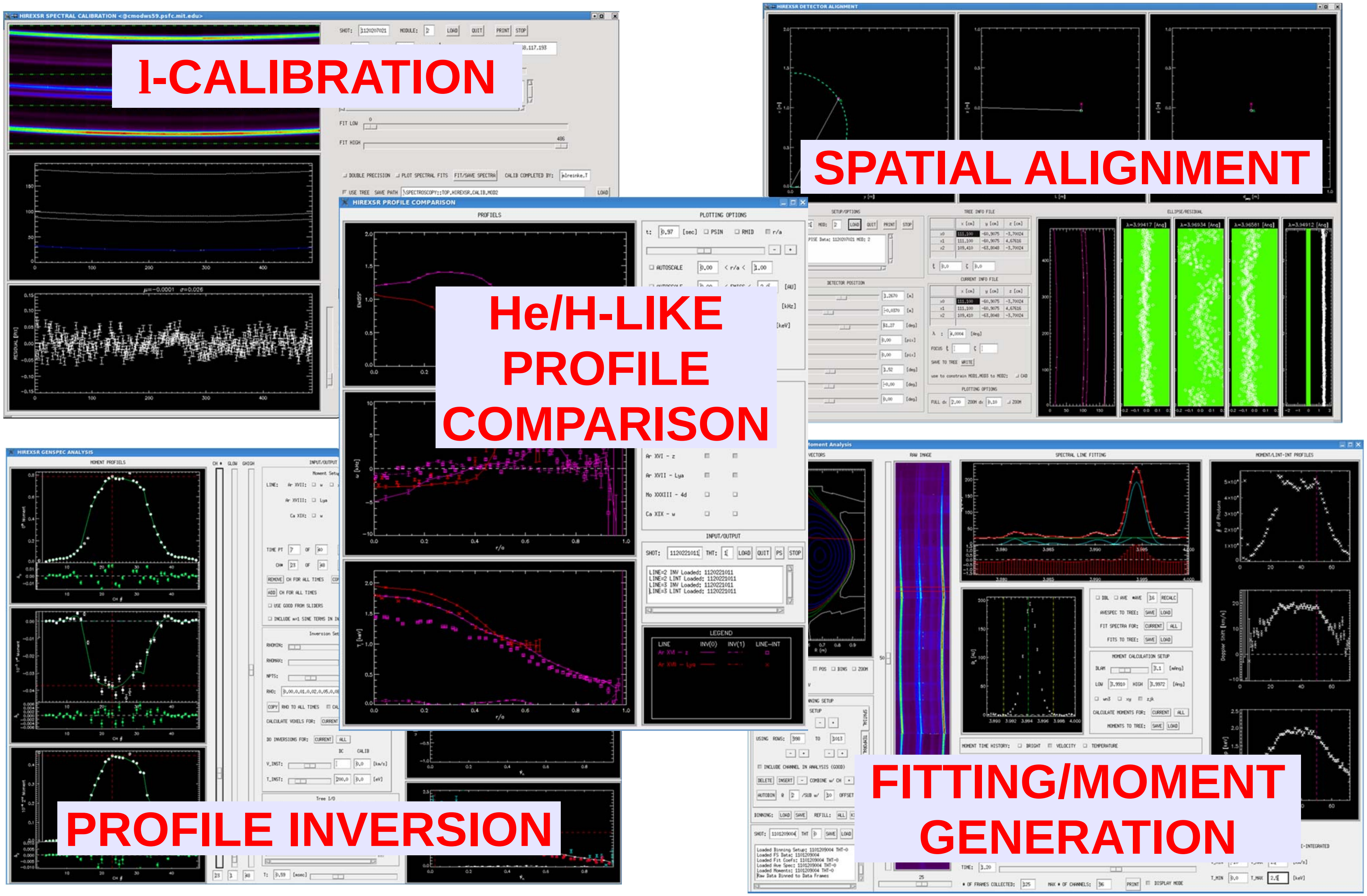


- Doppler tomography software for C-Mod's imaging crystal spectrometer developed for routine analysis
- inversion of line-integrated spectra necessary to obtain accurate local profiles
- data are being used to determine $\nabla T_i/T_i$ and $E \times B$ shear for gyro. transport analysis
- LBO impurity transport

Need to cross-check XICS against CXRS

The HIREXSR Analysis COde (THACO)

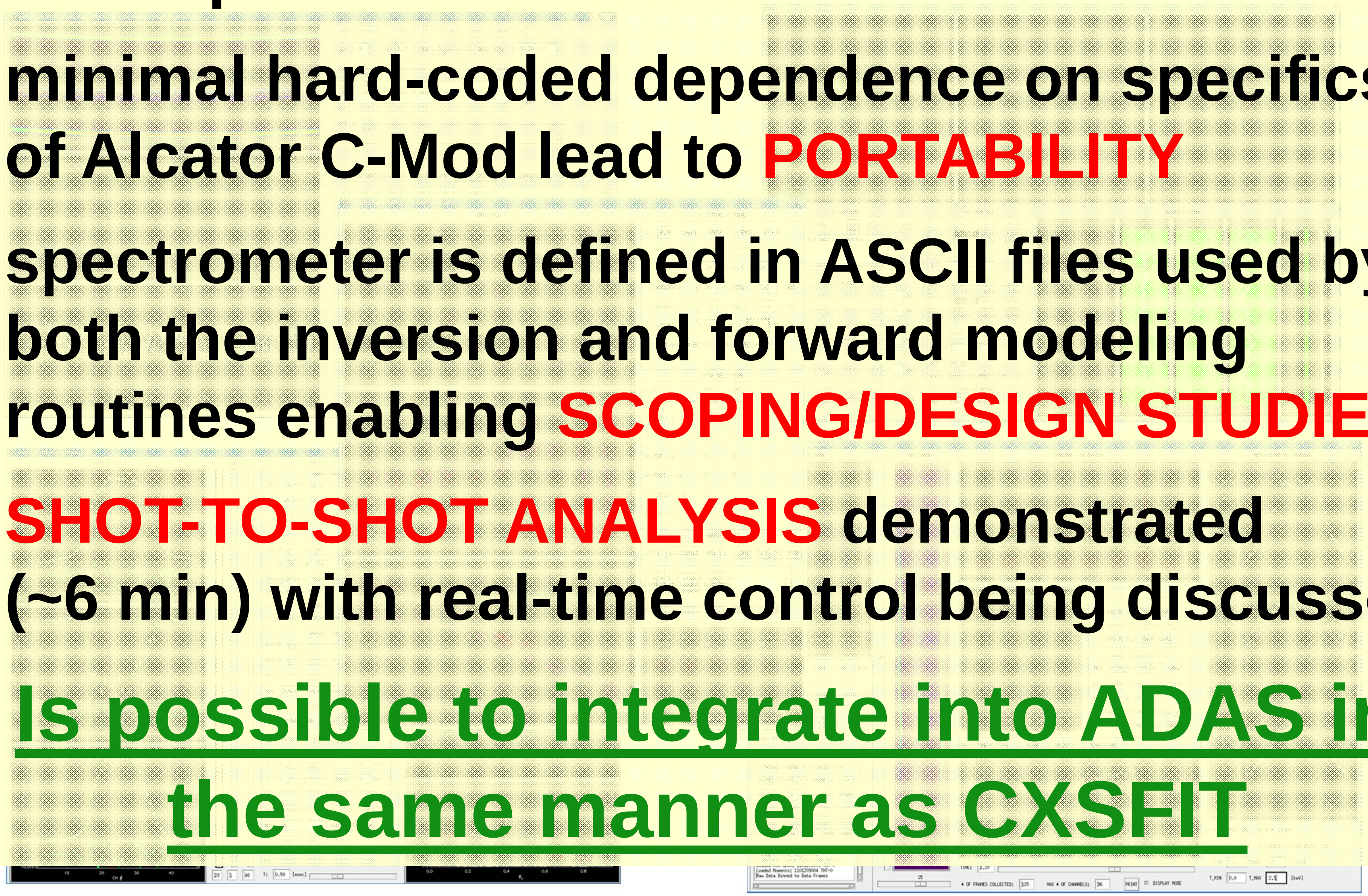
A package of GUI and command-line utilities for:



The HIREXSR Analysis COde (THACO)

- **developed in IDL for use with MDSPlus**
- **minimal hard-coded dependence on specifics of Alcator C-Mod lead to PORTABILITY**
- **spectrometer is defined in ASCII files used by both the inversion and forward modeling routines enabling SCOPING/DESIGN STUDIES**
- **SHOT-TO-SHOT ANALYSIS demonstrated (~6 min) with real-time control being discussed**

Is possible to integrate into ADAS in the same manner as CXSFIT



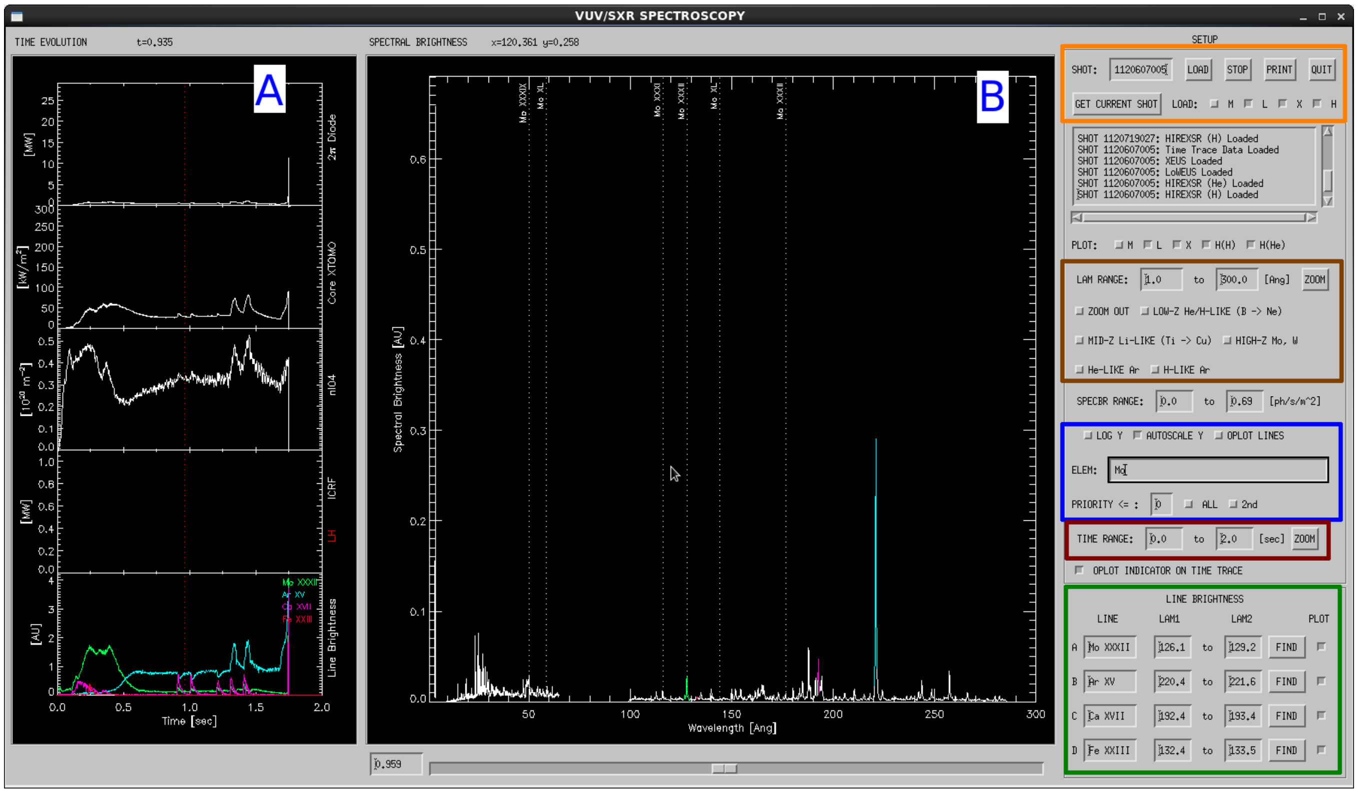
Cross-Machine Spectroscopy Analysis Tools

- C-Mod is working to develop IDL tools and a workflow for **machine independent spectroscopy analysis**
- significant duplication occurring at all tokamaks which utilize a similar diagnostic set of VUV/SXR instrumentation to characterize impurity content

not every part of the spectrum must contribute data

- employ a focus on 1 & 2 electron systems which are easy to model and have bright lines

See M.L. Reinke APS 2012



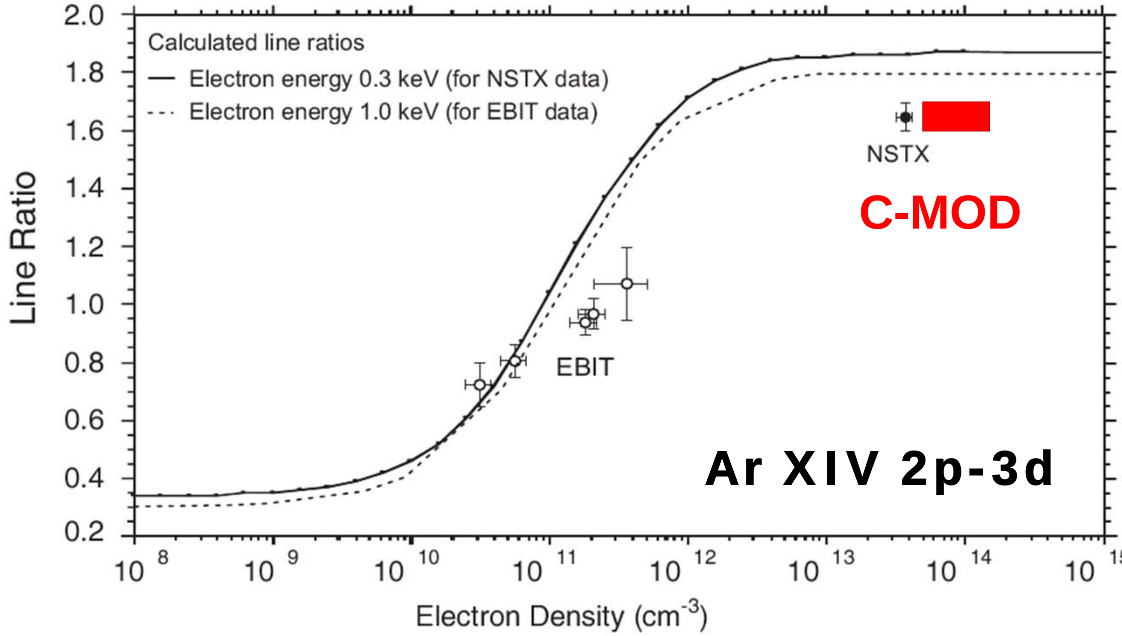
Line Ratios For Diagnosing Astrophysical Plasmas

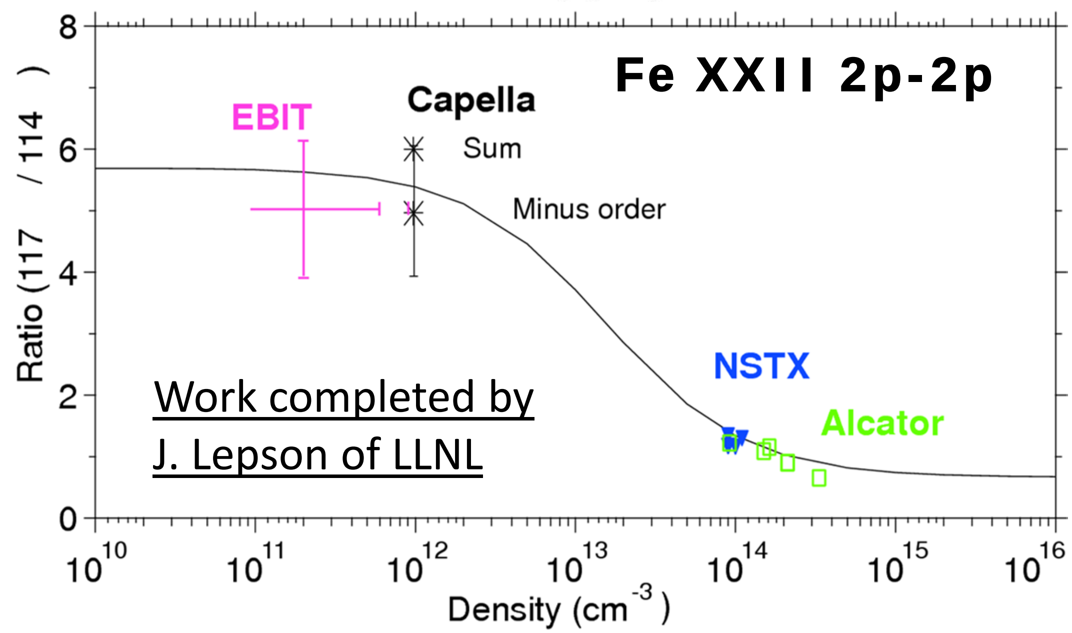
boron iso-elec. seq. is used for n_e diagnostic astrophysical plasmas

- C-Mod provides high density point for tests
- interested in doing single-device Z-scan of using laser blow-off

can work to validate the resonance vs. DR satellite lines for T_e diagnostic

- have data for He-like and H-like Ar and Ca
- “low priority”, help wanted





C-Mod Pioneered CXRS using Neutral Gas Puff

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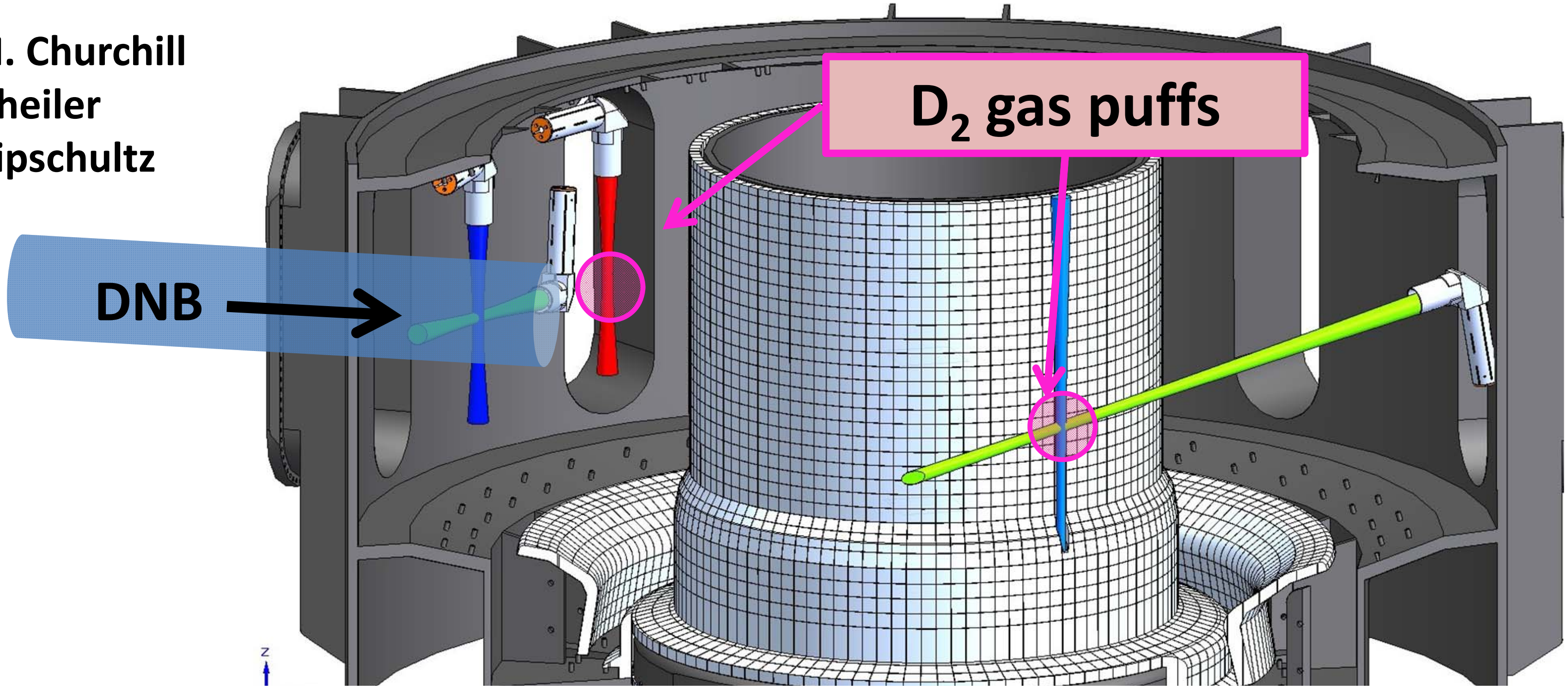
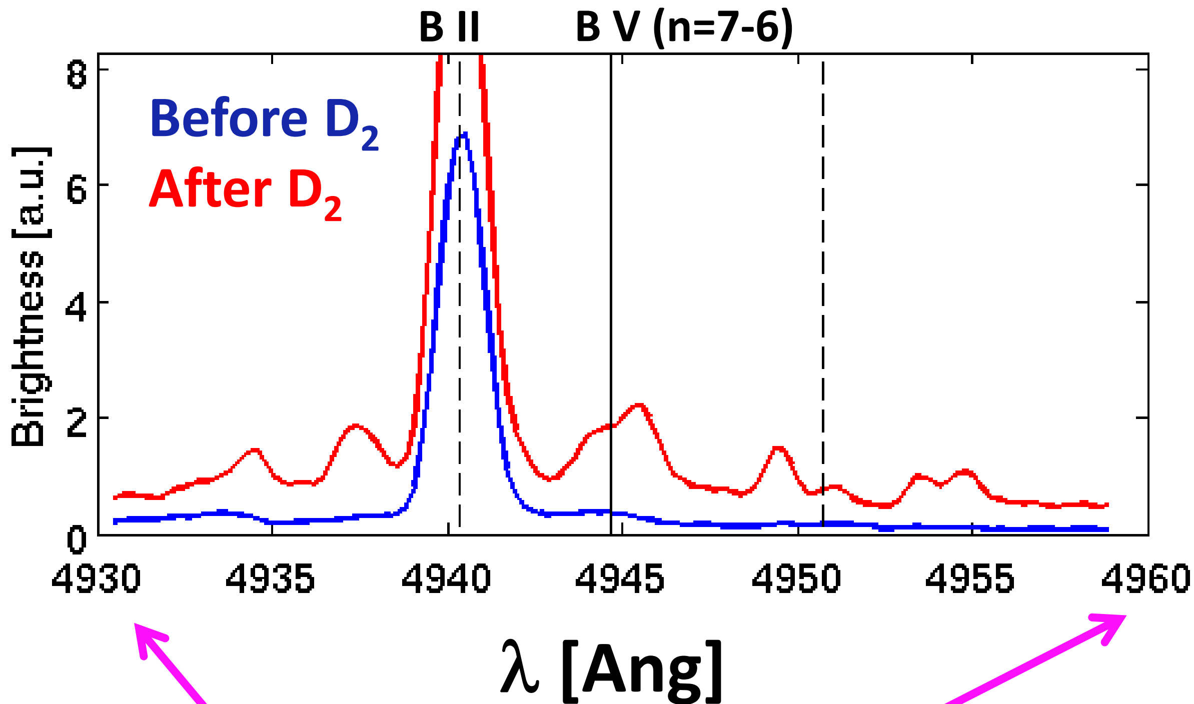
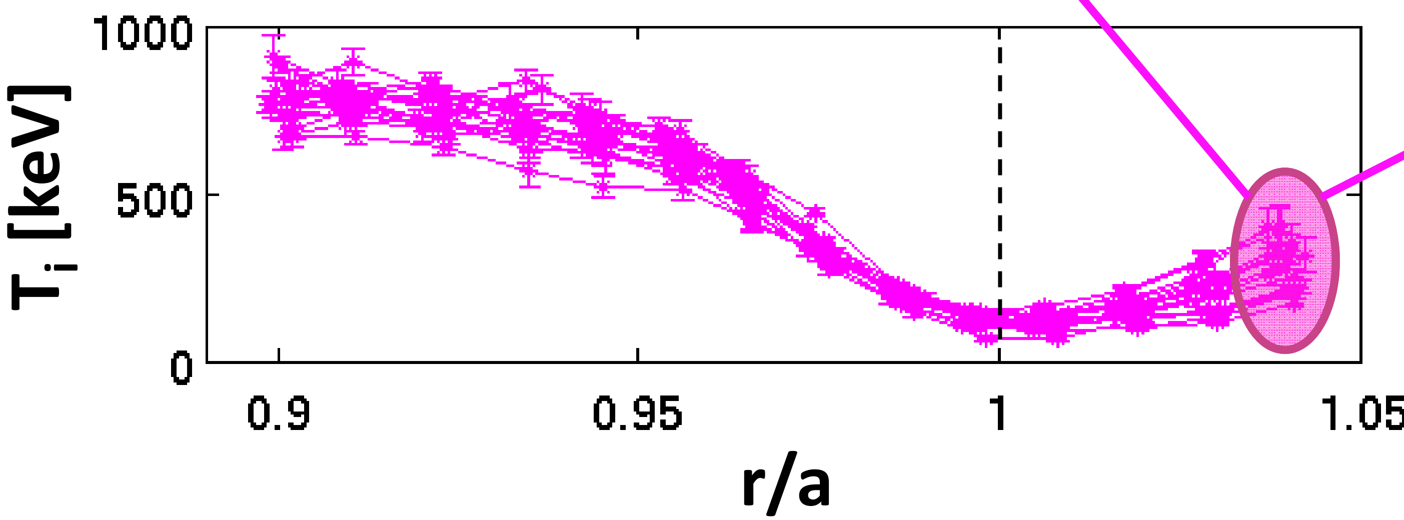


- DNB-based pedestal CXRS demonstrated high resolution T_i, flows, impurity density and radial electric field [R. McDermott PoP 2009]
- reliability issues with DNB have prevented continued use of this method
- use cold D_2 puff at inboard/outboard side to enhance CXRS
  - **the $D(n{=}2) + B^{5+} \rightarrow D^{+} + B^{4+}(n{=}7)$ reaction dominates the excitation**
  - the excited state reaction populates visible transition in all low-Z (dem. Ne)

Technique Complicated by Enhance Mol. Emission

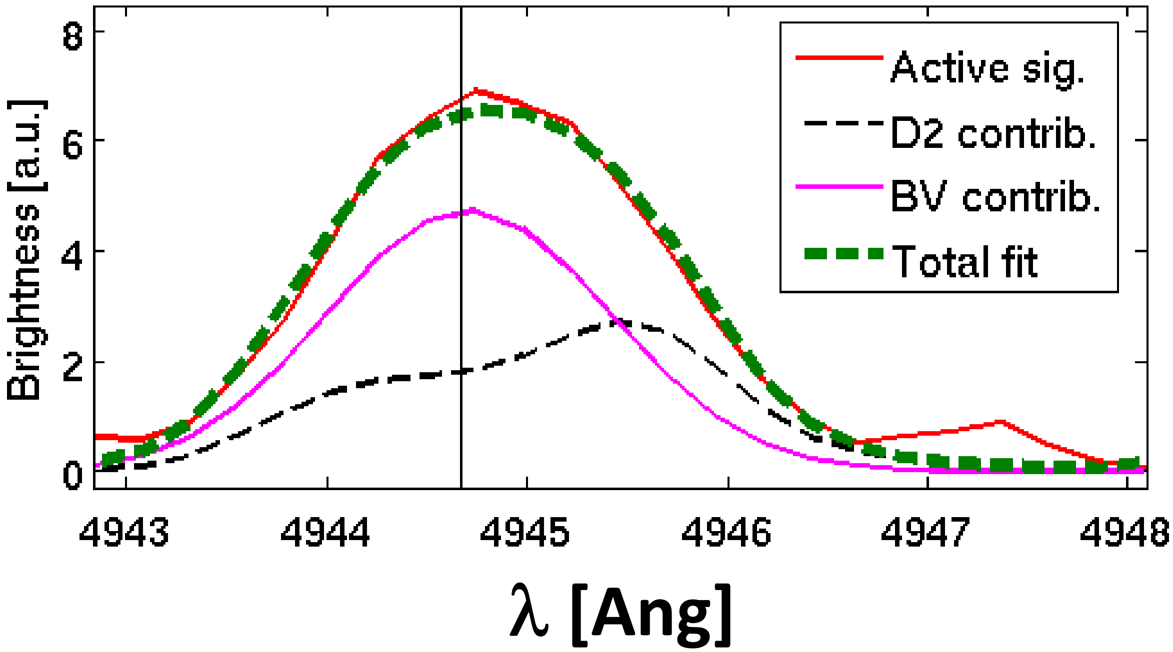
- near seperatrix, the D_2 gas puff produces strong molecular contributions
- these lines blend with the n=7-6 B V transition
- leads to over prediction of T_i and errors in the Doppler shift





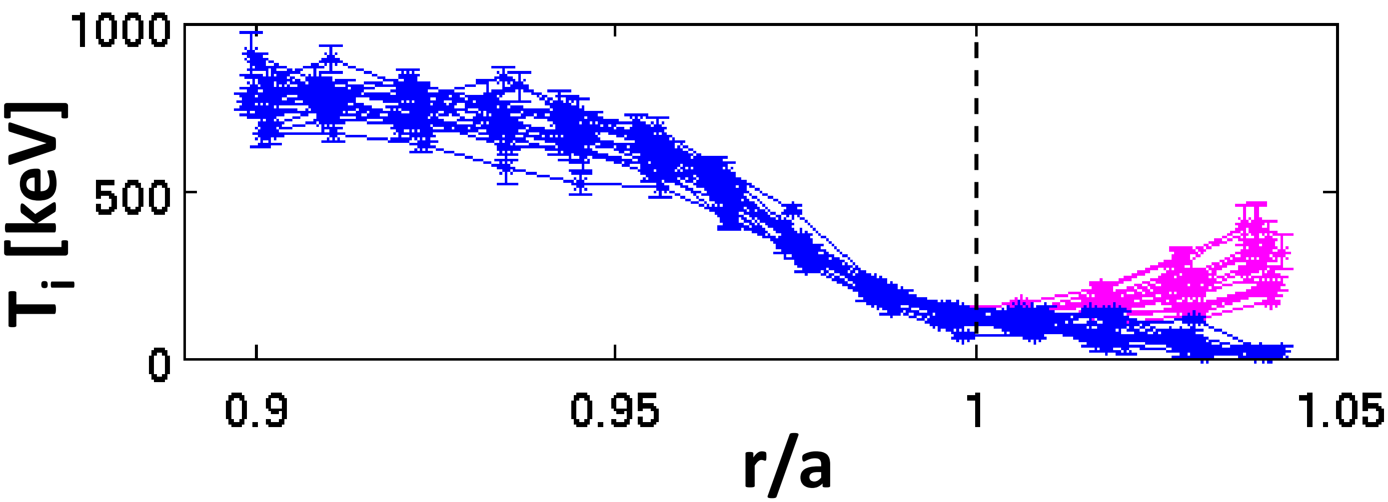
This effect NOT present when C-X induced with a H_2 or He gas puff

Correction Technique Based on Neighboring Lines



- scale a D_2 contribution based on neighboring molecular lines
- include in fit to find the active B V CXRS

can we use ADAS molecular emission modeling to validate?



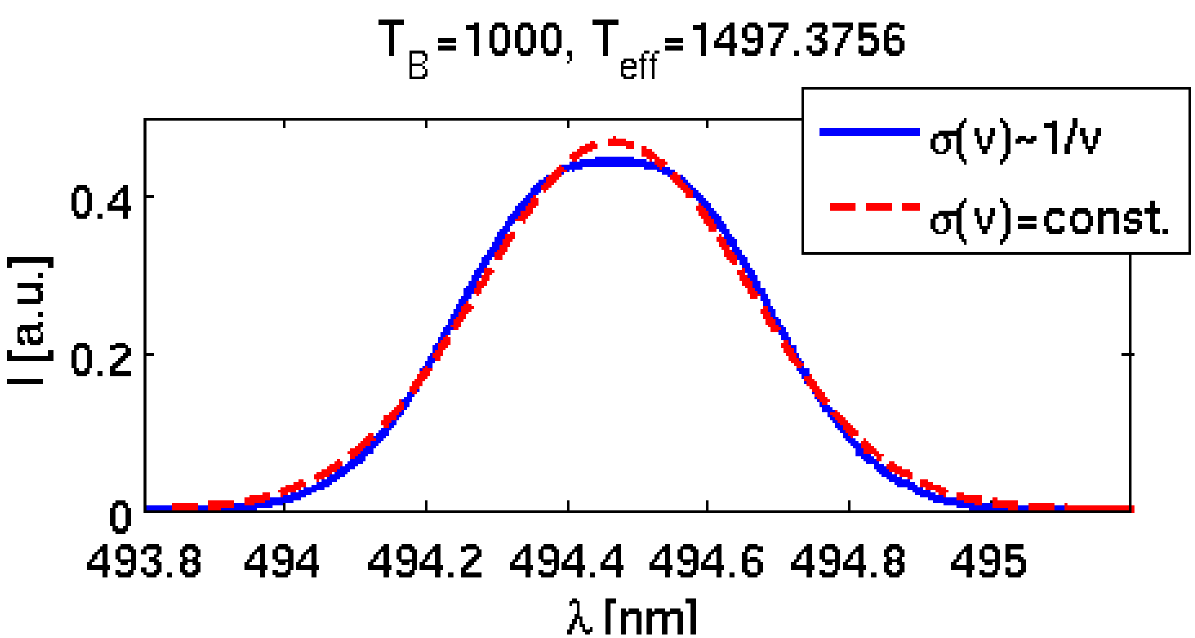
Cross-Section Corrections Need to Be Investigated

Since $v_B << v_D$ does not hold for gas puff CXRS, the local gas puff emission does not simplify to a simple Gaussian

$$Id\lambda \propto \int dv_D \cdot dv_{\perp B} \cdot f_D(v_D) \cdot f_B(v_B) \cdot |v_B - v_D| \cdot \sigma_{CX}(|v_B - v_D|) \cdot dv_{\| B}$$

How the cross-section behaves as the rel. velocity $\rightarrow$ 0, influences spectrum

Low-energy, n-resolved cross-sections not available for all low-Z impurities



Differences in line shape assuming $T_D / T_B = 0, \quad \langle v_B \rangle = 0$ and two simple forms for the CX cross section.

Effect much less dramatic for $T_D / T_B \geq 0.3$

Summary

Alcator C-Mod continues to make important contributions to the measurement, analysis and physics of impurity transport

- new 2D impurity source imaging
- pedestal CXRS using neutral gas puffs
- extended VUV/SXR coverage
- advanced modeling and analysis tools for Doppler tomography

Open to discussion/collaboration on these and other topics

we look forward to working together with the plasma, astro and atomic physics communities