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


MIT – Plasma Science and Fusion Center, Cambridge, MA, USA

2012 ADAS Workshop
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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, \( B_t < 8 \, \text{T} \), compact, \( R_o=0.68 \, [\text{m}] \) \( a=0.205 \, [\text{m}] \) tokamak with all solid metal (Mo) plasma facing components

\begin{align*}
\text{n}_{e,0} &< 1.0 \times 10^{21} \, \text{m}^{-3} \\
\text{T}_{e,0} &< 9 \, \text{keV}
\end{align*}

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

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

(*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” $1 < \lambda < 6$ nm, for H/He-like B → Ne
- FY 11 – installed a “LoWEUS” $10 < \lambda < 30$ 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 local \( T_i \), 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

\[
\text{Ar}^{17+} \text{Ly}_{\alpha,1} \text{ and Ly}_{\alpha,2} \quad \text{Ca}^{19+} \text{Ly}_{\alpha,1} \text{ and Ly}_{\alpha,2}
\]

Demonstration of good profile coverage for H-like Ca injections, even for \( T_e \approx 3 \) 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 $\lambda \sim 551$ Mo I emission
Initial Results Show Promise of Technique

- 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**

change in source across boronization clearly observed
MSE Real-time Background Subtraction

- 4 wavelength polychromator allows simultaneous measurement along the same sightline
  - MSE – pi emission
  - 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
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 $\nabla T_e / T_i$ 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:

- CALIBRATION
- SPATIAL ALIGNMENT
- He/H-LIKE PROFILE COMPARISON
- PROFILE INVERSION
- FITTING/MOMENT GENERATION

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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

**Work completed by J. Lepson of LLNL**

**M.L Reinke 9/24/12 – 2012 ADAS Workshop**
C-Mod Pioneered CXRS using Neutral Gas Puff

- 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 separatrix, 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

Before Correction

After Correction

can we use ADAS molecular emission modeling to validate?
Cross-Section Corrections Need to Be Investigated

Since \( v_B \ll v_D \) does not hold for gas puff CXRS, the local gas puff emission does not simplify to a simple Gaussian

\[
I d\lambda \propto \int dv_D \cdot dv_{\perp B} \cdot f_D(v_D) \cdot f_B(v_B) \cdot |v_B - v_D| \cdot \sigma_{CX}(|v_B - v_D|) \cdot dv_{\parallel B}
\]

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 \( T_D / T_B = 0 \), \( \langle v_B \rangle = 0 \) 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