Fuel retention measurements on Alcator C-Mod using Accelerator-based In-situ Materials Surveillance

Zach Hartwig

AIMS team
Harold Barnard,
Brandon Sorbom
Dick Lanza
Bruce Lipschultz
Pete Stahle
Dennis Whyte

Engineering
Alan Binus
Dave Terry
Gary Dekow
Ron Rosati
Henry Savelli
Tom Toland
Rui Vieira

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Plasma-material interactions places severe demands on the materials used to define the boundary layer

- Plasma-Material Interactions (PMI) is the coupled system that forms between \textit{magnetically confined plasmas} and plasma facing components (PFC).
Plasma-material interactions places severe demands on the materials used to define the boundary layer

- PMI instantly and continuously remakes the plasma-facing surface, significantly modifying material properties and plasma behavior
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- PMI instantly and continuously remakes the plasma-facing surface, significantly modifying material properties and plasma behavior.
PFC surface diagnostic requirements *today* are set by the PMI challenges faced by a *future* fusion reactor.

<table>
<thead>
<tr>
<th>PMI issue</th>
<th>Reactor challenge</th>
<th>Diagnostic challenge (in present devices)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel retention</td>
<td>$\leq 10^{-7} \frac{T_{\text{retained}}}{T_{\text{incident}}}$</td>
<td>Directly detect deuterium, tritium Depths of $\leq 10 \ \mu$m</td>
</tr>
<tr>
<td>Net thickness change</td>
<td>$\leq 1 \text{ mm year}^{-1}$</td>
<td>Sensitive to $\sim 100 \text{ nm}$ Dynamic range of $\leq 10 \ \mu$m</td>
</tr>
<tr>
<td>Material mixing</td>
<td>Prevent at all costs</td>
<td>Identify and quantify low-Z impurities</td>
</tr>
</tbody>
</table>

**All PFC measurements should:**
- have time resolution ($\sim$shot-to-shot or better)
- have poloidal and toroidal resolution
- be made over large fraction of PFCs
- be made as frequently as possible
I. Accelerator-based In-situ Materials Surveillance (AIMS)

II. Identification and quantification of isotopes

III. Measurements of PMI-driven surface changes

IV. Future prospects of AIMS and summary
(1) An RFQ injects 0.9 MeV D+ into a radial diagnostic port in between shots
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(2) Toroidal and vertical fields steer the D+ beam via the Lorentz force
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Toroidal and vertical fields steer the D+ beam via the Lorentz force.

D+ induce high-Q nuclear reactions with low-Z ions in first ~10μm of surface.
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(2) Toroidal and vertical fields steer the D+ beam via the Lorentz force.

(3) D+ induce high-Q nuclear reactions with low-Z ions in first ~10μm of surface.

(4) Neutron & gamma spectroscopy facilitates surface isotope quantification.
AIMS provides substantial advances in PFC surface diagnostic capabilities

- AIMS measurements can be made:
  - **in-situ** without vacuum break
  - **shot-to-shot frequency**
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  - in-situ without vacuum break
  - shot-to-shot frequency
  - of large areas of PFC surfaces (poloidally and toroidally)
  - **nondestructive** to materials (extremely low incident fluence)
  - **nonperturbing** to measurement (as in standard ion beam analysis)
AIMS measurements can be made:

- in-situ without vacuum break
- shot-to-shot frequency
- of large areas of PFC surfaces (poloidally and toroidally)
- nondestructive to materials (extremely low incident fluence)
- nonperturbing to measurement (as in standard ion beam analysis)
- nondisruptive to plasma or facility operations
- without requiring substantial resources (ex-situ facility; PFC removal; time)

AIMS provides substantial advances in PFC surface diagnostic capabilities
AIMS utilizes deuteron-induced nuclear reactions to directly measure the critical PMI issues.

<table>
<thead>
<tr>
<th>PMI Issue</th>
<th>Beam particle</th>
<th>Target nucleus</th>
<th>Detected particle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel retention</strong></td>
<td>deuteron</td>
<td>deuterium tritium</td>
<td>neutron (n)</td>
</tr>
<tr>
<td><strong>Erosion/redeposition</strong></td>
<td>deuteron</td>
<td>lithium-6 beryllium-9 boron-11</td>
<td>gamma (g) neutron (n)</td>
</tr>
<tr>
<td><strong>Surface impurities</strong></td>
<td>deuteron</td>
<td>carbon-12 nitrogen-14 oxygen-16</td>
<td>gamma (g)</td>
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</table>
The AIMS diagnostic on Alcator C-Mod

**RF Quadrupole accelerator (RFQ)**
- ~1 mA peak current
- 0.9 MeV D+ ions
- 50us bunches, 100 Hz

**Beamline**
- Focusing quadrupoles
- RFQ current measurement
- Gate valve

**Toroidal field (TF) coils**
- 0.0 – 0.2 T steady-state
- ~30 cm vertical beam sweep

**Neutron and gamma detectors**

**Molybdenum PFCs**
Advances in scintillation detector technology enable detection in an extremely hostile environment

- Particle detection in AIMS must be performed in an extremely hostile environment
  - High neutron flux ($\sim 10^{12}$ cm$^{-2}$ s$^{-1}$)
  - High magnetic fields (< 0.1 T)
  - Mechanical shock ($\sim 200$ g)
  - Compact geometry ($\sim$cm)
  - High counts rates ($> 10^5$ s$^{-1}$)
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- Silicon-based devices (SiAPD, SiPM) replace photomultiplier tubes to meet challenges
  - Gammas: $\text{LaBr}_3(\text{Ce})$-SiAPD
  - Neutrons: EJ301-PMT, EJ301-SiPM
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  - High neutron flux (~$10^{12}$ cm$^{-2}$ s$^{-1}$)
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  - Mechanical shock (~200 g)
  - Compact geometry (~cm)
  - High counts rates (>10$^5$ s$^{-1}$)

- Silicon-based devices (SiAPD, SiPM) replace photomultiplier tubes to meet challenges
  - Gammas : LaBr$_3$(Ce)-SiAPD
  - Neutrons : EJ301-PMT, EJ301-SiPM

- Full digitization of all detector pulses
  - Offline analysis, optimize algorithms
  - 60us digital window triggered from RFQ timing pulse eliminates $\approx (1 - f_{\text{RFQ}}) \approx 99.5 \%$ background
II. Identification and quantification of isotopes
Isotopes are identified and quantified using peaks in the gamma spectra

Peaks in the gamma energy spectra show identify isotopes in the PFC surface

- **0.662 MeV**: Cs-137 calibration source
- **0.953 MeV**: Boron on top of Mo PFC
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**Integral under the photo peak**

\[ \int d\sigma / d\Omega, \text{ RFQ/ detector params} \]

**Absolute** isotope concentrations (thickness) of any low-Z gamma producing isotope
Relative measurements of deuterium and boron can be extracted from the neutron energy spectrum.

1. Fit the neutron background
2. The integral above the fit proportional to deuterium
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An integral at high energy is proportional to boron.

At present: relative measurements of isotopic changes

In development: new neutron-based IBA methods for absolute isotopic concentrations
III. Measurements of PMI-driven surface changes
A timeline will be used to display plasma operations and PFC surface measurements.
PFC tiles were extracted at end of FY12 campaign for ex-situ IBA measurements

Extracted module of PFC tiles
“Snapshot” of boron deposition patterns only hints at the complex, dynamic physics of PMI

Ex-situ IBA leaves critical PMI questions unanswered!

- **Why** is there such strong variation **poloidally** and **toroidally**?
- **How** and **when** did such complex deposition patterns arise?
Intrashot AIMS provides time- and space-resolved measurements at multiple PFC locations.

AIMS provides the ability to remotely interrogate the critical PMI issues on many PFC surfaces on a plasma shot-to-shot timescale.
AIMS measured boron migration and net deposition on the inner wall during LSN diverted operation.

Lower single null shots:

- $I_p$ [MA]
- $N_{e\text{bar}}$ [$10^{20}$ m$^{-2}$]
- $T_e$ [keV]
- RF [MW]
- $P_{\text{rad}}$ [$10^{-7}$]
- $W_{\text{plasma}}$ [kJ]
AIMS measured boron migration and net deposition on the inner wall during LSN diverted operation.

- Inner wall is an area of **net** deposition:
  - $\sim$1-10 μm year$^{-1}$ [1] ($\sim$1-10 nm shot$^{-1}$)
  - $\sim$2-4 nm shot$^{-1}$ on inner divertor [2]

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- AIMS B deposition measurement:
  \[ 228 \pm 73 \frac{\text{nm}}{18 \text{ shots}} \approx 13 \pm 4 \frac{\text{nm}}{\text{shot}} \]

\(^{[2]}\) B. Lipschultz et al. Nucl. Fusion (2009) 045009
AIMS measured boron erosion during inner-wall limited plasmas; behavior consistent with expectations.
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\[ \Delta L_B = L_{B0} \left[ 1 - \exp \left( -s / \tau_B \right) \right] \]

- Degradation in benefits of boronizations used to estimate erosion

\[ \sim 5 < \Delta L_B < \sim 20 \text{ nm} \]

- Change in boron thickness
- Initial boron thickness
- Number of shots
- Boron effectiveness e-folding time

\[ 15 < \tau_B < 50 \] [1,2]

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- Clear change in deposition: diverted (LSN) → limited (IWL)

![Diagram showing time, shots, and net intrashot change in boron thickness](image)
AIMS measured boron erosion during inner-wall limited plasmas; behavior consistent with expectations.

- Clear change in deposition: diverted (LSN) limited (IWL)
- AIMS confirms very small erosion achievable in 4 shots
  - Estimate: ~5 – 20 nm
  - AIMS: 26 ± 36 nm

Previous experiment conclude that D retention in C-Mod cannot be attributed to boron; must be in bulk Mo PFCs.

- Static gas balance used to measure global D retention in C-Mod [1]

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- Static gas balance used to measure **global** D retention in C-Mod [1].
- Experiments comparing **clean** vs. **boronized** walls [1] suggest:
  - D retention does not saturate after ~25s of plasma **with B removed from PFCs**.

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- Experiments comparing **clean vs. boronized** walls [1] suggest:
  - D retention does not saturate after ~25s of plasma with B removed from PFCs
  - Maximum physically possible D retention in B layers cannot account for net retention

\[ R_{\text{dep}}^B \cdot \frac{N_D}{N_B} \cdot \frac{\rho N_A}{A} \cdot A_{\text{PFC}} \approx 10^{21} \text{ D s}^{-1} \]

\[ 2 \text{ nm s}^{-1} \quad 0.4 \quad 1.3 \times 10^{29} \text{ B m}^{-3} \]

C-Mod uses B\(_2\)D\(_6\) for boronization; B layer is deposited with D/B ~ 0.4 (saturated!)

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- Static gas balance used to measure **global** D retention in C-Mod [1]
- Experiments comparing **clean vs. boronized** walls [1] suggest:
  - D retention does not saturate after ~25s of plasma *with B removed from PFCs*
  - Maximum physically possible D retention in B layers cannot account for net retention
  - D retention occurs after boron layers are removed (from outer divertor)

Previous experiment conclude that D retention in C-Mod cannot be attributed to boron; must be in bulk Mo PFCs

- Static gas balance used to measure \textit{global} D retention in C-Mod \cite{1}
- Experiments comparing \textit{clean} vs. \textit{boronized} walls \cite{1} suggest:
  - D codeposition with boron cannot account for observed \textit{net} retention
  - D retention occurs after B has eroded

Theory: Many shots after boronization, B layers have reached saturation at D/B ~ 0.1; plasma is eroding/redepositing D-saturated boron layers

Issue: Has \textbf{never been experimentally measured}; only inferred

\[1\] B. Lipschultz \textit{et al.} Nucl. Fusion \textbf{49} (2009) 045009
AIMS showed erosion/redeposition of D-saturated boron; further suggests metal PFCs are responsible.
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Deuterium and boron changes are identical for both:
- LSN (codeposition)
- IWL (erosion)
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Deuterium and boron changes are identical for both:
- LSN (codeposition)
- IWL (erosion)

Evidence that plasma is eroding & redepositing D-saturated boron

Suggests that B layers remain saturated at D/B ~ 0.1 despite PMI and cannot be responsible for observed D retention.
AIMS measurements were acquired during end FY12 plasma campaign and wall conditioning

- **Boronization (BZN)**: Deposit ~150 nm boron on PFCs
  - 120 min, 10% D$_2$B$_6$ / 90% He, ECR @ R = 43-44 cm

Boronization deposition rate (QMB) [1]

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AIMS confirms the low boron deposition rate on the inner wall PFCs during boronization.

Quartz microbalance (QMB) : \(0.3-0.4 \text{ nm min}^{-1}\) @ 0-1 cm inside ECR
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Quartz microbalance (QMB): $0.3-0.4 \text{ nm min}^{-1}$ at 0-1 cm inside ECR

AIMS measurements @ 2 inner wall PFCs: $0.3 \pm 0.6 \text{ nm min}^{-1}$, $0.7 \pm 1.5 \text{ nm min}^{-1}$

AIMS is consistent with *absolute* boron deposition as measured by QMB (few atomic monolayer sensitivity!)

Boronization deposition rate

![Boronization deposition rate graph](image-url)
AIMS is consistent with B deposition profiles from QMB; suggests deuterium deposits neutrally in BZNs.

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Fractional $\Delta B : 1.13\pm0.09;\ 1.09\pm0.09;\ 1.16\pm0.10$
- Consistent with *poloidal* isotropy of boron deposition
- Low deposition consistent with ionic deposition

Fractional $\Delta B : 1.65\pm0.15$
- Consistent with *radial* dependence of boron deposition
AIMS is consistent with B deposition profiles from QMB; suggests deuterium deposits neutrally in BZNs.

\[ \Delta D > \Delta B \]

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Confirms radially dependent boron deposition profiles; suggests D may deposits isotropically as neutrals during boronization.
Prospects for AIMS and Summary
Proof-of-principle AIMS demonstrates a clear path for significant improvement in measurement capability

I. **Measurement sensitivity and times** can be greatly improved
   - Upgrade from 2 to 10 detectors: improve statistics
   - Increase detector solid angle: improve signal-to-noise
   - Upgrade RFQ accelerator, diagnostics: minimize error
Proof-of-principle AIMS demonstrates a clear path for significant improvement in measurement capability

I. Measurement sensitivity and times can be greatly improved

II. In-situ boron nitride beam target
   - Visual diagnosis of beam spot size
   - Validation of magnetic steering control
   - Experimental validation using well-characterized surface

PFC tiles

BN target
Proof-of-principle AIMS demonstrates a clear path for significant improvement in measurement capability

I. Measurement sensitivity and times can be greatly improved
II. In-situ boron nitride beam target
III. **Upgrade to TF, vertical B field coils current supplies**
   - Access large area of PFC surfaces poloidally and toroidally
Proof-of-principle AIMS demonstrates a clear path for significant improvement in measurement capability

I. Measurement sensitivity and times can be greatly improved
II. In-situ boron nitride beam target
III. Upgrade to TF, vertical B field coils current supplies
IV. AOD + AIMS couples a high-T PMI solution, extensive suite of edge plasma diagnostics, and a cutting-edge in-situ materials diagnostic

**Advanced Outer Divertor (AOD)**
- Bulk tungsten @ $T \leq 875$ K
- Toroidally aligned & continuous
- High flux expansion topologies

**AIMS measurement locations**
AIMS represents an important step forward for the understanding of PMI and materials performance

- AIMS remotely and nondestructively interrogates the critical PMI issues on large areas of PFCs on a plasma shot-to-shot timescale

- AIMS has experimentally demonstrated *in-situ* measurements of low-Z erosion/redeposition and fuel retention (in only ~3h!)

- Dedicated AIMS experiments upcoming at Alcator C-Mod
  - Migration, erosion & redeposition (Li, Be, B, C)
  - Fuel retention (D,T)
  - Safety (bulk T) and operational diagnostic (*e.g.* O impurities)
  - Critical data input for PMI modeling community
  - Dynamically link plasma conditions with material response
Additional material
EJ301-PMT neutron detectors require pulse shape discrimination to eliminate gammas from spectra.
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\[ FOM = \frac{\Delta}{\Gamma_n + \Gamma_\gamma} \approx 1.03 \]
EJ301-PMT neutron detectors require pulse shape discrimination to eliminate gammas from spectra.

Gammas are filtered out of EJ301-PMT neutron spectra with >99.87% accuracy.
ACRONYM combines Geant4 with custom extensions to perform AIMS simulation for Alcator C-Mod.

- **ACRONYM (Alcator C-Mod RFQ Optical and Nuclear Yield Model)** is a comprehensive synthetic diagnostic for AIMS [1]

- Relies on a number of standard Geant4 features:
  - Geometry from C-Mod Solid Edge models
  - C-Mod magnetic fields, materials
  - Modeling of inorganic scintillation detectors

- Custom extensions for AIMS
  - Parallelized with Open MPI
  - Low-energy nuclear reaction module
  - New model for simulating scintillation detectors

ACRONYM detector efficiency and spectra were validated against experiments.

ACRONYM optical models of AIMS detectors.
ACRONYM was used to evaluate detectors (design, position) and predict measurement feasibility

- ACRONYM played a critical role in:
  - Determining optimal detector choice and design
  - Optimizing detector position in Alcator C-Mod
  - Evaluating measurement feasibility

- Future work is planned to provide ACRONYM with the ability to extract absolute isotope concentrations from AIMS

![Simulated measurement of boron](image)
ACRONYM geometry, materials, and transport were validated against C-Mod neutron system calibrations.

**Alcator C-Mod neutron monitor calibrations [1]**: A $^{252}$Cf neutron source placed variously inside C-Mod vessel is counted by nearby fission detector

<table>
<thead>
<tr>
<th>Source Position</th>
<th>Experiment efficiency (counts / source $^{252}$Cf neutron)</th>
<th>ACRONYM efficiency ** (counts / source $^{252}$Cf neutron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT_BC</td>
<td>$2.77 \times 10^{-8}$</td>
<td>$1.84 \times 10^{-8}$</td>
</tr>
<tr>
<td>F</td>
<td>$3.28 \times 10^{-9}$</td>
<td>$3.13 \times 10^{-9}$</td>
</tr>
<tr>
<td>CT_AB</td>
<td>$4.13 \times 10^{-8}$</td>
<td>$4.85 \times 10^{-8}$</td>
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** Statistical uncertainty is less than small error induced by source position uncertainty

ACRONYM demonstrates agreement with a much harder experiment

ACRONYM provides predictive particle transport capability

ACRONYM detector efficiency and spectra were validated against experiments

- Detector intrinsic efficiency ($\varepsilon_i$) is crucial for interpretation of measurements. Need $\varepsilon_i$ as continuous function of gamma energy

$$\varepsilon_i = \frac{\text{Photopeak counts}}{\text{Gammas incident}}$$
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- Correct simulation of energy spectra is crucial for interpretation of experimental data
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ACRONYM provides a high-fidelity comprehensive “synthetic diagnostics” to complement AIMS technique
Neutrons from the $^2\text{H}(d,n)^3\text{He}$ reaction appear on top of a large neutron scattering background. Deuterium is identified and quantified in neutron spectra despite significant challenges.
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Neutrons from the $^2\text{H}(\text{d, n})^3\text{He}$ reaction appear on top of a large neutron scattering background. Peaks in the derivative of the EJ301-PMT detector energy spectra indicate monoenergetic particles.

The EJ301-PMT detector response to 480 keV monoenergetic particles is shown in the graph. The response is plotted as a solid line, and the absolute value of the derivative of the response with respect to energy is plotted as a dotted line.
Neutrons from the $^2\text{H}(d,n)^3\text{He}$ reaction appear on top of a large neutron scattering background. Peak deviates significantly from the scattering background, indicative of the detection of $^2\text{H}(d,n)^3\text{He}$ neutrons. Deuterium is identified and quantified in neutron spectra despite significant challenges.
Nuclear kinematics confirms the detection of deuterium and deuteron beam steering

- In AIMS, the **ejectile neutron energy** from the $^2\text{H}(d,n)^3\text{He}$ reaction is fully determined:
  - $E_0$ set by deuteron energy at reaction time
  - $\theta$ is fixed by the beam angle w.r.t. detectors

- Location of $^2\text{H}(d,n)^3\text{He}$ neutrons in neutron spectrum shifts with beam-detector angle

$$E_3 = E_T \left( \cos \theta \left[ \frac{D}{B} - \sin^2 \theta \right]^{1/2} \right)^2$$

where

$$B = \frac{m_1 m_3 (E_0 / E_T)}{(m_1 + m_2)(m_3 + m_4)}$$

$$D = \frac{m_2 m_3}{(m_1 + m_2)(m_3 + m_4)} \left[ 1 + \frac{m_1 Q}{m_2 E_T} \right]$$
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Nuclear kinematics confirms the detection of deuterium and deuteron beam steering

- In AIMS, the **ejectile neutron energy** from the $^2\text{H}(d,n)^3\text{He}$ reaction is fully determined:
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  - $\theta$ is fixed by the beam angle w.r.t. detectors

- Location of $^2\text{H}(d,n)^3\text{He}$ neutrons in neutron spectrum shifts with beam-detector angle

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<td>0.05</td>
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![Graph showing neutron spectrum derivative and angles θ = 124°, 143°, 157°]
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Energy shift of the peak follows nuclear kinematics, confirming deuterium detection and beam steering