Here Be Dragons: Plasma-wall interactions science for future fusion energy devices

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Nuclear Science and Engineering Department
Our map for the next 25 minutes ...

I. Prerequisites

II. Plasma-Wall Interactions (PWI)
   i. What are they?
   ii. Why are they important?
   iii. What have we done about studying them?

III. Near-term advances in PWI diagnostic capabilities

IV. Long-term plans for reactor-relevant PWI science
Prerequisite #1: Many people have made this talk possible

Special thanks:
Dennis Whyte

Thanks:
Harold Barnard, Paul Bonoli, Leslie Bromberg, Ian Faust, Mike Garrett, Christian Haakonsen, Dick Lanza, Bob Mumgaard, Geoff Olynyk, Josh Payne, Yuri Podpaly, Matt Reinke, Brandon Sorbom, Pete Stahl, and the Alcator C-Mod team
Prerequisite #2: PWI research lies at the intersection of many core subjects of the 3 NSE topical areas.
Prerequisite #3: Getting to know your magnetic fusion confinement device ...

- **Central solenoid magnets** (startup, current drive)
- **Poloidal field magnets** (plasma shaping and control)
- **Poloidal magnetic field** (secondary confinement)
- **Toroidal field magnets** (generates toroidal field)
- **Toroidal plasma current** (generates poloidal magnetic field)
- **Vacuum vessel**
- **Walls composed of plasma facing components (PFCs)**
- **Divertor (Exhaust port)**

**Cross section of Alcator C-Mod (MIT) tokamak core components**

- **Vertical diagnostic ports**
- **Horizontal diagnostic ports**
I. Plasma-Wall Interactions
Hic sunt dracones: a medieval cartographic practice of depicting monsters in place of the unknown

A portion of Carta Marina (Olaus Magnus, c. 1530 A.D.)
Hic sunt plasmæ superficies interactionus: a modern fusion science practice of leaving PWI undiagnosed
Plasma-boundary coupling results in modifications to core plasma and material surfaces in magnetic fusion devices

- Plasma-Wall Interactions (PWI) seeks to understand the coupled system that forms between magnetically confined plasmas and their physical boundary surfaces known as plasma facing components (PFC).

- PFCs are exposed to extremely hostile environments...
  - heat fluxes up to $\sim 10^9$ W/m$^2$
  - charged particle fluxes up to $\sim 10^5$ A/m$^2$
  - neutron fluxes and nuclear activation

- ...resulting in modifications to the PFC surfaces:
  - hydrogenic fuel retention (deuterium, tritium)
  - net erosion and redeposition
  - melting
  - isotope mixing
  - sputtering
PWI involves complex physical interactions that span 12 and 20 orders of magnitude in length and time
Examples from Alcator C-Mod demonstrate the destructive potential of PWI issues.

*Upper divertor PFC tiles*

*Midplane limiter PFC tiles*
Extrapolating to reactor-scale devices indicates the potential severity of PSI issues for fusion energy

<table>
<thead>
<tr>
<th>Issue / Parameter</th>
<th>Present Tokamaks</th>
<th>ITER</th>
<th>DEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiescent energy exhaust ( GJ / \text{day} )</td>
<td>(~ 10)</td>
<td>3,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Transient energy exhaust from plasma instabilities ( \Delta T \sim M J / A_{wall}(m^2) / \text{(1 ms)}^{1/2} )</td>
<td>(~ 2)</td>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>Yearly neutron damage in plasma-facing materials ( \text{displacements per atom} )</td>
<td>(~ 0)</td>
<td>(~ 0.5)</td>
<td>20</td>
</tr>
<tr>
<td>Max. gross material removal rate with 1% erosion yield ( (\text{mm} / \text{operational-year}) )</td>
<td>(&lt; 1)</td>
<td>300</td>
<td>3000</td>
</tr>
<tr>
<td>Tritium consumption ( \text{(g / day)} )</td>
<td>(&lt; 0.02)</td>
<td>20</td>
<td>1000</td>
</tr>
</tbody>
</table>

**Implications**

- Unknown affect on core plasma
- Increased cost
- Increased maintenance shut down
- Operational limits
- Shortened device and component lifetimes
- Feasibility of magnetic fusion energy
Visually depicting present and future tokamaks illustrates the PWI challenge for fusion energy.
Sometimes there's good reason to use log plots ...
A diversity of experiments are presently exploring PWI although almost all are *ex-situ* diagnosis.
Ex-situ ion beam analysis (IBA) has been the gold standard for PWI research

1. ~MeV ions are incident upon a material to be studied

2. Incident ions scatter/react with ions present in material

3. Particle detection and energy spectroscopy provides material property information

<table>
<thead>
<tr>
<th>Scattered particle</th>
<th>IBA technique</th>
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<tbody>
<tr>
<td>Incident ion</td>
<td>Rutherford backscattering (RBS)</td>
</tr>
<tr>
<td>Material ion</td>
<td>Elastic recoil detection (ERD)</td>
</tr>
<tr>
<td>X-rays</td>
<td>Particle induced X-ray emission (PIXE)</td>
</tr>
<tr>
<td>Gamma-rays</td>
<td>Particle induced Gamma-ray emission (PIGE)</td>
</tr>
<tr>
<td>Nuclear products</td>
<td>Nuclear reaction analysis (NRA)</td>
</tr>
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</table>
II. Near-term advances in PWI diagnostic capabilities
New *in-situ* diagnostics are required to significantly advance PWI science in magnetic fusion devices

- *Ex-situ* diagnostics and “benchtop” PWI experiments are critically limited
  - Unable to replicate tokamak-relevant PWI conditions (“benchtop”)
  - Limited PFC surfaces available for measurement (IBA)
  - “Archaeological” measurements lack dynamic PWI information (IBA)

- *In-situ* PWI surface diagnostics are severely limited in deployment and unable to meet all requirements

- The ideal PFC surface diagnostic would provide measurements:
  - *in-situ* without vacuum break
  - on a shot-to-shot frequency for time resolution and PWI dynamics
  - of large areas of PFC surfaces (poloidally and toroidally resolved)
  - of elemental/isotope discrimination to depths of ~10 microns
Basic principles of in-situ IBA for a tokamak

(1) Radio Frequency Quadrupole (RFQ) linear accelerator injects 0.9 MeV D+ into the vacuum vessel through a radial port.
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Basic principles of in-situ IBA for a tokamak

(1) Radio Frequency Quadrupole (RFQ) linear accelerator injects 0.9 MeV D+ beam into the vacuum vessel through a radial port.

(2) Tokamak magnetic fields provide steering via the Lorentz force:

(3) D+ induce high Q nuclear reactions with low Z isotopes in PFC surfaces producing ~MeV neutrons and gammas.

(4) In-vessel detection and energy spectroscopy provides a veritable cornucopia of PFC information.
A custom beam dynamics code is used to explore magnetic beam steering and PFC surface coverage.

Imagine unwrapping the 3D PFC surface into a 2D “skin”.

![Diagram of Alcator C-Mod with various labeled points and distances.](image)
Moderate height, angled injection provides excellent coverage with acceptable magnetic field.
Moderate height, angled injection provides excellent coverage with acceptable magnetic field.
ACRONYM is a Monte Carlo particle transport-in-matter simulation capable of modelling and detecting deuteron-induced nuclear reactions to enable analysis of plasma facing component (PFC) surface conditions.

ACRONYM features:
- Realistic C-Mod geometry and magnetic fields
- RFQ accelerator 0.9 MeV deuteron beam
- Fully functional synthetic neutron and gamma detectors
- Deuteron-induced nuclear reaction production module
- Parallel architecture (Open MPI) for scalable processing

*Alcator C-Mod RFQ Official Neutron Yield Model
First wall boron film thicknesses will be measured by gamma spectroscopy with LaBr3:Ce scintillator

- Alcator C-Mod deposits ~μm films of boron onto its Mo/W first wall to achieve high performance plasma discharges
  - We are completely blind to the deposition efficiency, film coverage of the first wall, and film evolution over time due to lack of surface diagnostic!

- The incident D+ beam will react with boron to produce gamma via the nuclear reaction: $^{11}\text{B} + ^2\text{H} \rightarrow \text{p} + ^{12}\text{B}^* \rightarrow ^{12}\text{B} + \gamma$
  - $E_\gamma$ is characteristic of $^{12}\text{B}$ nuclear level spacing and therefore uniquely identifies the presence of boron films on the PFCs
  - The number of $\gamma$'s emitted correlates to the thickness of the boron film
ACRONYM incorporates a deuteron-induced yield model for calculating gamma emission spectra

- The yield of 0.95 MeV gammas can be calculated with numeric integration of *:

\[ Y_{\text{total}} = N_d \sum_{i}^{M} n_i \int_{0}^{E_d} \frac{\sigma_i(E_d)}{S(E_d)} dE_d \]

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- \( N_d \) is the number of incident deuterons
- \( n_i \) is the number density of isotope \( i \)
- \( \sigma_i \) is the gamma production cross section
- \( S \) is the deuteron stopping power

Gamma production cross section data are found in nuclear databases or will be measured

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- D+ stopping power in elemental boron calculated with SRIM-2010
  - Both are fit with polynomials and folded into numerical integration

ACRONYM can produce realistic detector pulse height spectra from known boron thicknesses

- **ACRONYM** produces synthetic D+ induced gamma spectra at same location for *known boron thicknesses*

![Graphs showing synthetic gamma spectra for different boron thicknesses](image_url)

**Synthetic spectra for 4 thicknesses of boron at location shown in upper right**
ACRONYM synthetic gamma spectra will be used to interpret experimental data

- **Experimental measurements** at known location will produce D+ induced gamma spectra with *no knowledge* of boron thickness
ACRONYM synthetic gamma spectra will be used to interpret experimental data

- ACRONYM can be run iteratively with varied boron thicknesses until the experimental spectrum converges to the synthetic spectrum
AGNOSTIC* will be installed amidst a dizzying array of other diagnostics at B-port horizontal.

A solid model with cutaways of the proposed installation location for AGNOSTIC on Alcator C-Mod. (Lots of stuff not shown!)

* Accelerator-based
  Gamma and
  Neutron
  Observant
  Surface-diagnosing
  Tool for
  In-situ
  Components

Concrete igloo (shielding)

HiReX Sr Spectrometer (Plasma diagnostic)

Impurity injector (plasma transport studies)

Lyman-alpha camera (plasma diagnostic)

Hard X-Ray Camera (fast electron diagnostic)

B-port rules!
AGNOSTIC will be installed amidst a dizzying array of other diagnostics at B-port horizontal.

A solid model with cutaways of the proposed installation location for AGNOSTIC on Alcator C-Mod. (Lots of stuff not shown!)
AGNOSTIC consists of the RFQ accelerator, beamline, reentrant tube and particle detectors

- RFQ cavity (accelerates deuterons)
- RF input (provides accelerating electric field)
- Quadrupole (beam focusing)
- Gate valve (vacuum barrier)
- Cryopumps (provide vacuum)
- Gate valves
- Reentrant vacuum tube
- Neutron and gamma detectors
- 0.9 MeV deuteron beam
AGNOSTIC will be installed during the summer and the first *in-situ* PWI measurements are slated for late 2011.

<table>
<thead>
<tr>
<th>DIAGNOSTIC TIMELINE</th>
<th>Task</th>
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</table>
| 2009 to early-2011 (work complete or nearly complete) | Recommissioning of RFQ accelerator  
Development of synthetic diagnostic  
Assembly of detectors, data acquisition (DAQ) |
| Early-2011 to mid-2011 | Deuterium cross section measurements  
Engineering beamline, interface to C-Mod |
| Mid-2011 | Installation of RFQ on C-Mod  
Installation of detectors and DAQ |
| Mid-2011 to late-2011 | Validation of beam steering algorithms  
Validation of detectors, synthetic diagnostic |
| Late-2011 | **First in-situ PFC composition measurements** |
IV. Long-term plans for reactor-relevant PWI science
Building a viable tokamak fusion reactor will require achieving six “grand challenges”

- A divertor that can survive the heat flux
- Materials for the neutron environment
- Control of a self-heated burning plasma
- Non-inductive steady-state operation
- A closed tritium fuel cycle
- A realistic maintenance scheme

Icons courtesy of the inimitable G.M. Olynyk
Most of the grand challenges are intricately linked to PWI issues

- A divertor that can survive the heat flux
- Materials for the neutron environment
- Non-inductive steady-state operation
- A closed tritium fuel cycle
- A realistic maintenance scheme

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Minimizing the cost of fusion power will require operating conditions that pose significant PWI challenges.

- Approximately 4 MW/m² neutron power loading on first wall (electricity) requires approximately 1 MW/m² plasma power loading through boundary (exhaust).

  **PWI challenge:** All exhaust eventually impinges upon material surfaces as heat fluxes (~ 10 MW/m² and above).

Maximizing power production efficiency requires operating with hot (800K? 1000K?) first wall and blanket (You can't escape Carnot!).

  **PWI challenge:** Thermally-activated reaction rates (e.g. tritium diffusion and trapping) lead to a fundamentally new regime of PFC chemistry.

Continual 24/7 operation for power production.

  **PWI challenge:** > 30 TJ/m² to material surface from energetic plasma ions.
**Vulcan**: a tokamak conceptual design that matches reactor-relevant PWI at a fraction of the size and cost

Vulcan is 1/5 the size of a reactor (cost goes as ~$R^2$!) that achieves reactor-like PWI issues

<table>
<thead>
<tr>
<th>Physics of interest</th>
<th>Parameter scaling</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic physics in the divertor</td>
<td>$T_e/E_{\text{ionization}}, T_i/E_{\text{ionization}}, T_e/E_{\text{sputtering}}, T_i/E_{\text{sputtering}}$</td>
<td>matched</td>
</tr>
<tr>
<td>Magnetic geometry, especially in the divertor</td>
<td>Safety factor $q$, aspect ratio, ion gyroradius / mean free path</td>
<td>matched</td>
</tr>
<tr>
<td>Power width in SOL</td>
<td>Temperature gradient scale length to major radius ratio</td>
<td>assumed</td>
</tr>
<tr>
<td>SOL parallel heat flux</td>
<td>Stangeby 2-point model: $n R^{2/7} = c$ implies same $q_\parallel$</td>
<td>matched</td>
</tr>
<tr>
<td>Material erosion and redeposition in divertor</td>
<td>Ratio of ion mean free path to divertor scale length</td>
<td>worse in Vulcan</td>
</tr>
</tbody>
</table>
High-field side lower hybrid current drive system

Demountable high temperature superconducting magnets

Double vacuum vessel and gas cooled divertor modules
Series of Vulcan studies to be published in Fusion Engineering and Design

D.G. Whyte, G.M. Olynyk, et. al.
“Vulcan: a steady-state tokamak for reactor-relevant plasma--material interaction science”,
Fusion Eng. and Design, To be submitted.

“A study of demountable high-temperature superconducting toroidal-field magnets for the Vulcan tokamak conceptual design”,
Fusion Eng. and Design, To be submitted.

Y.A. Podpaly, G.M. Olynyk, M.L. Garrett, and P.T. Bonoli
“The lower hybrid current drive system for steady-state operation of the Vulcan tokamak conceptual design”
Fusion Eng. and Design, To be submitted.

H.S. Bernard and J.E. Payne.
”A High Temperature, Helium Cooled Vacuum Vessel and First Wall for the Vulcan tokamak conceptual design”
Fusion Eng. and Design, To be submitted.
The future of magnetic fusion energy and plasma-wall interactions?
Conclusion

The future of magnetic fusion energy and plasma-wall interactions!

- PWI is a tremendously complex physical phenomena that poses significant challenges to our understanding of magnetic confinement devices.
- New *in-situ* comprehensive diagnostics are poised to reveal a wealth of dynamic, reactor-relevant PWI science.
- The construction of a dedicated PWI research tokamak facility such as Vulcan could clear the ocean of “monsters” and determine a reactor-relevant solution to PWI issues in magnetic fusion energy.