DIONISOS:
A new experiment studying the dynamics of plasma-surface interactions

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Our present lack of confidence in PSI issues primarily arises from the poor diagnosis of PSI effects

- Most of the controlling PSI physics is in hand or in a “mature” research stage
  - Physical sputtering, chemical sputtering
  - Plasma edge sheath theory
  - Atomic physics (ionization, etc.)
  - *Notable exception: particle transport in edge plasmas.*

- By the same token, edge plasma diagnosis is mature.

- However we have essentially no direct diagnosis of how & when plasma-facing surfaces are being modified by the plasma.
The PSI diagnostic challenge

- The plasma edge is dominated by its own self-consistent recycling pattern of fuel and impurities
  - Easily implemented plasma diagnosis cannot inform us about the net surface effects (H retention, erosion, etc.)

- The lack of direct surface diagnosis cripples our ability to understand the net effects of PSI.
  - We have largely relied on surface "archeology" to inform us about surface modifications. This is unacceptable; the equivalent of basing ITER burn predictions on one-year integrated neutron fluence from JET!!
  - Dedicated ex-situ PSI experiments (e.g. DiMES) very expensive to implement (run-time) and covers << 1% of wall surfaces.

- The challenge is to develop reliable in-situ surface diagnostic techniques that can operate in real-time and be placed in many locations.
In-situ PSI diagnosis topics

1. Erosion & deposition using quartz crystal microbalances

2. DIONISOS: Accelerator-based ion beam surface analysis experiment being developed at UW-Madison

3. Radio-isotope alpha emission for remote, in-situ “ion beam analysis” in confinement experiments.
QMB: Quartz crystal microbalances

- Measures net mass change on surface coating of a crystal by changed resonance frequency.

- **Advantages:**
  - Extremely sensitive: can measure ~mono-layer net changes in surface
  - Large dynamic range: 0.1-> 1000 nm
  - Can measure both deposition and erosion of a pre-deposited film.
  - Commercially available technology.

- **Drawbacks:**
  - No element discrimination.
  - Cannot tolerate any significant heat flux: small thermal mass.
  - Highly temperature / environment sensitive
  - Limited absolute range: ~ 1 micron << expected deposit layers.
QMB: Quartz crystal microbalances

• **Implementation needs:**
  • Special design for in-vessel electronics (ceramic based) to tolerate high baking temperatures (~ 300 C)

• **Present status.**
  • QMB successfully implemented in JET divertor…clearly demonstrating need for real-time PSI diagnosis.
  • UW-Madison, MIT and GA now collaborating on implementation of QMBs in Alcator C-Mod (Mo/B) and DIII-D (C) tokamaks.

• **Summary:** Primarily due to their intolerance to heat flux, QMBs are relegated to measuring erosion/redeposition in “hidden” areas (baffles, main-wall ports, behind tiles, etc.). Going into new DIII-D lower divertor in tile gaps.
Ion Beam Analysis of Surfaces

- Interaction of ~MeV ions with surface atoms is accurately described from well-known physics
  - Rutherford elastic scattering ($M_{\text{target}} > M_{\text{projectile}}$)
  - Forward elastic recoil ($M_{\text{target}} < M_{\text{projectile}}$)
  - Inelastic nuclear reactions (all reaction σ known)
- Exploit this understanding to diagnose near-surface (~1-10 microns) properties of materials.

**Advantages:**
- Great flexibility: element/isotope sensitivity, erosion/deposition/H retention available in single diagnostic.
- Measurement accuracy over appropriate depth range for PSI.
- Proven application in fusion PSI (see examples from DiMES)
- Simple solid-state detectors for scattered charged particles

**Drawbacks:**
- Need ~MeV energy ions
DiMES examples of Ion Beam Analysis of Surfaces
Carbon erosion/deposition is determined by the change in depth of an implanted silicon marker measured by 2 MeV helium Rutherford backscattering (RBS). Detection limit ~ ±10 nm.

Metal erosion is determined from the change in thickness of thin metal films measured by RBS (W,V).

Nuclear reaction yields give areal density of:
- Deuterium: $D(\text{He}, p)\alpha$
- Boron: $^{10}\text{B}(p, \alpha)^7\text{Be}$

**Near-surface transport**

**H Retention**

**Low-Z erosion**

DIONISOS:
Dynamics of IONic Implantation & Sputtering On Surfaces

• A new experimental facility being constructed at UW-Madison.

• **Goal:** Accurately measure the real-time response of the PFC material surface to plasma bombardment using in-situ high-energy ion beam analysis.

• **Design philosophy:**
  • Exploit ion beam analysis (IBA) techniques
    • Mature analysis tool widely used in R&D.
    • Vastly different ion energies (30 eV vs. > 1 MeV) allow for simultaneous surface interaction with little interference.
  • Use previously developed axisymmetric plasma sources
    • *Helicon:* Steady-state plasma /w good density control.
    • *Plasma gun:* high density/flux pulsed plasma source.
  • Initially focus on fusion experiments, but generic PSI tool.
Principal component of DIONISOS is now operational at UW-Madison: *1.7 MV tandem ion accelerator*

- **Features:**
  - Dual sources (sputtering and RF plasma), > 100 beam species available.
  - High energy (≤ 10 MeV for higher Z beams)
  - High current beamlines (> 0.1 mA) for implantation and irradiation.
DIONISOS Experiment Setup

[Diagram of the experimental setup showing various components such as the accelerator, target, and analysis system.]
DIONISOS Experiment Setup

- MeV Ion beam
- In-situ implantation & surface diagnosis
- Biased & cooled
- Rotatable sample
- Sample access
- Helicon source
- Coils
Experimental R&D: Development of plasma compatible ion beam analysis detector assemblies

- Serves purpose of protecting s.s. detector from
  - Plasma light emission.
  - Low energy plasma ions.
  - Sputtered and CX neutrals.
Three proposed areas of study for DIONISOS

- Measurement and modeling of near-surface cross-field ion transport
  - Determine controlling parameters for the magnitude and locations of net erosion / redeposition of PFC relevant to fusion (C, W, Mo)

- The dynamic release of fuel and impurity particles from surfaces exposed to transient, high-density plasmas.

- The dynamics of hydrogenic / tritium fuel trapping in plasma-deposited films, for single and multiple species materials.
Plasma sources for DIONISOS

- **Helicon plasma source (collaboration with N. Hershkowitz)**
  - Steady-state ionizing plasma
  - Solenoid field convenient linear control of plasma density
  - H, D, Ne, Ar

- **Plasma gun (collaboration with G. Fiksel, C. Forest)**
  - Developed for helicity injection on MST (Fiksel et al).
  - Pulsed (~1-10 ms) H/D plasmas with ~60 s rep rate.
  - ~100% ionization, \( T_e \approx 20 \, \text{eV} \) high density (~\( 10^{20} \, \text{m}^{-3} \))
  - ~100 MW/m\(^2\) (10 MJ/m\(^2\)/s\(^{1/2}\)) per 100 V bias approaches ablation/melt limits.
  - Capable of current densities ~ kA / cm\(^2\)
Ion beam surface analysis tools are operational on DIONISOS

- Rutherford Backscattering Spectroscopy
- Elastic Recoil Detection (H detection)
- Nuclear Reaction Analysis.
- Particle Induced Gamma Emission.
  - Carbon-13 detection with ∼2 nm depth resolution for DIII-D experiment.
RBS measures net erosion rate of high-Z film to ~ 5 nm.

Forward recoil (ERD) provides depth-resolved H/D concentration.

Highly resolved spatial profiles of isotope resolved H species with NRA.
Schematic for IBA diagnosis of low-Z PFC materials

- RBS measures net erosion rate of bulk material by changes in high-Z marker previously implanted with ion beam.
- ERD and NRA provide real-time hydrogenic concentrations and diffusion in deposited films.
Schematic for IBA diagnosis of H dynamics in PFC

- Exploit large forward recoil cross-section for high mass projectiles
- Same ion-PFC species allows for high current, fast hydrogenic diagnosis
  - Case shown: ERD using C-H recoil can measure H profile in ~ 10 ms time
- Allows for dynamic study of H implantation, diffusion and release under transient conditions.
Remote IBA using radio-isotope alpha emitters

• While IBA is the tool of choice for surface diagnosis, how can we provide real-time measurements in a confinement device where we have no access with ion beam?

• Produce an ~mono-energetic alpha ion “beam” using natural alpha emitters
  – Present focus on Po-210 (138 day half-life, $E_{\alpha} = 5.4$ MeV
  – Balances need for alpha flux vs. diagnostic lifetime.

![Diagram of alpha beam generation and collimation](attachment:image.png)
Schematic of Alpha Surface Analyzers (ASA) design for real-time PSI diagnosis in confinement devices

- Exploit intrinsic magnetic field to rotate surface in/out of contact with main PFC surface.
  - Large thermal mass and contact allow for surfaces in high heat flux areas.
  - Controls exposure duration of surface in each discharge.

- In analysis position, the alpha scattering is detected by s.s. detectors for
  - RBS: net erosion/deposition and surface stoichiometry
  - ERD: Hydrogenic retention over ~ 5 microns.

- Po-210 source will allow for surface diagnosis between each shot (~10 minute acquisition time).
First tests of Alpha Surface Analyzers (ASA) design are being carried out for Alcator C-Mod

- Multi-layer B/Mo films allow for accurate measurements of net erosion, net deposition and mixed-material analysis in C-Mod.

- Other R&D
  - Po-210 radiochemistry for film deposition.
  - Detector geometry optimization.