Development of an accelerator based in-vessel surface diagnostic for Alcator C-Mod.

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Introduction

Accelerator based ion beam analysis techniques such as particle induced X-ray/gamma emission (PIXE, PIGE), Rutherford backscattering spectroscopy (RBS), and others provide tools to diagnose the elemental composition of plasma facing surfaces. These techniques have been used successfully to study PFCs after removal from C-Mod and other devices. Many plasma surface interactions occur on short timescales that cannot be studied through laboratory measurements of cumulative effects. The need for improved time resolution motivates the development of in-vessel surface diagnostics.

Laboratory Measurements of Tungsten Migration using PIXE

PIXE was used to measure the erosion and migration patterns of a Tungsten tracer in Alcator C-Mod. Measurements such as these provide useful information about the cumulative effects of the plasma over an experimental campaign.

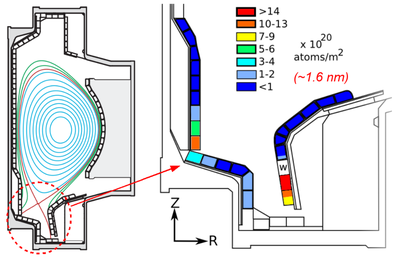

Figure 1: *Left: Poloidal cross section of Alcator C-Mod. Right: Color map of measured W surface deposition.*

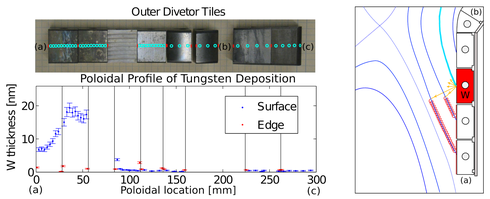

Figure 2: *Top left: Photo of outer divertor tiles. Bottom left: measured tungsten deposition. Right: Illustration of sputtering followed by ionization and redeposition.*

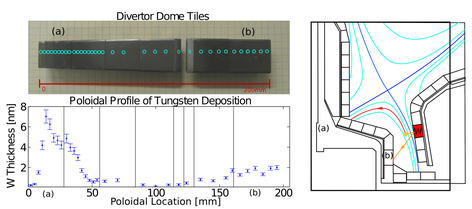

Figure 3: *Top left: Photo of divertor dome tiles. Bottom left: measured W deposition on the divertor dome. Right: schematic of tungsten migration across the private flux region.*

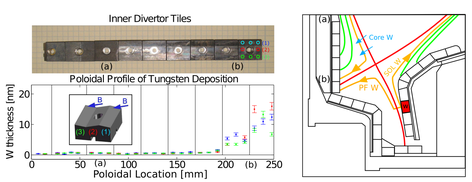

Figure 4: *Top left: Photo of inner divertor tiles. Bottom left: measured W deposition on the inner divertor. Right: schematic with possible mechanisms for W transport.*

[Plasma Facing Components Meeting August 2011, Oakridge National Laboratories: Fusion Energy Division]

In-Vessel Diagnostic Overview

- Surface analysis is typically performed on components after they are removed from C-mod following plasma exposure. This makes it difficult to differentiate between the effects of a variety of plasma discharges throughout an experimental campaign.
- A novel diagnostic using a radio-frequency quadrapole accelerator (RFQ) is currently in development for making in In-vessel surface measurements.
- In-vessel measurement capability improves the frequency of surface measurements from once per year to once per discharge.

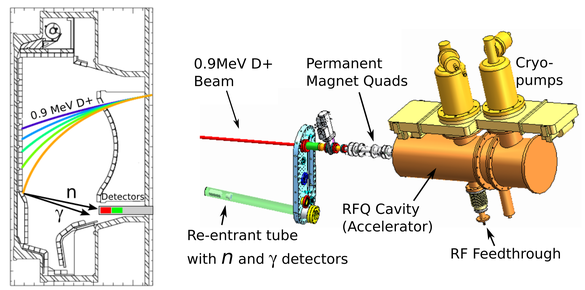

Figure 5: *CAD model of the RFQ Diagnostic with C-Mod. A 0.9 MeV D^+ beam is injected through a horizontal port. The toroidal and vertical field coils are used to target the beam and detectors in a re-entrant tube are used for n^o and γ spectroscopy.*

- The RFQ produces a 0.9 MeV deuterium beam which is targeted at PFCs of interest using C-Mod's toroidal and vertical field coils.
- Spectroscopy of neutrons and gammas will enable the study of short timescale changes in deuterium retention, erosion of surface films such as boron, and other PMI processes.

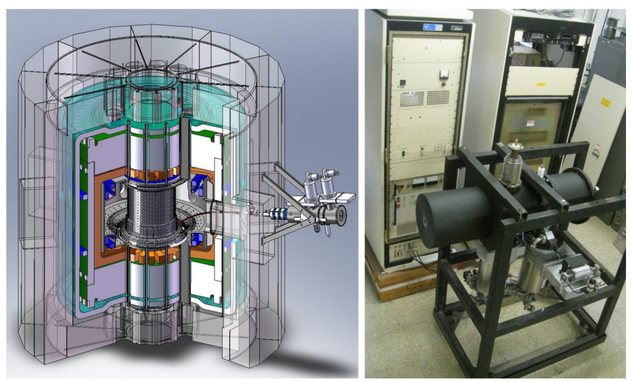

Figure 6: *Preliminary CAD model of the RFQ interfaced with C-Mod.*

Beam Transport

- C-Mod fields were modeled and used to calculate possible trajectories to assess and optimize the positioning of the accelerator to maximize beam access to the first wall.
- The beam will be injected with downward and toroidal angle with a combination of toroidal and vertical fields to access a large region of the first wall, shown in fig. 7.
- Permanent magnet quadrupoles are used for beam focusing.

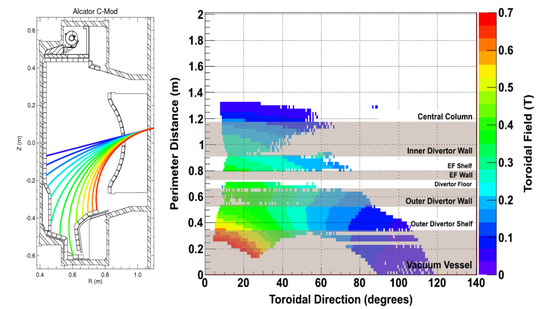

Figure 7: *D^+ beam steering is accomplished by varying the toroidal and vertical fields to target first-wall tiles in C-Mod. Beam trajectories were calculated to generate a map of accessible regions of the first wall.*

- Preliminary analysis of the traverse beam evolution was accomplished with TRACE3D (fig. 8) [K.R.Crandal, D.P.Rusthoi, Trace 3-D Doc., LANL 1997].
- Analysis shows that 1-2 cm spot sizes are achievable allowing for a resolution on the order of ~1 tile.

Figure 8: *TRACE3D plot of the evolution of the transverse D^+ beam envelope as it passes through 3 permanent magnet quads and a C-Mod–like toroidal B-field (100deg bend).*

Neutron and Gamma Spectroscopy

Many (d,γ) and (d,n) reactions exist in the <0.9 MeV range, especially for low-Z elements. The following two reactions are highly relevant for C-Mod and allow for the study of the evolution boronization films and deuterium retention.

$$^{11}_{5}\mathrm{B} + ^{2}_{1}\mathrm{H} \longrightarrow ^{12}_{5}\mathrm{B}^* + p^+ \longrightarrow ^{12}_{5}\mathrm{B} + \gamma\,(0.95MeV, 1.7MeV)$$

$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \longrightarrow ^{3}_{2}\mathrm{He} + n^o\,(2.45MeV)$$

- Lanthanum Bromide ($LaBr_3$:Ce) will be used for gamma detection.
- Liquid organic scintillator BC501A will be used for neutron detection.
- The detector signals will be digitized, processed and analyzed computationally. (Flash ADC / FPGA for digital pulse processing / ACRONYM)

Neutron and Gamma Spectroscopy (continued)

Interpretation of the detector measurements requires computational modeling due to n and γ scattering and attenuation in the complex C-Mod geometry.

Alcator C-Mod RFQ Official Neutron Yield Model (ACRONYM)

- ACRONYM was developed as a synthetic diagnostic to model the measurement technique and detectors in a realistic C-Mod Geometry [Z,Hartwig].
- ACRONYM is a Monte Carlo particle transport-in-matter simulation capable of modeling and detecting deuteron-induced nuclear reactions to enable quantitative measurements of the elemental composition of PFC surfaces.
- The physics basis for ACRONYM is provided by the GEANT4 platform [S. Agostinelli et al.: Geant4 - a simulation toolkit, Nuc. Inst. and Methods A 506 (2003) 250-303]

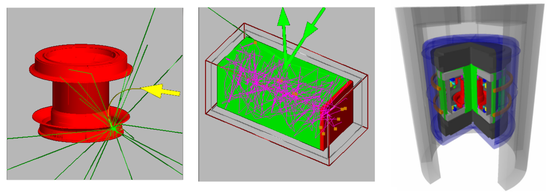

Figure 9: *Visualizations generated by ACRONYM: (left) Photon tracks from an incident deuteron beam. (center) A simulation of a gamma ray inducing light emission in a $LaBr_3$:Ce scintillator, followed by absorption by an avalanche photo-diode. (right) The complete geometry of C-Mod visualized in ACRONYM.*

RFQ Diagnostic Status and Installation

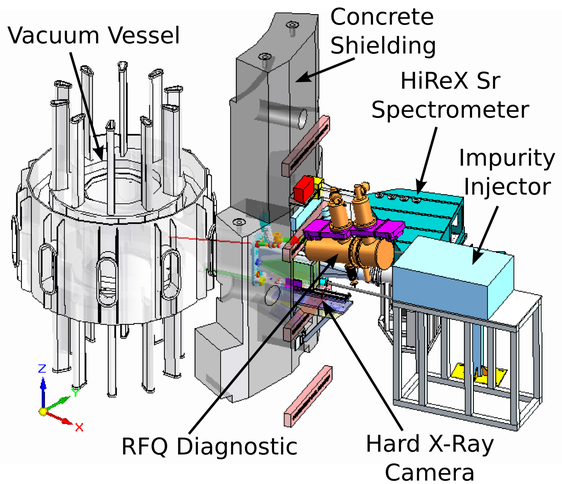

Figure 10: *CAD Model of planned installation location on C-Mod.*

1. The RFQ control system is currently being upgraded for remote operation in the C-Mod cell (summer 2011).
2. Detectors and digitizers are assembled are being configured (summer 2011).
3. Upon completion of upgrades, laboratory tests will begin (fall 2011–spring 2012):
   - Beam characterization (transverse emittance, energy stability, etc.).
   - Verification of n and γ spectroscopy techniques.
   - Experimental verification of ACRONYM.
   - Measurement of (d,γ) & (d,n) cross sections.
4. Installation on C-Mod is planned for spring of 2012 (fig. 10).