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Simulated plasma facing component measurements for an *in situ* surface diagnostic on Alcator C-Mod[a)]

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The ideal *in situ* plasma facing component (PFC) diagnostic for magnetic fusion devices would perform surface element and isotope composition measurements on a shot-to-shot (~10 min) time scale with ~1 μm depth and ~1 cm spatial resolution over large areas of PFCs. To this end, the experimental adaptation of the customary laboratory surface diagnostic—nuclear scattering of MeV ions—to the Alcator C-Mod tokamak is being guided by ACRONYM, a Geant4 synthetic diagnostic. The diagnostic technique and ACRONYM are described, and synthetic measurements of film thickness for boron-coated PFCs are presented. © *2010 American Institute of Physics.*
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I. INTRODUCTION

Plasma facing components (PFCs) serve as the true boundary condition for magnetically confined fusion plasmas, resulting in the formation of dynamic coupled systems known as plasma surface interactions (PSIs). Confined plasma conditions are known to depend strongly on PFC surface conditions, such as material composition and hydrogenic fuel inventory, while the same PFC surface conditions are simultaneously modified by exposure to the confined plasmas. A thorough understanding of PSI would result in a significant improvement in plasma and PFC performance and will be critical to the success of future long-pulse fusion energy devices, as PSI processes are expected to limit operations and device lifetime due to severe large-scale modifications of PFCs.[1] However, while comprehensive plasma diagnostics are routinely used to measure plasma parameters, there presently exists no *in situ* routine diagnosis of PFC surface conditions. To address this critical need, we propose a novel accelerator-based diagnostic that would, for the first time, diagnose surface conditions *in situ* over a large fraction of PFCs with high spatial, depth, and temporal resolution.

II. ION BEAM ANALYSIS IN THE TOKAMAK

The proposed diagnostic relies on the adaptation of ion beam analysis (IBA)—surface composition reconstruction via the analysis of ~MeV ion-induced elastic and inelastic nuclear reaction products—to the magnetic fusion environment.[2] The enabling innovation of the diagnostic is the ability to electromagnetically steer the charged ion beam via the Lorentz force, $\mathbf{F}=q(\mathbf{E}+\mathbf{v}\mathrm{x}\mathbf{B})$, to PFC surfaces inside the vacuum vessel using the idle toroidal field (TF) and vertical field (VF) magnetic coils between plasma discharges. By facilitating IBA over a large fraction of PFCs on a plasma shot-to-shot time scale, the proposed diagnostic would provide the first ever temporally resolved measurements of PSI phenomena inside a magnetic fusion device.

The proposed diagnostic procedure for *in situ* IBA, as illustrated in Fig. 1, is described.

(1) A compact radiofrequency quadrupole accelerator injects a 1 mA beam of 0.9 MeV deuteron ions (D+) into the vacuum vessel through a radial port.
(2) The TF and VF coils are used to magnetically steer the beam to the desired PFC.
(3) D+ ions induce high Q nuclear reactions in PFC surfaces producing ~MeV neutrons and gammas.
(4) In-vessel detection and analysis of nuclear reaction products yield PFC surface compositions.

III. NUCLEAR REACTIONS AND DETECTION

The analysis of ion-induced nuclear reaction products is the core of ion beam analysis. For the *in situ* diagnosis of PFCs, several D+ induced nuclear reactions are of particular interest:

(1) $\mathbf{D}+\mathbf{D}\rightarrow\mathbf{n}+{}^{3}\mathbf{He}$: neutron (n) detection provides for the detection of retained deuterium plasma fuel; and
(2) $\mathbf{D}+{}^{\mathbf{A}}\mathbf{X}\rightarrow\mathbf{p}+\boldsymbol{\gamma}+{}^{\mathbf{A+1}}\mathbf{X}$: gamma ($\gamma$) detection provides for the detection of low-Z isotopes (^{A}X).

Neutron and gamma detection requires unshielded detectors placed inside the vacuum vessel since heavily shielded or external detectors prohibitively complicate the detector response function. In-vessel detectors also facilitate high statistics measurements by maximizing the detector solid angle with respect to the deuteron-induced nuclear reactions. NE-213 liquid organic scintillator, fiber-coupled to *ex situ* photomultiplier tubes, will be used for neutron detection, and $\mathrm{LaBr_3{:}Ce}$ organic crystal scintillator, with silicon avalanche photodiode readouts, will be used for gamma detection. Such

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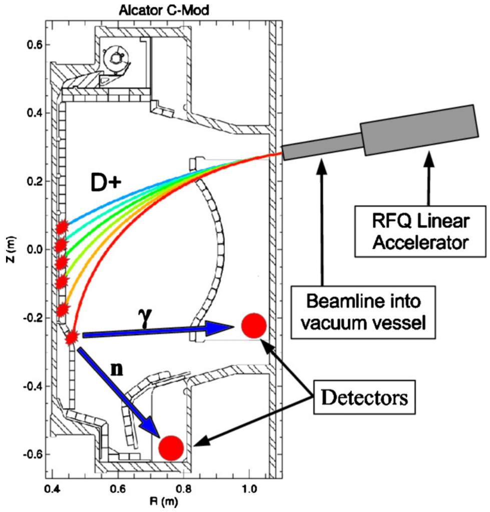

FIG. 1. (Color online) An illustration of the diagnostic procedure for *in situ* surface diagnosis on the Alcator C-Mod tokamak.

detectors satisfy in-vessel engineering constraints and have excellent detection performance for high energy neutrons and gammas.[3,4]

IV. ACRONYM: A SYNTHETIC DIAGNOSTIC FOR *IN SITU* IBA ON ALCATOR C-MOD

A. Overview of ACRONYM

Based on the Geant4 toolkit[5] for simulating the passage of particles through matter, ACRONYM (Alcator C-Mod RFQ Official Neutron Yield Model) is a comprehensive synthetic diagnostic for *in situ* IBA on the Alcator C-Mod tokamak. ACRONYM is capable of simulating each step in the proposed diagnostic procedure within the complex geometry and materials that compose the C-Mod superstructure. Currently guiding diagnostic development, ACRONYM will be critical tool for interpreting experimental data from the physical diagnostic.

B. Validation of ACRONYM

The validation of ACRONYM geometry, materials, and neutron transport was performed by reproducing the results of the 1994 C-Mod neutron diagnostic system calibration.[6] Using a ^{252}Cf neutron source placed at discrete locations inside the vacuum vessel, external neutron detectors, used to measure the neutron production rate during plasma discharges, were calibrated before the start of the plasma campaign. Calibration results were given in terms of the detector efficiencies, in units of counts per ^{252}Cf source neutron. The synthetic calibration setup and the three ^{252}Cf source positions used to validate ACRONYM are shown in Fig. 2.

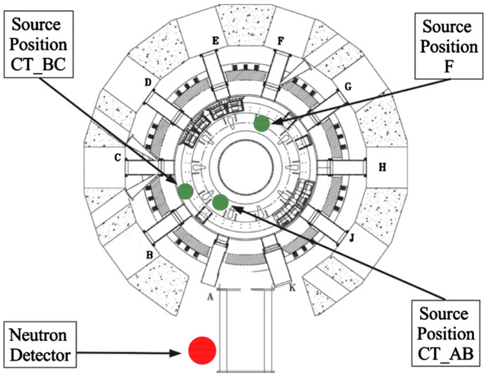

FIG. 2. (Color online) Top view of C-Mod. The external neutron detector and validation source positions are highlighted.

Validation simulation results, showing good agreement, appear in Table I. It should be noted that small in-vessel instrumentation and other ambient equipment that is not modeled in ACRONYM will provide additional uncertainty on the simulated detector efficiencies. Furthermore, by encompassing the entire superstructure of C-Mod, the validation simulations were far more ambitious than the primary use of ACRONYM, which is to simulate measurements within the interior of the tokamak.

C. Synthetic diagnosis of boron film thickness

The first wall of Alcator C-Mod is composed of molybdenum and tungsten PFCs, although significant improvements to plasma performance can be achieved by operating with micron-thick films of boron on the surface of the PFCs.[7] The boron film is applied by a plasma deposition process using diborane gas (B_2H_6). Once plasma operation begins, PSI processes such as erosion modify the initial boron films. However, due to the lack of a PFC surface diagnostic, we are blind to the initial efficiency and spatial uniformity of the boron film, as well as its time evolution in response to plasma conditions.

To simulate the *in situ* measurement of boron film thicknesses, ACRONYM incorporates a gamma production model for the $^{11}B(d,p+g)^{12}B$ reaction. For D+ ions onto pure boron film, the gamma yield, Y, is

$$Y(E_{D+},n) = \Phi \int_0^{R(E_{D+})} n(x)\sigma(E_{D+})dx, \tag{1}$$

where Φ is the number of impacting D+ ions, $R(E_{D+})$ is the range of the D+ ions in pure boron, n(x) is the boron number density, and $\sigma(E_{D+})$ is the reaction cross section.[8] $R(E_{D+})$ for 0.9 MeV D+ ions was calculated using the stopping and range of ions in matter,[9] and experimental cross section data were obtained from Sziki *et al.*[10] The model was validated by comparing calculated thick target yields (TTYs), i.e., targets for which $R(E_{D+})$ is less than the target thickness, to experimentally measured TTYs for incident D+ energies below

TABLE I. Experimental and ACRONYM neutron detector efficiencies for three ^{252}Cf calibration positions. Units of efficiency are in detector counts per ^{252}Cf source neutron.

Source position	Experiment efficiency (counts/source n)	ACRONYM efficiency (counts/source n)
CT_AB	4.13×10^{-8}	$(4.85 \pm 0.21) \times 10^{-8}$
CT_BC	2.77×10^{-8}	$(1.84 \pm 0.13) \times 10^{-8}$
F	3.28×10^{-9}	$(3.13 \pm 0.38) \times 10^{-9}$

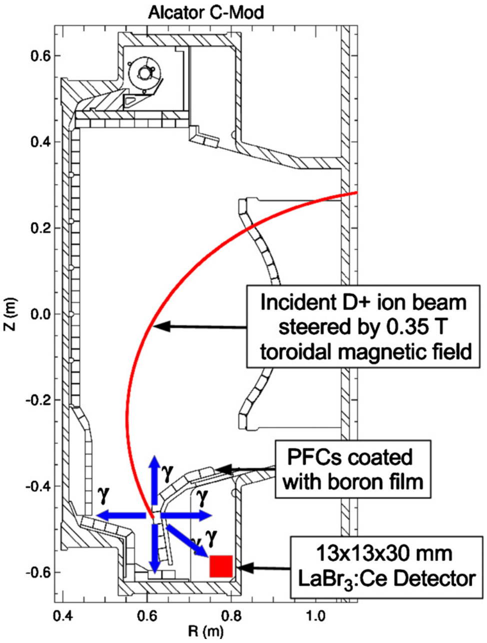

FIG. 3. (Color online) *In situ* diagnosis of boron film thickness

1 MeV from Elekes *et al.*[11] Calculated TTYs were within experimental error.

Consequently, ACRONYM can produce realistic LaBr3:Ce detector energy spectrums corresponding to known boron film thicknesses on PFCs anywhere in the first wall. This capability is enabling optimization of detector design and position within the vessel and will be critical for interpreting boron film thickness measurements once the diagnostic is installed, as described below.

ACRONYM was used to synthetically diagnose 0.2, 0.8, 1.4, and 2.0 μm thick boron films, as illustrated in Fig. 3. Shown in Fig. 4 are the corresponding detector energy spectra from the ^{11}B(d,p+g)^{12}B reaction. The large peak at ~0.2 MeV is the Compton backscatter peak produced by gammas that have scattered off the ambient geometry of C-Mod before being detected. More important for boron diagnosis is the smaller photoabsorption peak at ~0.95 MeV that provides for unequivocal identification of boron. Integrating under this peak provides a direct measure of boron film thickness, as evident from Fig. 5. Once the physical diagnostic is installed, experimentally obtained energy spectra will be similar to those in Fig. 4 but without *a priori* knowledge of the boron thickness. By matching the photoabsorption peak areas from the experimental diagnosis to those synthetically produced by ACRONYM, the physical boron thickness can be determined.

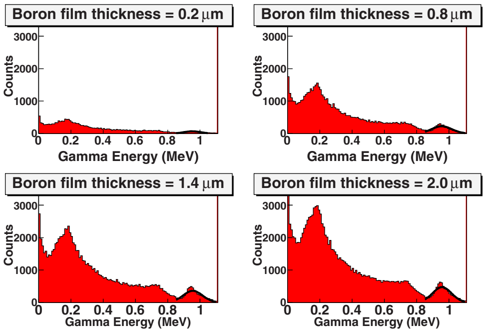

FIG. 4. (Color online) LaBr$_3$:Ce detector gamma energy spectra for four thicknesses of boron film.

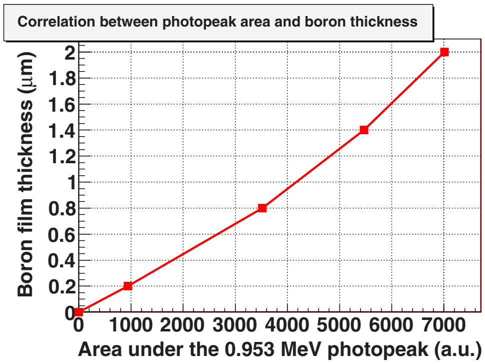

FIG. 5. (Color online) The area under the 0.953 MeV photoabsorption peak area can be used to determine boron film thickness.

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