Final Report

"Development of an accelerator-based diagnostic for plasma-facing surfaces in magnetic confinement devices"

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1. Executive Summary

The focus of this work was the development of the Accelerator-based In-situ Material Surveillance (AIMS) diagnostic. The understanding of plasma-material interaction processes in fusion devices has been greatly hampered by the lack of ability to measure the surface ~micron layers of solid surfaces that are in contact with and greatly modified by the boundary fusion plasma. AIMS was the first diagnostic developed and deployed that allowed non-destructive surface measurements with adequate spatial and time resolution. The deployment was primarily carried out on the Alcator C-Mod tokamak.

AIMS diagnostic goal is to remotely generate isotopic concentration maps on a plasma shot-to-shot timescale that cover a large fraction of the plasma-facing surface inside of a magnetic fusion device without the need for vacuum breaks or physical access to the material surfaces. The diagnostic used a compact (~ 1 m), high-current (~ 1 milliamp) radio-frequency quadrupole accelerator to inject 0.9 MeV deuterons into the Alcator C-Mod tokamak. The tokamak magnetic fields were controlled– in between plasma shots – to steer the deuterons to material surfaces where the deuterons cause high-Q nuclear reactions with low-Z isotopes up to 5 microns into the material. The induced neutrons and gamma rays are measured with scintillation detectors; energy spectra analysis provides quantitative reconstruction of surface compositions. Experimental validation showed that low-Z isotopes such as deuterium and boron can be quantified on the material surfaces, and that magnetic steering provides access to different measurement locations.

AIMS measurements of D retention on inner wall PFCs were acquired during diverted and limited plasma operations and during wall conditioning experiments om Alcator C-Mod. Intershot measurements demonstrate the local erosion and co-deposition of boron films on PFC surfaces with a constant D-B ratio. This is consistent with previous results suggesting that D co-=deposition with boron is insufficient to account for the net retention observed in Alcator C-Mod. Changes

in deuterium concentration during boronization, electron cyclotron and glow cleanings were also measured.

These initial results were limited to studying low-Z surface properties, because the Coulomb barrier precludes nuclear reactions between high-Z elements and the ∼1 MeV AIMS deuteron beam. In order to measure the high-Z erosion of interest in Alcator C-Mod and future fusion devices, a new technique using deuteron-induced gamma emission and a low-Z depth marker was developed using implanted depth markers as a method of measuring bulk erosion and redeposition. This method is dubbed DEA: Depth marker Erosion with AIMS. DEA simulations and experiments were used to validate this technique, both in the laboratory and via experiments in the EAST tokamak. Based on these results, the DEA technique, using ion beam implanted depth markers as a reference to the surface in order to monitor surfaces for erosion and redeposition, is a viable option as a diagnostic, both in and ex situ.

These markers show stability to temperature, the tokamak environment, and multiple probing beams. The ex-situ (eDEA) method, which uses resonances in the cross sections of gamma producing reactions to track the surface, was used to successfully measure erosion in samples that were exposed in the EAST tokamak. The in-situ (iDEA) method, which uses the gamma yield ratio to monitor changes to the surface, was used to differentiate between markers implanted to different depths. Both techniques were successfully simulated, and both presented unique challenges experimentally and in data analysis. In particular, the eDEA probing beam was found to have energy variations leading to initial experimental uncertainty, and the iDEA gamma spectra had conflicting gamma peaks which make data analysis difficult. However, the end result is a promising framework for a diagnostic technique that supplements the abilities of AIMS and expands the possibilities of surface diagnostics in fusion devices.

While the results of this work are overwhelmingly encouraging for further development of AIMS in general, and the DEA technique specifically, several areas require significant development before this diagnostic is as robust and widely

applicable as a surface diagnostic ought to be. Recommended future work includes the development of a cross section/yield measurement database, erosion tests with secondary verification of results using a fiducial mark from a focused ion beam, and acquiring a new accelerator with a more reliable high energy proton and deuterium beam

The project resulted in 14 publications, including the PhD theses of three MIT graduate students, cited in the included bibliography.

2. Introduction and Description

The magnetic fusion community has long understood that plasma confinement and control are intricately linked to plasma-facing component (PFC) surface conditions. For example, the application of special surface treatments to minimize sputtered PFC contamination in the core plasma resulted in world record fusion performance metrics on the TFTR and Alcator C-Mod tokamaks. Similarly, exposure to fusion-grade plasmas substantially modifies the properties of the PFC materials through plasma-material interactions (PMI). Incident plasma ions cause erosion and redeposition of PFC material through physical and chemical sputtering, leading to shortened PFC lifetimes and complex changes in surface morphology that affect plasma behavior. The deuterium and tritium plasma fuel can be retained in the PFC surfaces, either in redeposited material (carbon or beryllium PFCs) or in structurally damaged crystalline metals (molybdenum or tungsten PFCs).

In present devices, the retained fuel recycles into the plasma as neutral atoms from the PFC surface and interferes with external fueling, one of the principal means of plasma control. Although recycling is not expected to be an issue for steady-state reactors, long-term fuel retention in neutron damaged PFCs or co-deposited material may still present a challenge. Furthermore, the bulk retention of tritium is a nuclear safety matter and an operational issue since a limited onsite inventory requires tritium recovery for sufficient plasma fuel. The isotopic

composition of the PFC surface, such as the thickness of deposited boron film on PFCs in Alcator C-Mod, plays an important role in controlling the PMI dynamics of sputtering, neutral recycling, and fuel retention.

In addition to the lack of PFC diagnostics, the necessity to understand and mitigate PMI effects is hindered by the relatively short plasma pulses (~ s/pulse), low cumulative exposure times (~ 1000 s/year), and low incident heat flux (< 1 MW/m^2) to PFCs in most present-day devices. In contrast, the path to a steady-state fusion energy reactor, will add several orders of magnitude to pulse duration (1000 s/pulse), cumulative exposure time (10^5 s/year), and incident heat flux (~ 10 MW/m^2). Deleterious PMI effects that are partially observed or accessible in present devices will become critical for the physics of plasma confinement as well as the engineering of robust material structures.

In order to advance fusion energy towards a realistic commercial power plant, a comprehensive understanding of PMI science is required. This is the goal of AIMS which is based on a novel application of ion beam analysis.

3. Research

3.1. Diagnostic Design

A successful and widely applied method for characterizing material surfaces that have been modified by PMI has been the application of ion beam analysis (IBA). IBA uses ~ MeV ion beams in a variety of ion scattering, nuclear reaction, and atomic physics techniques to infer elemental and isotopic composition. PFCs are removed from the fusion device typically after several months to years of facility operation and brought to a dedicated offsite ion beam facility for analysis. An alternative method is to insert PFC samples into the fusion device on extendable probes before extraction for IBA analysis. Although considered the gold standard in PFC diagnosis, the intrinsically “archaeological” nature of such measurements prevents linking discrete plasma conditions to PFC surface responses, is spatially

limited to the extracted PFCs or inserted samples, and can be resource intensive for the fusion facility. The quintessence of AIMS is the adaptation of standard IBA from the traditional ex situ laboratory setting to the in-situ tokamak environment. The principal steps involved in AIMS are depicted in Figure 1, which shows a cross section of the Alcator C-Mod tokamak. Figure 2 shows a cut out of AIMS diagnostic installation on Alcator C-Mod which provides scaled perspective.

A compact linear deuteron accelerator is connected to the tokamak vacuum system at one of the radial diagnostic ports. In between plasma shots, it injects a beam of $\sim$ MeV deuterons into the tokamak vacuum vessel. Using the tokamak magnetic field coils, the beam can be steered electromagnetically via the Lorentz force. Constant magnetic field provides a steady-state, localized measurement, while controlled changes to the magnetic field move the beam to new measurement locations. The beam can effectively be swept around the inside of the fusion device, resulting in a map of the PFC surface isotopic content with the spatial resolution set by the deuteron beam spot size on the PFCs.

When the $\sim$ MeV deuterons impact the first wall, they induce high Q nuclear reactions with isotopes from hydrogen (Z = 1) to calcium (Z = 20) producing high energy neutrons and gammas. Nearby particle detectors perform spectroscopy of the neutrons and gammas from which the isotopic content of the PFC surface can be reconstructed. Due to the penetrating nature of the neutrons and gammas, the nearby detectors do not require line of sight to the PFC measurement location. The measurement depth into the PFC surface is dependent on the incident deuteron beam energy but is on the order of a few microns for $\sim$ MeV deuteron beams.

While the basic principles remain the same – analyzing materials by detecting accelerated ion-induced nuclear scattering products – AIMS represents a significant reinvention of almost all aspects of standard IBA as shown in Table I, which illustrates the principal differences. In standard IBA, small beam currents result in manageable detector count rates and minimum radiation risk. The beam energy is variable, enabling the experimenter to exploit energy thresholds and

resonances in the reaction cross section. Deuteron beams are typically not used due to the large neutron radiation generated by deuteron-induced nuclear reactions. Although x-rays and gammas are used in certain techniques, charged particles are preferred due to detector efficiencies approaching 100%, straightforward data analysis, and well validated experimental techniques.

Due to limited diagnostic space, AIMS utilizes a compact linear accelerator known as a radiofrequency quadrupole (RFQ) accelerator. RFQs employ resonant RF cavities with four machined axial vane structures to produce spatially varying fields near the beam axis. The specially designed field structure bunches and accelerates the beam while simultaneously providing strong transverse focusing. The combination of bunching, focusing, and accelerating with RF rather than ~ MV DC voltages allows RFQ cavities to be extremely compact high current ion accelerators, typically achieving acceleration gradients of 1 MeV/m per nucleon. The compact size enables the use of RFQs for the AIMS but restricts the beam energy variability since each RFQ is fabricated for a single mass to charge ratio and final output particle beam energy although in principle micron thick stopping foils could be used to reduce the beam energy at the PFC surface.

AIMS uses a RFQ accelerator to produce ~ MeV deuterons that can provide quantification of many isotopes between hydrogen and calcium. The nuclear reactions most relevant for diagnosing PMI are shown in Table 2. Two types of reactions are used in AIMS, principally because they provide high energy neutrons and gammas that can penetrate the several centimeters of detector shielding that is required in the fusion environment. In the first reaction type, the incident deuteron is stripped of either its proton or neutron; the residual excited nucleus returns to its ground state via gamma emission. The gamma energy is equal to the isotopically unique nuclear energy level spacing, providing unequivocal isotopic identification. In the second type, the deuteron fuses with the target nucleus, ejecting a neutron and leaving the residual nucleus in the ground state. In this case, the targets of interest are deuterium and tritium nuclei. The ejected neutron kinetic energy is a function of the reaction type, the incident deuteron kinetic energy at the time of reaction, and the angle between the deuteron and neutron

trajectories. At a particular measurement location in AIMS, the angle is fixed; therefore, the neutron kinetic energy can be used to identify deuterium or tritium as well as to potentially provide rough depth-resolution for the measurement.

3.2. Instrumentation

MIT RFQ is a refurbished prototype 0.9MeV deuterium ion accelerator from ACCSYS Technology Inc. The accelerator cavity measures 1.02 m in length (Figure 2). with 72.6 cm quadrupole vanes and is powered by a 425 MHz 60kW RF system. Significant upgrades to the controls, instrumentation, mechanical support structure, and vacuum system were required for integration into the tokamak environment. The accelerator controls and instrumentation were upgraded to digital Group 3 fiber optic loop controllers for remote operation in the high radiation environment of the tokamak cell. In addition, the mechanical support structure and vacuum system were redesigned to fit in the confined space surrounding the tokamak port while allowing for precision alignment of the RFQ cavity to the port flange.

Before coupling to the Alcator C-Mod vacuum system, the accelerator was aligned using a laser mounted in the accelerator ion source to ensure that the axis of the acceleration cavity was co-linear with the axis of the injection flange. A precision alignment was critical for two reasons: to ensure fidelity between the beam dynamics codes and the experimental beamline; and because there was insufficient space for electrostatic beam alignment optics between the RFQ and the tokamak port flange.

To achieve $\sim$ 2 cm spatial resolution on the target PFCs – roughly the width of a molybdenum PFC tile in Alcator C-Mod – beam optics are necessary to maintain a focused beam over the $\sim$ 2 m trajectory through the beamline and tokamak vacuum vessel. Because the iron-core magnetic quadrupoles typically used to focus ion beams can perturb the plasma magnetic fields or create unacceptable structural forces on the beamline, a set of three permanent magnet quadrupoles (PMQ) were used because of their compact size and zero net magnetic field. A

wide-band ferrite current transformer from Pearson Electronics with amplification and noise suppression. The transformer was installed at the point in the beamline immediately before injection to accurately measure the deuteron current entering the vacuum vessel.

Unlike the ideal laboratory environment of ex situ IBA neutron and gamma spectroscopy presents significant challenges in the tokamak environment. The superstructure of the fusion device causes substantial amounts of down-scattered particles that obscure the prompt, un-scattered reaction products in detector spectra. The detectors must work in magnetic fields close to the PFC measurement locations to maximize solid angle and signal-to-noise ratio. The limited diagnostic space restricts detectors to ~10 cm in linear dimension, and the possibility of severe mechanical shock from plasma disruptions necessitate robust detectors. High energy neutron fluxes during plasma shots require radiation-hard detector electronics. Finally, the use of high peak current RFQs results in instantaneous detector counts rates that can approach 10^6 per second.

Such a hostile detection environment prevents the use of almost all standard spectroscopy detectors; however, the recent emergence of large surface area (~ 1 cm^2) photonic readout devices, such as the silicon avalanche photodiode (SiAPD) and silicon photomultiplier (SiPM), have enabled new types of advanced scintillation crystal detectors. These detectors are mechanically robust, radiation hard, operable at very high count rates, geometrically compact, and insensitive to magnetic fields, making them a feasible choice for AIMS.

Figure 3 shows two sample detectors used in AIMS. The neutron detector is composed of a EJ301 liquid organic scintillator within a 1.6 mm thick canister of aluminum. A 6 mm Borofloat window transmits scintillation photons to an optically coupled Hamamatsu R6095 1-in. photomultiplier tube with bi-alkali photocathode for readout. While the EJ301-PMT configuration detects both gammas and neutrons, standard pulse processing techniques can be used to digitally discriminate between them using the particle-dependent decay tail times of the scintillation pulses.

The gamma detector was manufactured by Saint-Gobain and is composed of a cerium doped Lanthanum Bromide (LaBr3) scintillator crystal optically coupled to a Hamamatsu silicon avalanche photodiode for readout. An internal charge-sensitive preamplifier aids in pulse shaping. All components are enclosed in a 2 mm thick stainless-steel case. The detector has been ruggedized against mechanical shock. The LaBr3 -SiAPD also has the advantage of being blind to neutrons, preventing interference with the gamma spectroscopy. Figure 4 shows examples of calibration spectra used in the AIMS development.

3.3. Modeling tools developed for AIMS

Two important components of AIMS were comprehensive simulations of PFC surface measurements and high-fidelity modeling of the deuteron beam dynamics. Simulation provided a flexible design tool to evaluate the impact of tokamak geometry, detector design, and instrumentation location on the measurement capabilities of AIMS. Once the experiment design is implemented and fully modeled as a "synthetic diagnostic," the simulations were used to interpret the experimental results and provide the experimental parameters required for maintaining optimized beam focusing and steering.

The IBA simulation tool called ACRONYM (Alcator C-Mod RFQ Optical and Nuclear Yield Model) is a Geant4-based Monte Carlo synthetic diagnostic that is used to model AIMS on the Alcator C-Mod tokamak. ACRONYM is capable of simulating all aspects of AIMS measurements due to three features. First, we have modeled the full geometry, materials, and magnetic fields of the Alcator C-Mod tokamak. Second, we have developed a new computational model for energy- and particle-dependent scintillator responses that enable high precision modeling of LaBr3 - SiAPD and EJ301-PMT detectors in complex experimental environments. Third, we have implemented a deuteron-induced nuclear reaction module in Geant4 to simulate the deuteron beam interacting with the PFC surface. As an example, Figure 5 shows a simulated LaBr3 - SiAPD energy spectrum for the synthetic diagnosis of a micron thick boron film layer on a molybdenum PFC surface in

Alcator C-Mod in the lower divertor. Despite the large scattering background from C-Mod geometry, a peak at 0.953 MeV from the 11 B(d,pγ)12 B reaction uniquely confirms the presence of boron; the integral under the gaussian fit to the peak provides a quantitative measure of the absolute boron content. Because it calculates realistic detector responses for known PFC surface compositions, ACRONYM facilitates the interpretation of experimental data where the surface composition is not known.

Two codes have been developed to model the RFQ deuteron beam dynamics in the three-dimensional environment of the beamline and Alcator C-Mod vacuum vessel (see Figure 6). The first code implements a simple integrator on the equations of motion of a single deuteron in the magnetic steering fields. Coupled to a realistic 3D boundary of the PFC surfaces, the code is capable of determining the accessible PFC surfaces as a function of the steering magnetic field magnitudes. The code was primarily used to optimize the injection position and angle of the RFQ during the design phase. A study for the final installation position, plotting the accessible PFCs as a function of toroidal magnetic field, is shown in top part of Figure 6.

While useful for fast parameter sweep studies and estimates of magnetic steering, treating the RFQ beam as a single particle overlooks many important aspects of simulating high current accelerator beams in magnetic fields. Important effects, such as 3D spatial and velocity distribution focusing limits, steering field and gradient finite beam width effects, space charge expansion and beam energy distribution effects on dispersion must be accounted for to correctly optimize the parameters of the PMQ focusing and predict the spatial resolution of the beam on the surface of the PFCs. While existing beam transport codes account for these effects, they are not general enough to model the beam interactions in the complex magnetic fields and geometry of the tokamak. To account for this shortcoming, we developed a custom beam transport code that can be used to optimize the transverse beam dynamics in the PMQ system and tokamak magnetic fields. The code first computes the beam centroid trajectory through the magnetic fields to the PFC surface; the fields are calculated using a

Biot-Savart solver for the toroidal field and an elliptic integral solution for the vertical field. Then, the code discretizes the beam trajectory into many small segments, each of which is sequentially input into TRACE3D to simulate the beam distribution evolution distribution as it progresses along the centroid trajectory from the RFQ to the PFC surface. Finally, a normal projection of the beam distribution on the PFC surface gives the final spatial resolution, allowing optimized PMQ positions to be determined. As an example, the spatial resolution of the beam on the central column PFCs as a function of the toroidal magnetic field coil current is shown in bottom part of Figure 6, showing that spatial resolution of a few centimeters is possible.

3.4. Results from AIMS on Alcator C-Mod

The AIMS diagnostic underwent thorough vetting on Alcator C-Mod including calibration of the beam steering and current. To validate the isotope detection capability of the LaBr3 -SiAPD detector in Alcator C-Mod, we directed the deuteron beam to a single PFC location on the inner wall. The result is shown in Figure 7 of interrogation of the inner wall of Alcator C-Mod. The spectrum is primarily composed of a large background due to unavoidable Compton scattering off the dense structure of the tokamak. While the background is substantial, four discrete gamma peaks are statistically significant above the background. The 0.511 MeV peak results when positron annihilation gammas from ambient material are detected. The positrons are a result of high energy gammas (~2 MeV) inducing pair production in material near the detector. The 0.662 MeV peak is caused by a cesium-137 check source that is purposefully attached to the detector for in-situ calibration. The 0.847 MeV peak results from inelastic neutron scattering off the significant amount of steel in the vacuum components of Alcator C-Mod via the reaction 56 Fe(n, nγ)56 Fe. Finally, for the purposes of diagnosing PMI, the most important peak is the 0.953 MeV peak that is produced by un-scattered gammas from the 11 B(d, pγ)12 B reaction. The area of the peak, calculated by integrating a gaussian fit to the peak after subtracting a calculated background spectrum, can be used in conjunction with the beam and detector parameters to quantify boron on the PFC surface.

The absolute value of the derivative of the EJ301-PMT neutron spectra at three different angles appear in Figure 8 . The shaded vertical bars represent the predicted peak energy of neutrons from 2 H(d, n)3 He surface reactions at three incident deuteron-ejectile neutron angles: 124◦ , 143◦ , 157◦ . Despite some scatter at lower energies, the key feature – the 7 statistically significant, adjacent points that deviate from the scattering background to form the peak – clearly shift higher in energy as the angle changes in close agreement with the kinematic predictions. We attributed the degradation in the peak structure with increasing angle to a larger spread in the beam projection on the PFC tiles, which is caused by the high current beam effects in magnetic fields. The results demonstrate two key points. First, the beam dynamics codes, which were used to calculate the angles between the incident deuterons and ejectile neutrons as inputs to the nuclear kinematic predictions shown in Figure 8 , correctly simulate the trajectory of the beam in the magnetic steering fields and the impact location on the PFCs. Second, the three measurements of deuterium show the feasibility of providing spatially resolved maps of isotopic content across a large surface area of PFCs, confirming the ability of steering the deuteron beam with the tokamak magnetic fields.

Following the cessation of Alcator operations, the project validated the in-situ AIMS measurements by removing the section of inner wall tiles and performing external beam analysis on them (Figure 9). The full set of results is documented in Barnard thesis, but an example is shown in Figure 10 where the absolute Boron film thickness measured by AIMS was validated. However, unlike the ex situ analysis the AIMS results are fully time resolved through boronizations and plasma discharges. This exercise proved that AIMS met it diagnostic goals. The Hartwig2015 paper from a PSI conference presentation summarized these results and interpreted their significance.

3.5. Development of In-situ Depth Markers

Further direct use of AIMS was stopped by the C-Mod closure and the end-of-life failure of the RFQ accelerator. Therefore, the focus of the project switched to the development of a method to measure the erosion of high-Z materials using in-situ depth markers that could couple to a functional AIMS diagnostic. This method was dubbed DEA (Depth-marker Erosion for AIMS).

Figure 11 illustrates the premise behind DEA. As the probing ion beam travels through the surface, the particles lose energy to the electrons and nuclei in the material and slow down. Simultaneously, the particles begin to interact with the implanted marker. These interactions will primarily occur at the peak of the marker distribution, but will begin earlier where the implanted beam straggle has left a significant concentration of material.

Choosing the marker species and, to a lesser extent, choosing the probing beam species are important considerations. The implanted marker must be naturally absent from or present in only trace quantities in a tokamak. The probing beam selection is determined based on the application of the technique and the choice of marker isotope. For external DEA, the possibilities for the probing beam are confined only by the accelerator availability, which makes the technique very flexible for use in different machines. The marker species ideally has a resonance with a potential probing beam. In-situ DEA requires a deuteron beam in order to make the other AIMS measurements (most importantly, measuring deuterium retention, which depends on DD fusion); as such, the implanted marker can only be a species that has a gamma-producing reaction with deuterium.

By measuring the gamma yields at one or more gamma energies at one or more incident beam energies, the location of the marker can be determined. This allows for calculation of changes in the surface, i.e. erosion or redeposition. While DEA can be used on its own to make measurements of the surface, it is best used as an enhancement of the AIMS technique, combining the low-Z measurements that can be made with AIMS with the high-Z/bulk measurements possible with DEA.

The project experimentally explored several different combinations of markers and beam species (see Kesler thesis for details). Simultaneously numerical simulations were developed that provided a synthetic diagnostic to correlate the changes in the gamma yields to the apparent depth of the marker (Figure 12). This showed that the technique could uniquely identify erosion and deposition of intrinsic PFC surfaced including high-Z PFCs. This effort culminated in experimental trials that determined the viability of the technique , including the measurement of high-Z net erosion and deposition in the EAST tokamak (Figure 12).

4. Conclusions

The project successfully developed a novel in-situ surface diagnostic for magnetic fusion. AIMS was designed and installed on Alcator C-Mod and made unique measurements of boron layers and fuel deposition with spatial and time resolution significantly better than previous PMI diagnostics. The project resulted in 14 publications and was the basis for 3 doctoral student theses. By any scientific measure it was a success.

The full promise of AIMS is yet to be realized. The end of Alcator C-Mod operations necessarily hampered the further deployment of the diagnostic. In addition, the RFQ accelerator experience technical end-of-lifetime damage, and given the budget limitations of the grant and the end of C-Mod, replacement of the accelerator was not pursued. Nonetheless further high-value research development of in-situ erosion markers was successful, which provided even further motivation for the deployment of an AIMS in future magnetic fusion experiments.

5. Figures

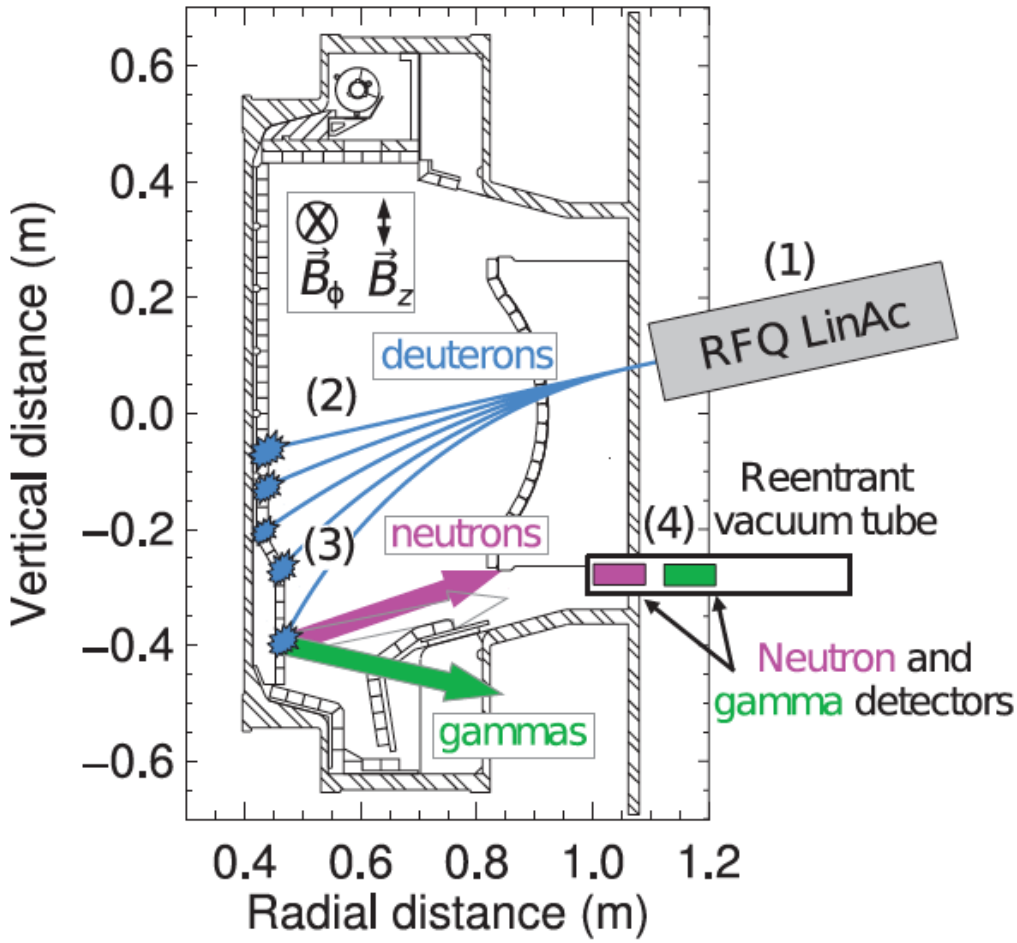

Figure 1 A depiction of AIMS on a cross section of the Alcator C-Mod tokamak showing (1) the RFQ linear accelerator, (2) magnetic beam steering, (3) nuclear reactions in materials, and (4) particle detection.

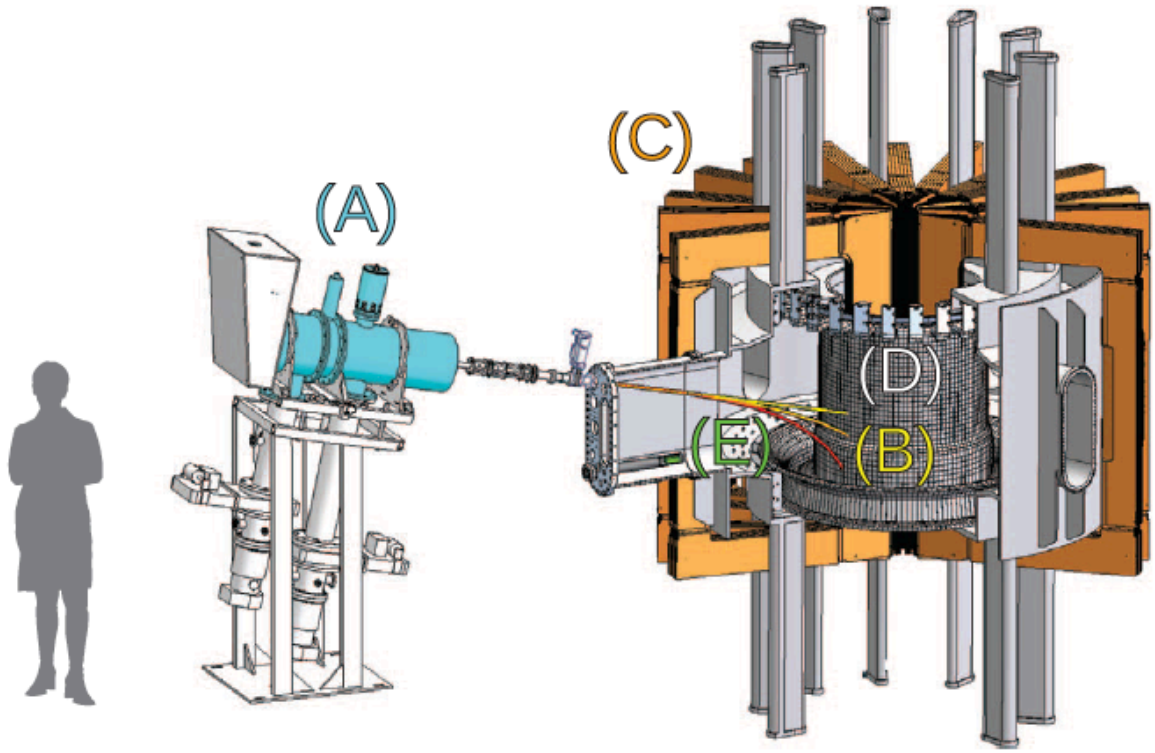

Figure 2 The AIMS diagnostic installed on the Alcator C-Mod tokamak showing (a) the RFQ accelerator, (b) three different beam trajectories, (c) the toroidal field magnets used for beam steering, (d) the PFC tiles, and (e) the reentrant particle detectors.

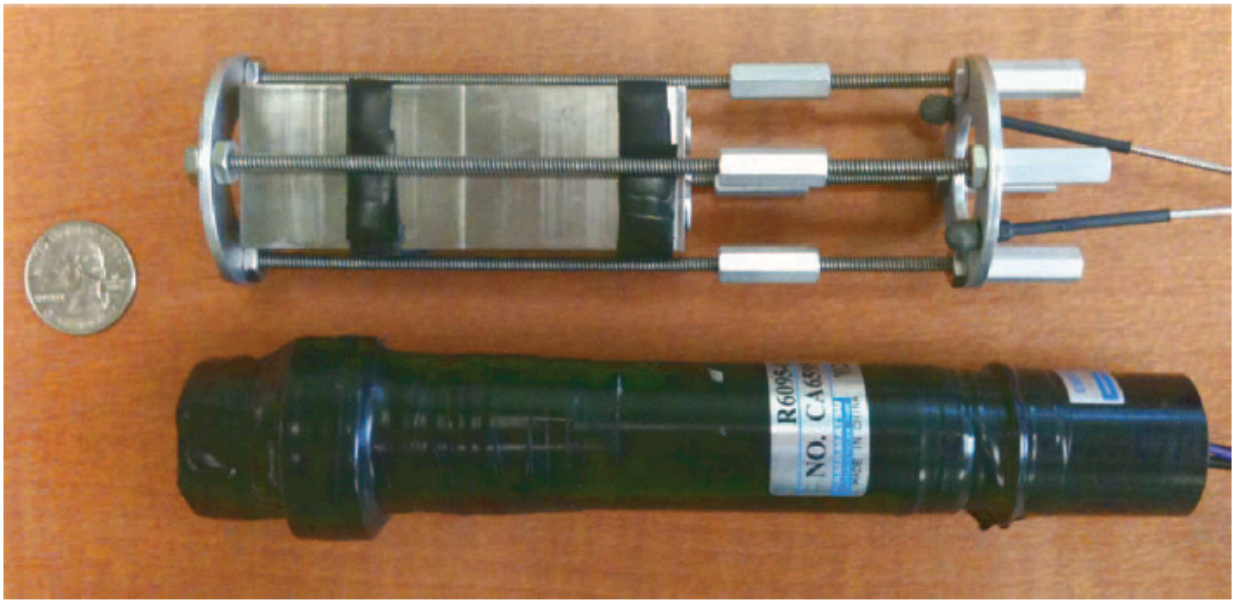

Figure 3 The LaBr3-SiAPD gamma detector (top) and the EJ301-PMT neutron detector (bottom) shown next to a U.S. quarter for scale. The LaBr3-SiAPD detector is shown in the cartridge that secures it inside the reentrant vacuum tube.

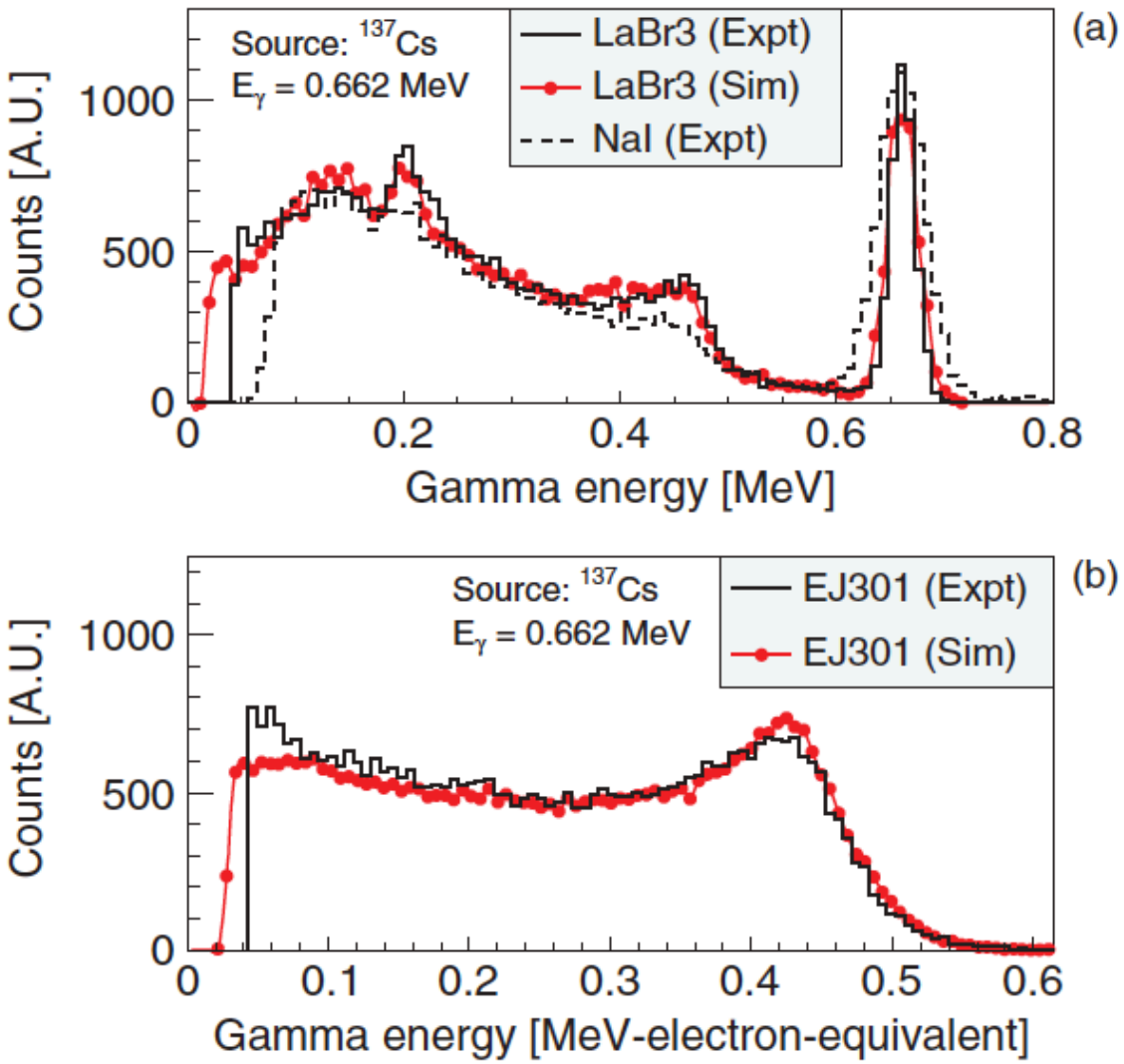

Figure 4 Example calibration spectra for the AIMS detectors.

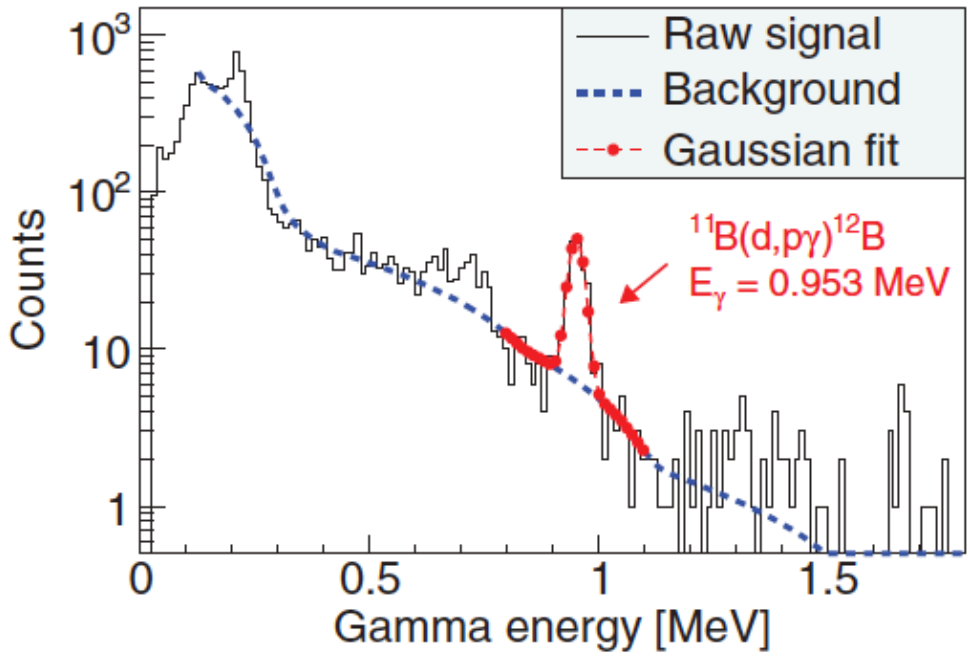

Figure 5. A simulated gamma spectrum from ACRONYM indicating the measurement of boron film on a molybdenum PFC surface. The 0.953 photopeak confirms from a 11B-D gamma reaction confirms the presence of the boron while the amplitude of the peak quantifies the boron film's thickness.

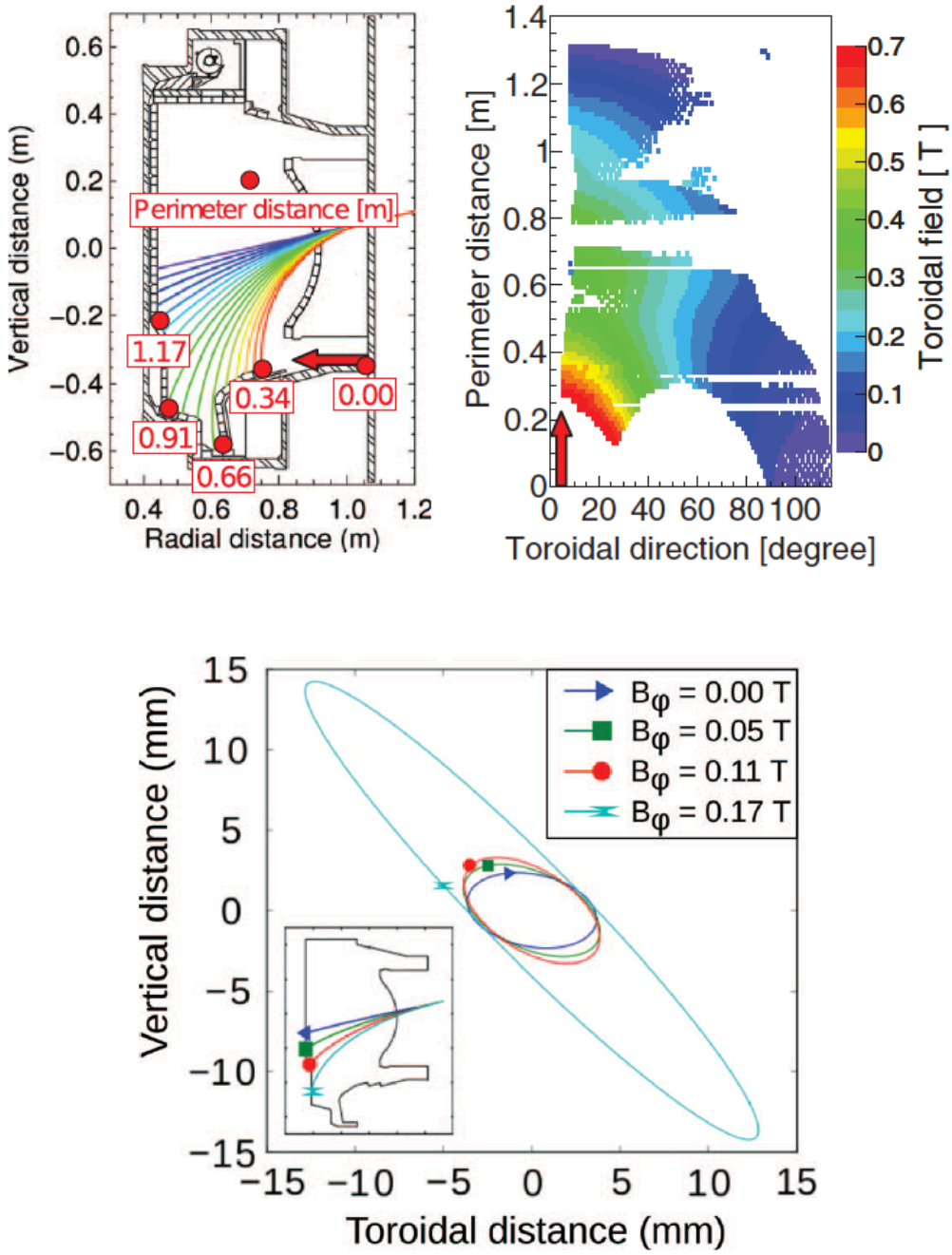

Figure 6 Results of beam steering (top) and focusing (bottom) models.

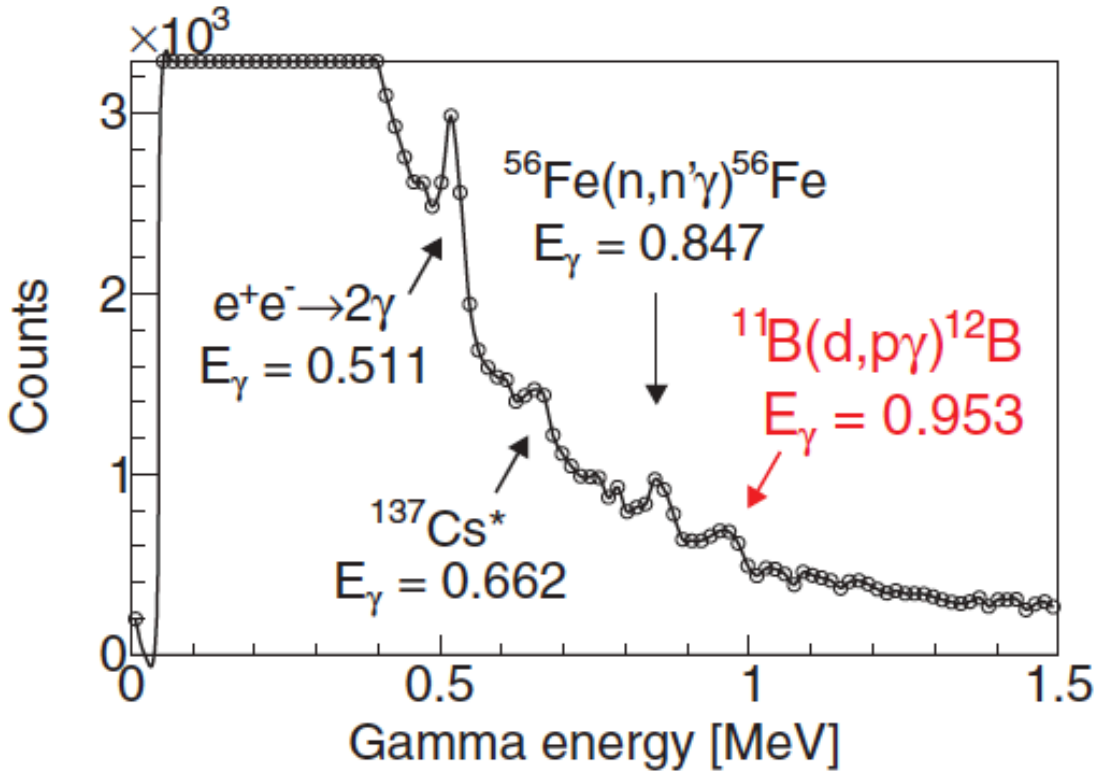

Figure 7 Example spectrum of gammas to measure boron film on the inner wall of Alcator C-Mod

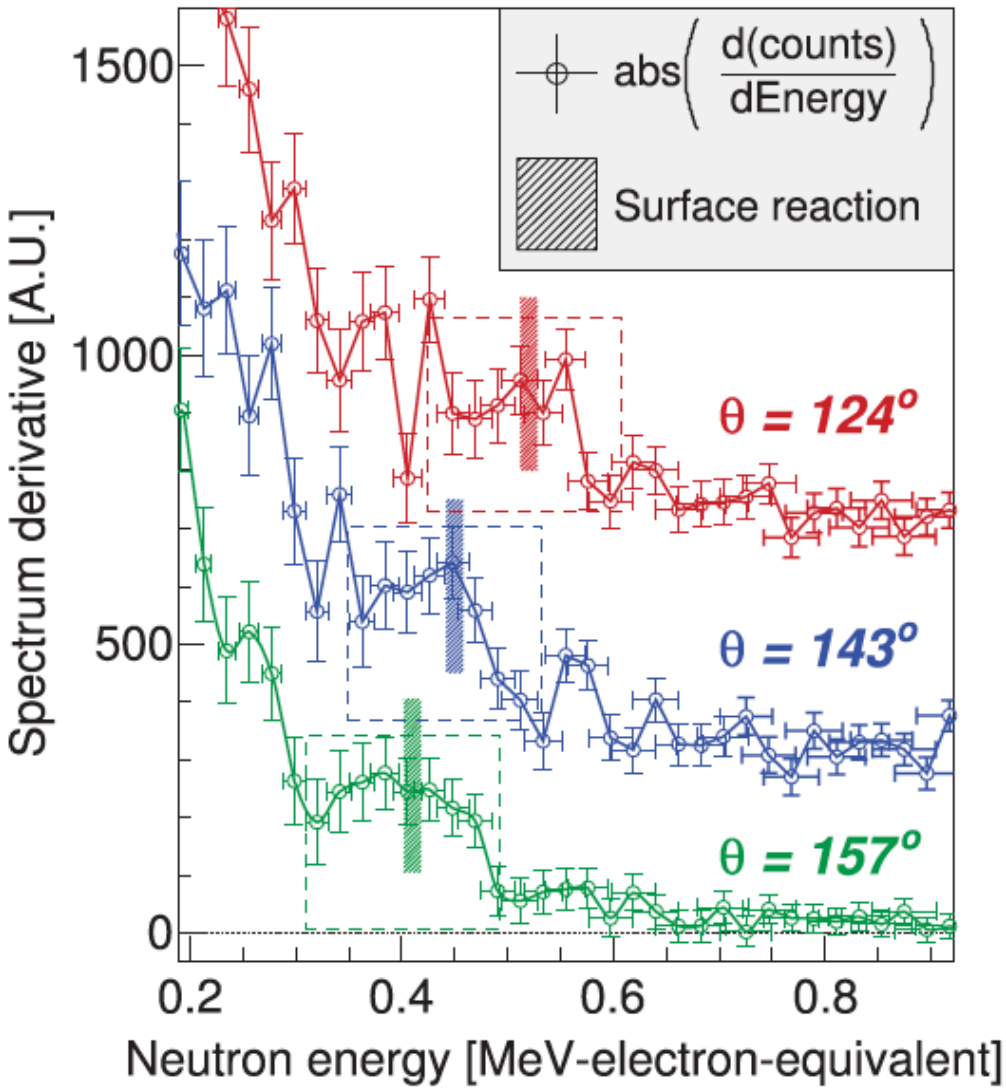

Figure 8. Example neutron spectra of deuterium co-deposition at the inner wall of Alcator C-Mod. The apparent shift in neutron energy is expected from the varying kinematics of the neutron-inducing reaction.

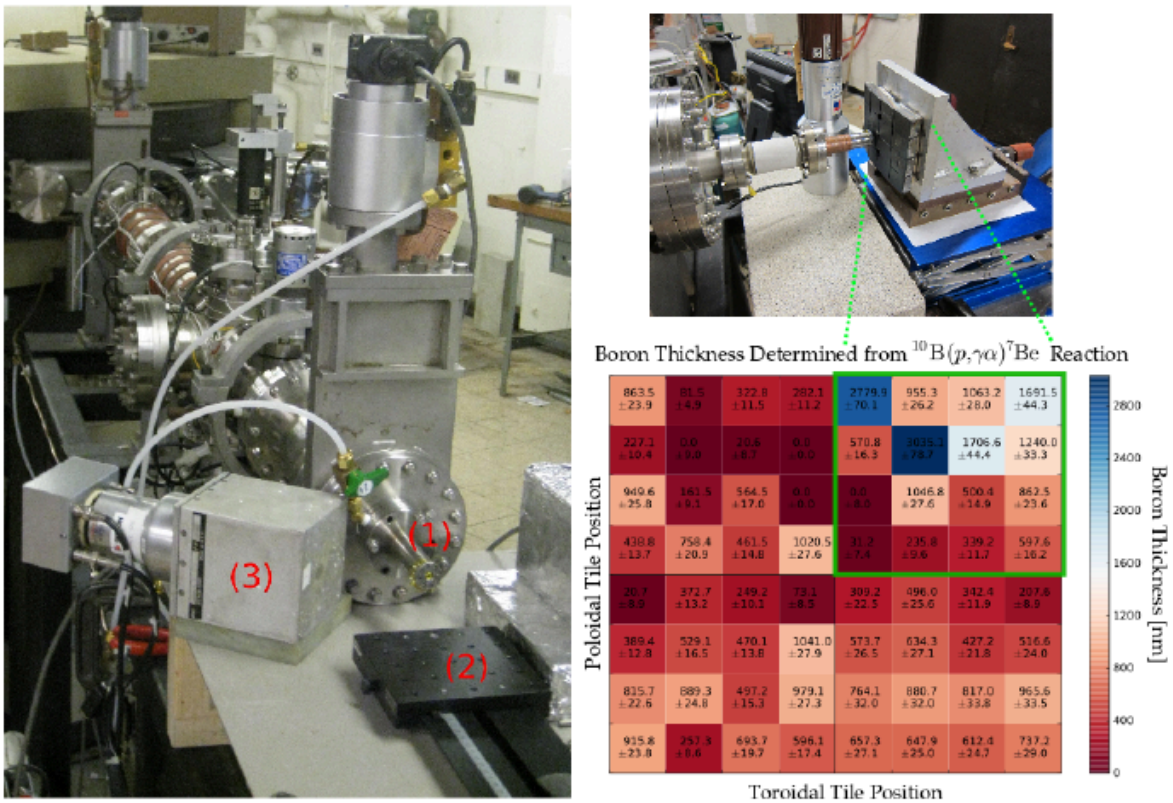

Figure 9 Photos of the external beam setup to measure ex-situ the boron film thickness of the inner wall tiles in Alcator C-Mod. This provided a confirmation of the AIMS in-situ results

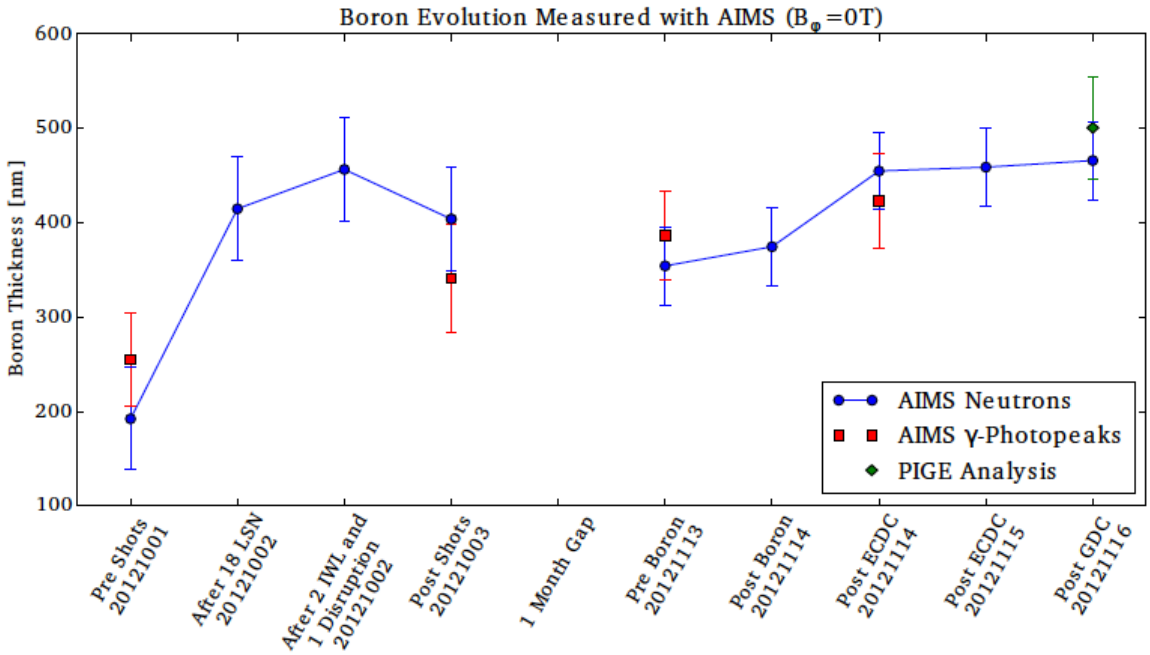

Figure 9. Comparison of in-situ and ex-situ boron film thickness at the inner wall of Alcator C-Mod.

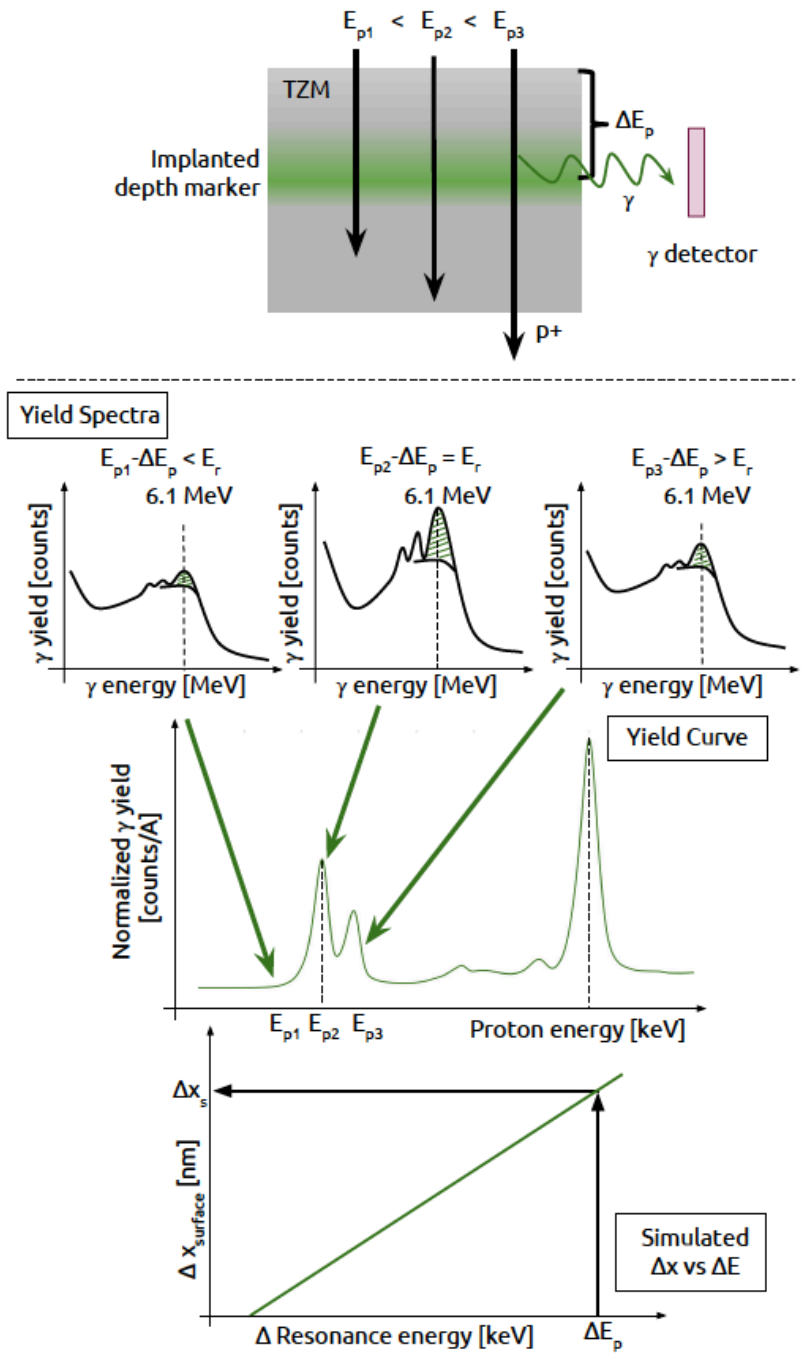

Figure 11 Principles of the ex situ DEA method are illustrated. The gamma spectra from many proton energies are measured. The chosen gamma energy is analyzed and integrated at each proton energy, leading to the production of a gamma yield curve as seen in the bottom of the figure. Each of the resonances seen can be analyzed for a centroid and a width, revealing information about the depth and distribution of the implanted marker.

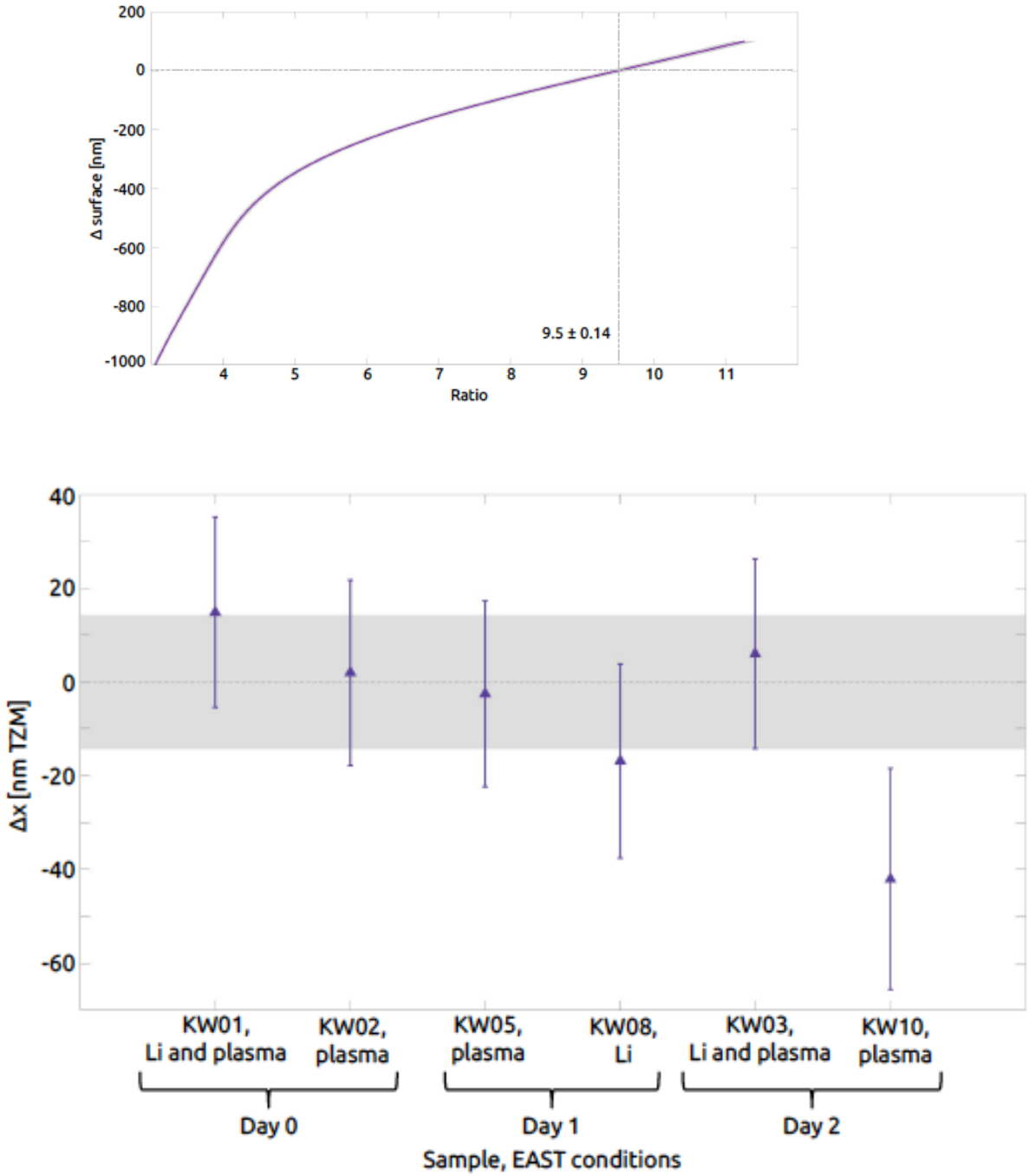

Figure 12 (Top) Simulations correlating the ratio in gamma peaks to depth marker thickness. (Bottom) Results from using the depth marker technique on sample exposed in the EAST tokamak.

6. Tables

Parameter	Standard IBA	AIMS
Accelerator	Electrostatic, $>m^3$	RF, $\sim 0.1\ m^3$
Beam ion species	$Z \lesssim 26$; rarely ^2H	^2H
Beam energy	Variable $\lesssim 5.0$ MeV	Fixed
Beam current (nA)	$\sim 10^0$–10^3	$\sim 10^6$
Beam duty cycle (%)	100%	$\sim 1\%$
Detected species	Ions, x-rays, γ	Neutrons, γ
Detector distance (m)	~ 0.1	~ 1
Detector solid angle (sr)	$\sim 10^{-1}$	$\sim 10^{-3}$
Detector view	Line-of-sight	Shielded
Detector count rates (s^{-1})	$\sim 10^3$	$\sim 10^5$–10^6
Kinematic geometry	Fixed	Variable

Table 1 The key parameters of interest for ion beam analysis (IBA) show the significant challenges that were overcome in order to adapt standard laboratory techniques for AIMS.

PMI issue	Reaction	Particle	Energy (MeV)
Fuel retention	$^{2}H(d,n)^{3}He$	n	~2–5
	$^{3}H(d,n)^{4}He$	n	~13–16
PFC condition	$^{12}C(d,p\gamma)^{13}C$	γ	3.089
	$^{14}N(d,p\gamma)^{15}N$	γ	1.885, 2.297
	$^{16}O(d,p\gamma)^{17}O$	γ	0.874
Net erosion	$^{7}Li(d,p\gamma)^{8}Li$	γ	0.478
	$^{9}Be(d,n\gamma)^{10}B$	γ	0.718
	$^{11}B(d,p\gamma)^{12}B$	γ	0.953, 1.674
Transport	$^{12}C(d,p\gamma)^{13}C$	γ	3.089
	$^{13}C(d,p\gamma)^{14}C$	γ	2.313

Table 2 The deuteron-induced nuclear reactions that can be used to diagnose PMI shown with the corresponding detected particle type and energy.

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