TABLE OF CONTENTS

Executive Summary

Dynamics of Plasma-Surface Interactions Using In-situ Ion Beam Analysis

The plasma-surface interface composes one of the most interesting and important fields of study in plasma physics, and in the application of plasma physics to magnetic confinement fusion research. Both the plasma and the material surface simultaneously change characteristics due to their interaction, and affect each other in a complex, non-linear manner. This dynamic interaction leads to several effects, such as net erosion of plasma-facing surfaces, tritium retention in deposit layers and plasma impurity contamination, which are all estimated to limit the viability of long-pulse plasma fusion devices. However, in general, these phenomena remain relatively poorly understood, primarily due to the lack of proper plasma-surface diagnosis.

A new experimental facility is proposed that will greatly enhance the fundamental understanding of plasma-surface interactions (PSI). **The innovative feature of the facility is its ability to measure accurately the real-time response of the material surface to the plasma bombardment using in situ high-energy ion beam analysis**. This unique ability allows for a study of situations where near-surface impurity/fuel ionizations and plasma transport dominate the plasma-surface interaction. In these cases the ability to diagnose surface modifications actually provides a powerful new tool for diagnosing and understanding plasma behavior near surfaces. The PSI issues in magnetic fusion research, where high densities are typical, definitely fall into this category and will be the focus of the proposed research. Specifically the major research topics proposed are:

- Measurement and modeling of near-surface cross-field ion transport. This study seeks to determine the controlling parameters for the magnitudes and locations of net erosion / redeposition of plasma-facing materials relevant to fusion (carbon, molybdenum, tungsten).

- 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 or multiple species materials.

While proposed for fusion research, the device clearly has utility in any application where plasmas are used for modifying surfaces (e.g., ion implantation, etching, thin-film deposition) and should therefore be considered to be a generic PSI tool.

Material samples will be exposed to cylindrical plasmas (hydrogenic, helium or argon) with a constant axial magnetic field (< 0.1 T) applied for plasma confinement. A helicon plasma source is used to produce steady-state, moderate density plasmas, or alternatively, a plasma gun will be used to produce pulsed, high particle/power density plasmas. A 1.7 MV terminal tandem accelerator provides a mono-energetic, scanning, ion

beam to the sample in order to probe the characteristics of the first several microns of the material. The versatile dual-source accelerator available at UW-Madison provides ion beams of essentially any element with beam energies of 0.1 to 10 MeV. High current beamlines are also available for implanting depth-marking impurities into samples. This then allows for a wide variety of established ion beam analysis techniques to be used for near-surface diagnosis, such as Rutherford backscattering spectroscopy, elastic recoil detection and nuclear reaction analysis. Combined, these ion beam techniques can measure spatial profiles of target material net erosion/deposition, as well as depth-resolved impurity stochiometry (including hydrogenic species) during plasma bombardment. The development of ion beam analysis detectors compatible with the plasma environment is described. Simultaneous with surface diagnosis, target material erosion by sputtering and its ionization in the plasma is diagnosed using optical emission spectroscopy techniques. Plasma parameters will be measured by a Langmuir probe.

Taken together, these plasma and surface diagnostics will provide extremely high quality benchmarks for existing particle transport codes used in fusion research such as WBC [Brooks 2002], UEDGE [Rognlien 1994] and DIVIMP [Stangeby 1992]. The proposed facility is also highly complimentary to existing experimental PSI research efforts in fusion on ion-surface interactions (e.g., IIAX [Allain 2001]), high-power experimental simulators of fusion edge plasmas (e.g., PISCES [Goebel 1987]) and confinement device PSI experiments (e.g., DiMES on the DIII-D tokamak [Wong 1998]).

1. Introduction & Motivation

Plasma-surface interactions (PSI) have long been appreciated to be one of the most critical issues in magnetic confinement fusion research [McCracken 1976, Meservey 1980]. The mechanical and thermal demands on plasma-facing materials in a steady-state fusion device are extreme. Perhaps more critical, it is known that the behavior of the plasma-surface boundary plays a key role in determining the fusion performance of the core plasma. Present confinement devices have demonstrated this clearly, where high-performance discharges were "discovered" by applying conditioning techniques to plasma-facing surfaces (e.g., TFTR "supershots" [Dylla 1989], VH-mode on DIII-D [Jackson 1991]). In a sense this is not surprising since the plasma-surface interface essentially sets the "boundary condition" for the plasma. Indeed it is now understood that the operational success of future burning plasma devices will hinge critically on PSI issues such as: 1) the erosion of plasma-facing surfaces, 2) tritium fuel retention in surfaces, 3) control of plasma density and H isotope mixture with wall fuelling, and 4) the minimization of core plasma impurities (e.g., ITER [Federici 2001]).

At the same time, the complex non-linear nature of PSI in fusion devices presents a most difficult challenge for diagnosis. For this reason the fundamental understanding and predictive capability on PSI issues is relatively poor. Indeed major PSI results of present devices remain unsolved; such as the magnitude and location of tritium retention in the JET tokamak [Coad 2001, Brooks 2003] and the controlling source of core impurity contamination [Kallenbach 1999, Whyte 2001]. The PSI research to-date has followed two essentially independent paths. Laboratory PSI research has focused on understanding the specifics of ion-solid interactions (implantation, reflection, sputtering, etc.) with many successes in discovering its underlying principles [Federici 2001]. Confinement device PSI is typically limited to measuring the magnitude of plasma recycling from surfaces, impurity and radiation levels in the edge plasma, and their effect on overall fusion performance. The important gap to bridge between these two areas of research is the understanding of the how the plasma and wall surface dynamically affect one another.

These dynamics are particularly important in fusion PSI where the high particle and power density boundary plasma ensures that neutral particles leaving the wall (through desorption or sputtering) are ionized at distances much smaller that the device size (see schematic of PSI in Fig. 1). Therefore, the great majority of these ionized particles are returned promptly to the surface, thus setting up a self-consistent equilibrium between the plasma and surface, i.e., recycling. This *gross* recycling is readily measured by non-intrusive techniques such as optical emission spectroscopy. However it is the details of near-surface plasma properties that govern the important *net* PSI effects, namely net erosion, T trapping in deposits and plasma contamination. These arise from both spatial asymmetries in plasma parameters leading to non-uniform particle sputtering, and from the details of the near-surface ion plasma transport parallel and perpendicular to the magnetic field (Fig. 1). Because they are so much smaller in relative magnitude, these *net* effects cannot be measured reliably by *gross* diagnostic techniques. **Therefore, simultaneous diagnoses of both the surface and plasma dynamic response are needed to improve understanding of the plasma-surface interactions.**

We propose here to develop an experimental device that provides spatially and depth-resolved material surface diagnosis based on high-energy ion beam analysis (IBA), obtained simultaneously with plasma bombardment and diagnosis. This facility will take advantage of well-established IBA surface analysis techniques. Indeed, ex-situ IBA analysis of material samples exposed in confinement devices have been largely responsible for our current understanding of the importance of the net PSI processes mentioned above [Wampler 1995, Whyte 1999, Maier 1999, Krieger 2001]. The development of real-time in-situ surface diagnosis is important for two reasons:

1) It allows one to follow the dynamic evolution of the plasma-surface interactions.

2) It allows for a much greater range of experimental flexibility. Surface diagnosis can be readily obtained under different plasma conditions without the need for time-consuming removal and ex-situ surface analysis of plasma-exposed samples.

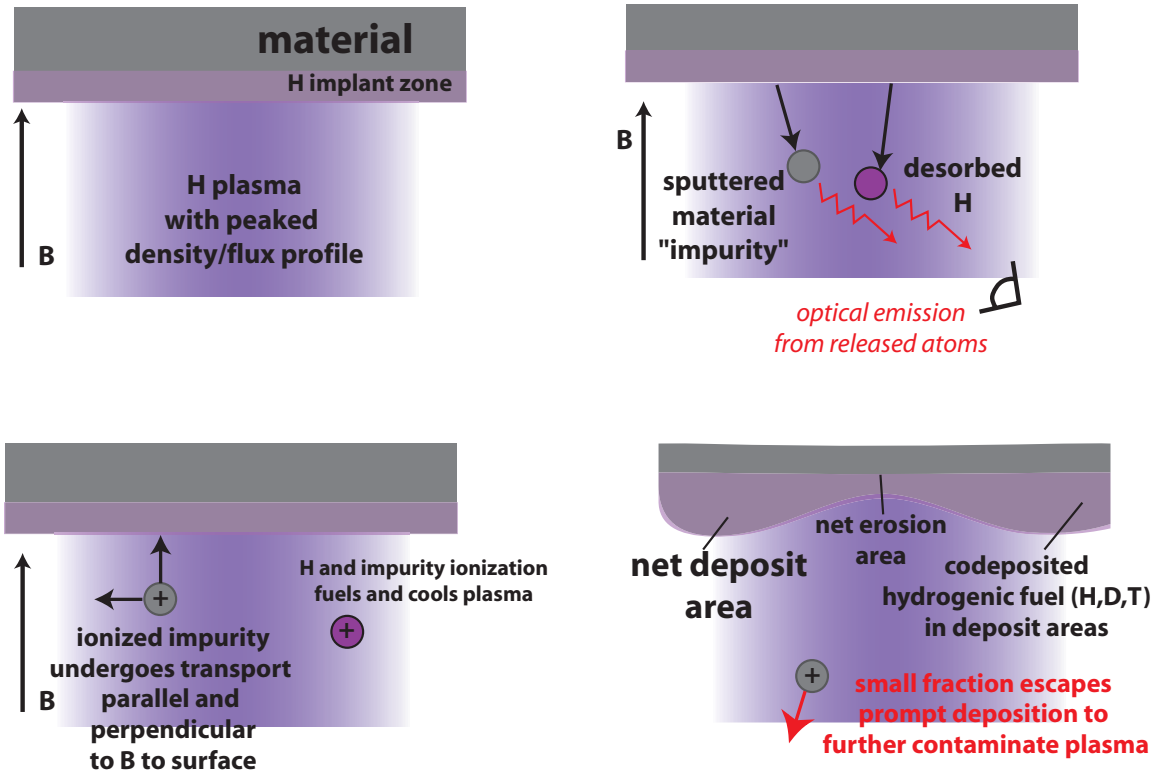

Fig. 1 *Schematic of fusion plasma-surface interaction processes. (Top left) Static plasma exposure (Top right) Gross PSI processes of sputtering and desorption (Bottom left) Near-surface plasma processes (Bottom right) Net PSI effects: erosion, deposition, hydrogenic trapping and plasma contamination.*

2. Experimental Facility to Study the Dynamics of Plasma-Surface Interactions

2.1. Overview of the experimental facility

It is first important to note the overall design philosophy for the proposed experimental facility. Our interest principally lies in advancing the state of the art in plasma-surface interaction diagnosis by a carefully chosen combination of established ion beam analysis techniques with proven plasma sources / technology**.** The primary technological challenge is therefore the integration of the high-energy IBA into a plasma environment appropriate for fusion PSI research.

There is no fundamental incompatibility in the combination of IBA and low temperature laboratory plasmas. The two operate in vastly different energy regimes: with plasma temperatures and sheath potential < 100 V, compared to ion energy > 1 MeV typically used for IBA. The moderate magnetic fields used for lab plasmas (< 0.1 T) and low gas/plasma densities very weakly affect the high-energy ion beams. Indeed, the combination of IBA with low-density processing plasma was successfully demonstrated in a previous study [Moeller 1998].

An overview of the proposed experimental device is shown in Fig. 2. As can be seen, the device is largely comprised of the tandem accelerator needed to produce the high-energy ion beams. The capabilities of the accelerator installed at the University of Wisconsin - Madison are briefly discussed in Section 2.3.

The focus of this proposal is rather the construction of a specially designed plasma "end-station" to be added to the accelerator (details in Fig. 3). This design allows for the exposure of material samples to linear, cylindrical plasmas with simultaneous micro-probing of the sample surface using the high-energy ion beam. The analyzing ion beam (diameter ~ 1-2 mm, angle of incidence to plasma: 45 degrees) is scanned across the surface using an electrostatic scanner in order to obtain spatially resolved surface diagnosis (one or two dimensional). The

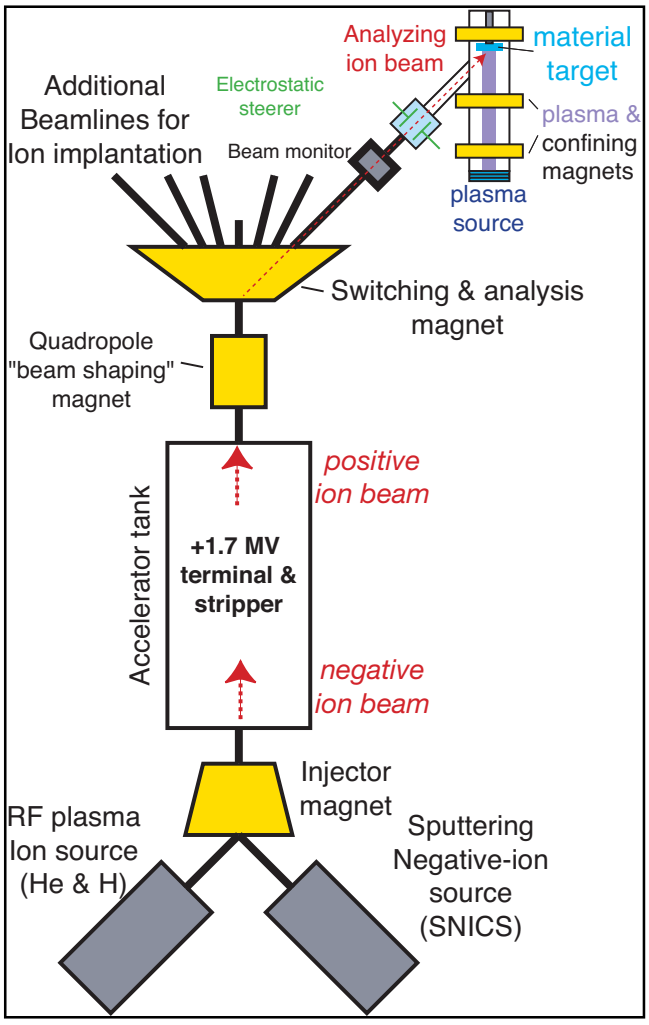

Fig. 2 *Overview of the experimental facility.*

accelerator system vacuum quality is maintained by differentially pumping across a narrowing aperture close to the steerer. The plasma will be produced in a moderate solenoid field in order to provide plasma confinement and to mimic ion plasma near-surface transport found in fusion devices (Fig. 1). The plasma sources and sample manipulator for controlling plasma exposure conditions are outlined in Section 2.2. The design of the plasma-compatible solid-state detector assemblies used for IBA is described in Section 2.4. The details of the IBA diagnostic techniques and plasma diagnosis are described in Section 3.

2.2. Plasma sources and materials target

Plasmas will be produced and confined in a steady-state axial magnetic field. An axial magnetic field of ≤ 0.05 T will be produced by a water-cooled electromagnetic coil set consisting of 3 to 4 coils distributed along the plasma column. The cylindrical plasma dimensions will be as follows: diameter ~ 2 cm, length ~40-50 cm. The plasma is situated in a vacuum chamber with turbo-molecular pumping. Gas fill pressure (≤ 1 Pa) for the plasma will be varied using mass-flow controllers. The source end of the vacuum chamber will be compatible with the installation of either a helicon RF source or a plasma gun source. We plan to use hydrogen, deuterium, helium and argon plasmas for fusion PSI research.

We propose to use a helicon source for steady-state plasma bombardment of samples. Helicon plasma sources are recognized and widely used as sources of high-density, low temperature plasmas (see for example [Zhu 1989, Breun 1995, Gilland 1998, Scharer 2002]). These sources function with an axial magnetic field and an inductive antenna that is used to generate helicon waves that penetrate into the central plasma and heat electrons away from the walls. Helicon sources are relatively simple in their operation and design, and have several features making them ideal for our application. Helicon sources are intrinsically steady-state with application of a constant magnetic field, making them suitable for experiments needing large ion fluence to the material sample. An antenna external to the vacuum system performs the plasma ionization and heating, easing maintenance and

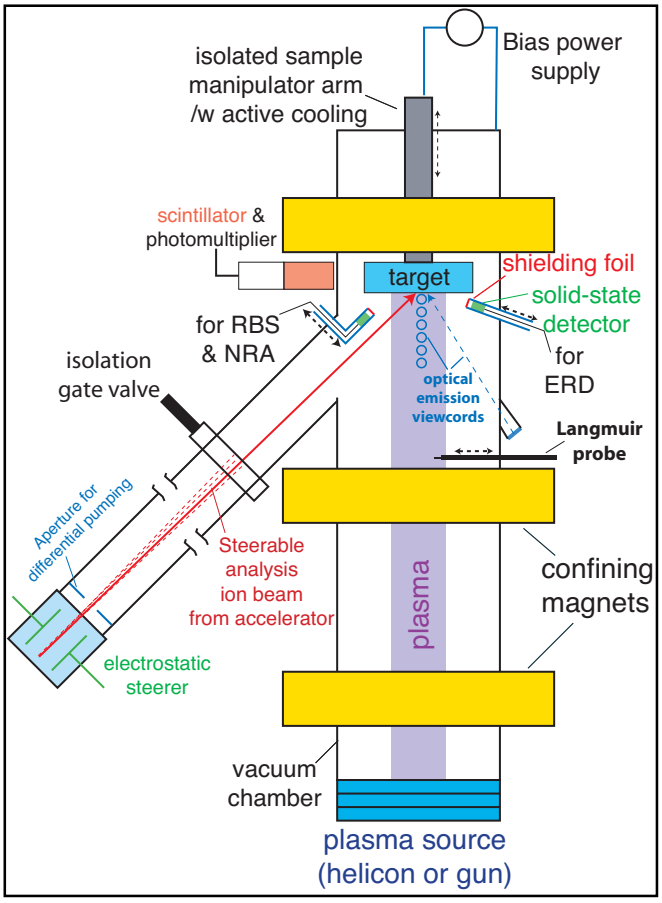

Fig. 3 *Schematic of the plasma chamber, sample holder, analyzing ion beam and diagnostic locations.*

access. The widespread use of helicon sources makes their purchase construction relatively inexpensive. Electron temperatures of helicon plasmas are ~3-15 eV (depending on the plasma species), which is very typical of the temperature of fusion edge plasmas. The achievable plasma density, n_e, for helicon (m=1) sources follows the scaling law,

$$\frac{B}{n_e a} \propto \frac{\omega}{k_z},$$

where B is the axial magnetic field, a is the plasma radius, and ω and k_z are the helicon wave frequency and axial wave number respectively. Additionally, the plasma density can be decreased dramatically with reduced input power to the antennae. As a result, helicon source exhibit an extremely large range of plasma densities (10^{10} – 10^{14} cm^{-3}) [Zhu 1989, Breun 1995]. This density flexibility is particularly desirable for PSI research where one wishes to control both the plasma ion flux and the ionization distance in the near-surface plasma. The middle of this density range (~10^{12} – 10^{13} cm^{-3}) matches the ion flux found in fusion experiments (due to the normal incidence plasma in our experiment), whilst the upper density range (>10^{13} in argon) more closely matches fusion absolute densities and ionization distances. We propose to use a single turn antennae coupled to a 1 kW, 13.6 Mhz RF amplifier driven through a capacitive match box in order to produce a ~ 1 cm radius plasma. The relatively small size of the plasma chosen for this design allows us to obtain higher absolute densities/fluxes at minimal cost and power, yet does not compromise the spatial resolution of the IBA (beam size ~ 1 mm). It is interesting to note that at fixed B the scaling law fixes the minimum ratio of ionization mean-free path (MFP∝$1/n_e$) to size scale (a), which is the most important parameter to control for studying net PSI effects. Based on previous experiments [Gilland 1998] with helicon sources we expect to obtain plasma density of up to ~ 5x10^{13} cm^{-3} in argon plasmas and up to ~8x10^{12} cm^{-3} with hydrogenic plasmas for B~0.05 T, 1 kW of power and P_{gas}<1 Pa. Given that ionization rate coefficients of candidate materials are ~ 0.5-1x10^{-7} cm^3/s for T_e~10 eV, and that sputtered atomic ejection velocities ~ 1-5 x10^5 cm/s, we can expect ionization MFP to range from ~0.1 cm and upward for sputtered material atoms. Therefore our designed plasma characteristics are appropriate since we are particularly interested in cases with MFP / a ≤ 1 for studying net PSI phenomena and dynamics.

As an alternative to the helicon source, we propose to use a plasma gun to produce high density pulsed hydrogenic plasmas The helicon and gun plasma sources would be designed to be interchangeable on the end of the plasma vacuum chamber. The guns are a miniature electrostatic plasma source developed at UW-Madison [Fiksel 1996]. The gun functions as a clean source of high density (< 10^{14} cm^3), low temperature (5 - 15 eV) plasma [Den Hartog 1997]. The gun produces a high ionization fraction (~100%) plasma for a 10-20 ms duration with a repetition period ~ 1 minute. The gun plasma is a virtual plasma electrode capable of sourcing an electron emission current density of 1 kA/cm^2. These guns are now being used in several laboratory plasma experiments [RSX, RWX]. Their high density and current make them particularly appropriate for studying the PSI effects of transient plasma particle and energy flux to surfaces (such as caused by ELM instabilities in confinement devices).

A sample manipulator will control the plasma bombardment conditions of the material (Fig. 3). The isolated manipulator will be capable of electrical biasing (< 200 V) in order to vary the incident plasma ion energy and incident power at the surface.

Additionally the manipulator will be equipped with active water cooling in order to control the surface temperature. The original manipulator will not be capable of retraction for reasons of simplicity, although this feature may be added at a future date. Rather, samples will be changed by argon venting the plasma chamber behind the gate valve isolating the plasma chamber and the accelerator (Fig. 3). We plan to design the sample holding mechanism to allow for various angles of incident for the plasma and ion beam, although normal incidence plasmas will be the most typical.

2.3. Tandem accelerator ion beam

High-energy ion beams will be produced by a 1.7 MV terminal voltage tandem ion accelerator (Model 5SDH-4, National Electrostatics Corporation Pelletron accelerator) installed at UW-Madison (Fig. 4). The accelerator features dual ions sources for producing negative ions with a sputtering source or an RF plasma source (Fig. 2). This versatility allows for ion beam production of nearly any element (several rare earth elements do not form negative ions). The sources produce ion beam currents ranging from a few μA for the gaseous elements used in IBA (e.g. He and N from the RF source) to ~1 mA for elements like silicon used for ion implantation. Negative ions are accelerated to 1.7 MV at the terminal where they then undergo electron stripping in a N_2 gas chamber. The positive ions are then further accelerated to ground potential at the accelerator exit. Therefore, for an ion with charge Z, the available ion energy is 1.7 MV x (Z+1), so for example He^{++} beams have energy ≤ 5.1 MeV. The maximum ion energy available is ~ 10 MeV (e.g., for silicon) and mostly depends on the stripping efficiency of the ions into the higher charge states. At exit from the accelerator tank, a quadropole magnet shapes the beam. Finally a single ion charge state / energy is selected by a switching magnet that sends the analyzed beam down one of six beam-lines attached at various angles. The plasma chamber will be situated on the 45 degree beamline equipped with an electrostatic beam steerer for directing the beam. Faraday cups and beam profile monitors are also installed to measure beam current and shape respectively. Two additional beamlines at –15 and +15 degrees are presently equipped for high-current (> 0.1 mA) ion implantation and will be used for impurity depth-marker implantation of samples. A feedback system maintains the ion beam energy constant to within +/- 500 V. The accelerator operates in steady-state.

Fig. 3 *Photograph of the National Electrostatics ion accelerator. The dual ion sources are seen at left. The large tank contains the pellet charging chain and termimal. The analyzing magnet is at the right.*

2.4. Plasma-compatible solid-state detector assemblies

As previously stated, there is no fundamental obstacle to the use of IBA in a plasma environment. However the plasma environment does necessitate extra care in protection of the standard solid-state semiconductor detectors used for the energy-resolved charge-particle detection required in IBA [Moeller 1998]. These detectors must view the region where the ion beam and surface intersect in order to detect the backscattered or recoiled high-energy particles from the surface. While the detectors can in theory be far removed from the surface this sacrifices sensitivity due to the vanishing solid angle subtended by the detector. Equally, depth resolution of the IBA is compromised if the detector is too close to the sample. A desirable location for the detectors is ~3-5 cm of the surface as depicted in Fig. 3. Fortunately, this location is outside the main plasma column (another reason to favor a smaller radius plasma in our design). However, bare detectors would be bombarded by sufficient plasma ion and electron fluence to seriously degrade the detector's energy resolution. In addition, the detectors are sensitive to light emission and their performance will be degraded by the nearby, highly emitting plasma column.

As a solution to these problems we propose to position the solid-state detectors in specially designed housings (Fig. 5), which has several protective features. The entrance to the housing is shuttered for protection when the detector is not in use. Driving current through a small coil attached to the shutter will open (by JxB forces) the rotating shutter, whose default position is closed. During operation, the primary protection for the detector will be a thin (1-10 μm) aluminum foil positioned immediately in front of the detector. This serves to block both plasma light and energetic neutrals (caused by either plasma charge-exchange or neutralized ions reflected from the material surface) from the detector. A metallic grid that can be biased to ≤ +50 V, along with the front portion of the housing is used to repel plasma ions and to stop them from quickly eroding through the thin Al film. The high transparency grid (>75%) will only slightly affect the detection efficiency while its low voltage will not affect the scattered high-energy ions used for IBA. Aluminum is chosen as the foil material since it is readily available in the

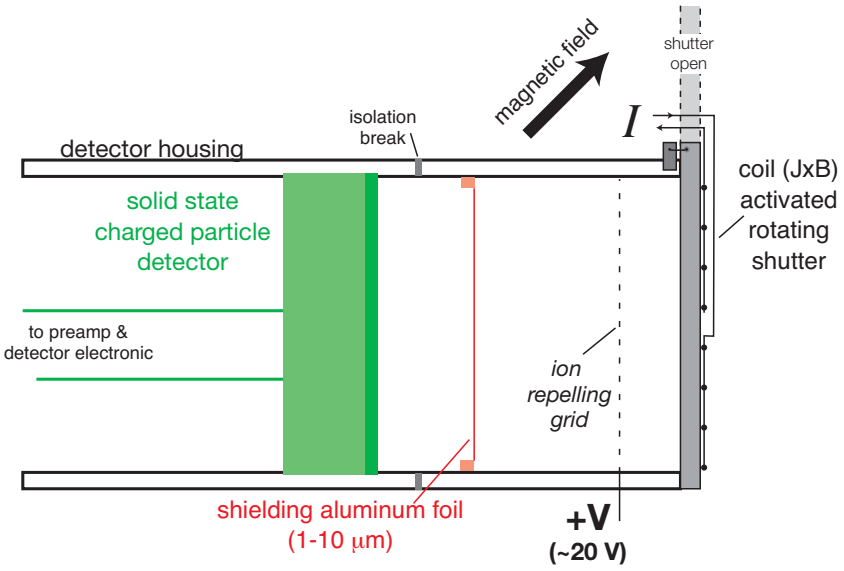

Fig. 4 *Schematic of the protective housing for solid-state detectors used in ion beam analysis in a plasma enviornment.*

thicknesses needed and it is immune to chemical erosion from hydrogenic atoms. The presence of the foil also has minimal impact on the IBA techniques (Section 3.1). Since the foils are of known depth and material, their effect can be exactly accounted for in the ion beam energy analysis. Indeed, it is standard practice to use ~10 μm foils to block directly scattered energetic heavy beam ions for elastic recoil detection (ERD) or to block backscattered beam ions for nuclear reaction analysis (NRA). While foils are typically not used for Rutherford backscattering spectroscopy (RBS), a minimally thick protection foil (1-2 μm) will degrade energy/depth resolution and element discrimination by an acceptably small amount. Blinded vent slits in the housing will prevent pressure differential across the films under vacuum. Finally, plasma heating of the detector and housing may be a concern, even outside of the main plasma column. This heating is unwanted since an elevated ambient temperature strongly increases the noise level on the detectors. Therefore we propose to use external copper water-cooling channels wrapped around the housing to control the detector temperature (not shown in Fig. 5). The water-cooling system will be thermostatically linked to internal thermocouple reading of the detector temperature in order to achieve constant detector temperatures.

The scintillators used for detection of nuclear reaction induced gamma emission are situated outside the vacuum chamber and therefore do not require special protection

3. Diagnostic Methods to Study Dynamics of Plasma-Surface Interactions

At the core of our proposed experiment is the idea that simultaneous diagnosis of the surface and plasma response will lead to greater fundamental understanding of the plasma-surface interactions processes. Therefore, we now describe the basics features of the surface and plasma diagnostic methods that will be used. In reality, both of these fields are well-developed and mature disciplines; and the goal of our research is certainly not to re-invent them. Rather the following sections are intended to outline the exploitation of these developed diagnostic techniques, particularly focusing on the IBA surface diagnosis relevant in fusion PSI research.

3.1. Ion beam analysis of surfaces

Ion beam analysis (IBA) is a proven method to measure precisely the elemental stochiometry and structure of material surfaces [Tesmer]. The basic principle of IBA is that mono-energetic ions in the MeV energy range will penetrate and react in a known manner in the first few microns of a material surface. Energy-resolved detection of the interacting or reaction ion products provides for depth-resolved probing of the surface in the area impacted by the high-energy ion beam. This translates into a lateral spatial resolution ~ 1 mm for a typical ion beam. Several features of IBA make it ideal for fusion PSI research, as witnessed by it widespread use for ex-situ surface analysis [Berhisch 1984, Doyle 1984, Wampler 1995, Maier 1999, Krieger 2001]. The typical depth resolution of IBA is ~1-10 nm, making it ideal to study the near-surface material layer that interacts with the plasma. The detection techniques are typically non-destructive if the analyzing beam current is kept sufficiently low to avoid local surface damage and heating. Also, because IBA techniques are based on well-known and precisely calculated

ion-material interactions, absolute measurements of surface / volumetric concentrations and depth profiles are typically achieved without the need for external calibration. Finally, since the depth resolution of IBA techniques is based on energy loss of incident ions, it is intrinsically referenced to the true "atomic" surface, making IBA relatively insensitive to surface roughness.

Rutherford backscattering spectroscopy (RBS) is probably the most widely used IBA technique. In RBS, a light element ion beam (almost always He) is incident at or near normal incidence to the surface. Helium ions backscattered from the material are measured by an energy-resolved solid-state detector located 160-180 degrees from the beam direction [Tesmer]. Since the angle of the ion beam and backscattered particles are exactly known the kinematics of the Rutherford scattering cross-section are also known. At the immediate material surface, elements of different masses can thus be distinguished by the energy of the detected backscattered beam ion. Furthermore, the incident and backscattered beam lose energy as they travel through the material and back to the surface, primarily through inelastic collisions with the atomic electrons [Ziegler]. If the material elemental composition is known the RBS energy spectrum can be directly translated into a depth profile. Deviations from Rutherford scattering can be avoided with the appropriate choice of ion beam energy for the target material (although in some cases the higher inelastic cross-sections can actually be used to enhance sensitivity to certain elements [Tesmer, Martin 1988]).

The Rutherford (Coulomb) scattering cross section varies quadratically as the target nuclear charge, i.e., Z^2. Therefore, for high-Z fusion materials (Mo, W), RBS of thin films deposited on low-Z substrates is an ideal method for measuring net erosion or deposition (Fig. 6) [Wampler 1999]. RBS is also efficient at measuring high-Z heavy elements implanted in low-Z materials. The net erosion / deposition of low-Z fusion materials can thus be obtained from higher Z implanted depth markers (e.g., [Wampler 1995, Whyte 1999]). As a specific example, we would propose to use the high-current beamlines of our ion accelerator to implant moderate to high-Z tracer elements in carbon. With the high energies available from the accelerator we can place the depth markers relatively far into the carbon material samples (e.g., 4 MeV silicon will implant ~2 microns into the surface [Ziegler]). The backscattered He energy spectrum (beam energy 5 MeV) from the implanted Si can then be monitored to indicate net changes in the carbon surface "thickness" during plasma exposure, thus measuring net erosion or deposition (Fig. 7).

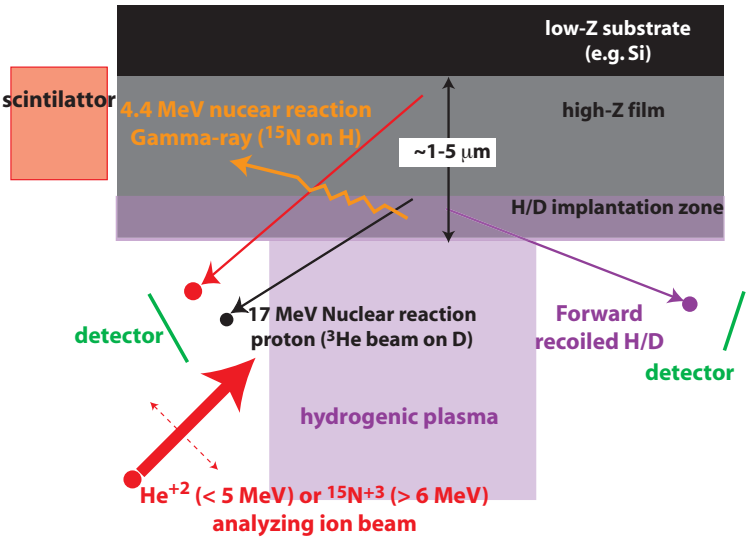

Fig. 5 *Schematic of ion beam analysis techniques for thin film high-Z plasma-facing materials deposited on a low-Z substrate. Shown is film thickness measurement by RBS and hydrogenic depth profiles using either ERD, particle induced gamma-ray emission ($^{15}N \rightarrow r\ H$) or NRA ($^{3}He \rightarrow r\ D$).*

Elastic recoil detection (ERD), like RBS, relies on Rutherford

scattering of the incident ions on the target materials. However in the case of ERD, the energy spectrum of lower-Z elements, forward recoiled by collisions with the higher-Z beam ions, is measured. Due to the collision geometry, both the beam and detector are ideally set at somewhat oblique angles to the surface (Fig. 7). Directly scattered beam ions are blocked from entering the detector by an appropriately thick (~10 microns) range foil. Because the kinematics are essentially the inverse of those used in RBS, ERD is used for detection and depth profiling of low-Z elements in materials. In particular, it is the technique of choice for measuring hydrogenic species with the standard ^{4}He beam used in RBS [Doyle 1979]. It is should be noted that the typical plasma, detector, beam and sample geometries shown in Fig. 3 have been chosen to provide a compromise between the need for RBS element / mass discrimination and the oblique incidence required for ERD.

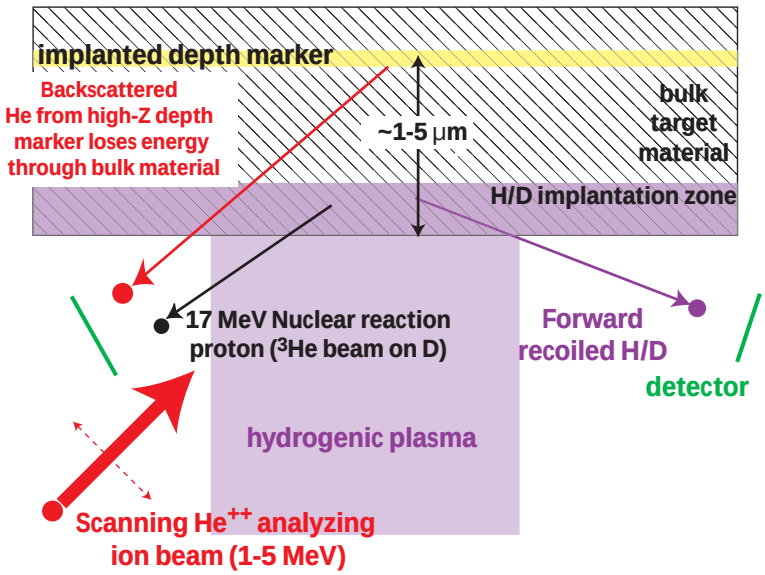

Fig. 6 *Schematic of ion beam analysis techniques for bulk low-Z plasma-facing materials. Shown is net erosion/deposition measurement by RBS of a previously implanted depth marker and hydrogenic depth profiles using either ERD or NRA (^{3}He →r D).*

Nuclear reaction analysis (NRA) measures the reaction products of inelastic nuclear reactions between the ion beam and material elements. NRA is a technique that is particularly suited for measuring specific isotopes at to very low concentrations. Accurate depth profiling of the isotope is measured by energy loss of the reaction products through the material, as in RBS and ERD. A wide variety of nuclear reactions exist that are too numerous to all mention here. Two specific NRA particle-particle reactions used in fusion PSI research [Wampler 1995, Wampler 1999] are described for example. The first is the measurement of deuterium hydrogen isotopes using ^{3}He beams. The ^{3}He(D,p)^{4}H reaction cross section has a broad resonance near 0.4 MeV and has a net energy value, Q=18.352 MeV [Moller 1980]. The reaction products can be measured by a thick surface-barrier detector located adjacent to the detector used for RBS (Figs. 6-7). Another useful NRA reaction is ^{11}B(p,α)^{8}Be with Q=8.6 MeV, used to detect boron with a proton beam with energy ~1-2 MeV. Boron coatings are a widely used surface treatment technique in fusion and the PSI interaction of boron with fusion materials is therefore of great interest.

Particle-induced gamma-ray emission is another form of nuclear reaction that is particularly well suited to measure hydrogen in fusion PSI applications. In this case an incident ^{15}N beam interacts with embedded hydrogen to produce 4.43 MeV gamma rays. This reaction has a high cross section peaked at E_{15N} = 6.385 MeV with an extremely narrow energy resonance of ~2 keV. This narrow resonance makes the reaction particularly well suited for highly resolved (~1 nm) H depth profiles. Depth profiles are

obtained by scanning the beam energy above the resonance energy so that the ion-material energy loss moves the resonance deeper into the sample. Other particle-induced gamma-ray emission reactions are also available but are not discussed here. Energy-resolved gamma ray energy emissions are measured by a scintillator /photo-multiplier assembly that resides close to the target but outside the vacuum chamber (Figs. 3 & 6).

3.2. Plasma diagnosis & Optical emission spectroscopy

Plasma diagnosis will be obtained with a reciprocating Langmuir probe (Fig. 3). The probe will be of standard design for magnetically confined axial plasmas (see for example [LaBombard 1989]) with I-V characteristics obtained by scanning the potential of the double-probe tip formation. The probe measures plasma density and electron temperature. Plasma spatial profiles are obtained by mechanically scanning the probe tips across the plasma column. The probe body will be protected in a graphite casing. If need be, a stationary single Langmuir probe will be placed in the target assembly in lieu of the scanning probe, although this is much less desirable.

Optical emission spectroscopy (OES) is a powerful tool to diagnose the sputtering and recycling of target material and plasma fuel species in the near-target plasma region. Indeed, OES is widely used in fusion PSI research, in both laboratory plasmas [Whyte NF 2001] and confinement plasma devices [Whyte JNM 2001, Isler 2001]. Besides this useful link back to fusion PSI research, OES has several advantages:

- Visible spectroscopy is non invasive and requires simple optical window access.
- Spectral lines provide unambiguous element identification.
- Visible light spectrometers and detectors are relatively inexpensive and easy to calibrate.
- Quantitative assessment of the material erosion can be obtained with knowledge of the plasma parameters and calculated atomic rate coefficients [Summers 1994].

We propose to install multiple fiber optic arrays viewing the plasma through quartz windows (Fig. 3). The collected plasma light will be fed to a photometrically calibrated grating spectrometer equipped with a two-dimensional CCD camera. The efflux of target material caused by sputtering is measured from the intensity of optical emissions from the atomic species near the target [Doerner 2001]. Likewise, the spatial profile of the ionization of the same atoms is obtained from a spatial profile of their emissions. The velocity of the atoms as they are sputtered from the surface by plasma bombardment can be measured from the Doppler shift of atomic emission with a view normal to the surface (Fig. 3).

4. Research topics

In the following sections, high-priority research topics will be outlined for the new experimental facility. As previously stated the facility is a generic tool for PSI research. However the near-term focus will be on topics concerning plasma-surface interactions in magnetic confinement fusion.

4.1. Near-surface cross-field plasma transport

The edge plasmas of fusion devices are characterized by long distances parallel to the magnetic field (> 10 m) compared to cross-field distances to material object (< 10 cm) [Stangeby]. Cross-field ion transport is the critically important process in determining the behavior of these edge plasma and the consequences of the plasma interaction with surfaces. Nevertheless, the exact nature of the cross-field transport is not fundamentally understood, chiefly because of the difficulties of its diagnosis in the plasma. The magnitude of the "anomalous" cross-field diffusion coefficients is typicaly prescribed into interpretive and predictive edge plasma models (e.g., UEDGE 2-D plasma fluid code [Rognlien 1994]). Recent experiments [LaBombard 2001] and theory [Krasheninnikov] have indicated that perhaps a convective transport model is more appropriate for the edge plasma. This lack of understanding remains a serious deficiency in our ability to predict the behavior of fusion confinement edge plasmas.

We propose to develop a set of experiments that carefully diagnoses the magnitude and trends of cross-field ion transport through the in situ measurement of surface net erosion/redeposition (E/R) profiles. This exploits the unique feature of our experiment to measure spatial net erosion and redeposition of various materials using IBA techniques (Section 3.1), simultaneous with plasma bombardment. The cylindrical symmetry allows us to obtain a profile from lateral scans of the analyzing ion beam across the sample surface.

As schematically shown in Fig. 1, particles sputtered from the surface will undergo ionization in the vicinity of the target. Two competing processes, perpendicular and parallel to magnetic field, then transport the ions. Taken together these processes cause a net transfer material from certain areas (net erosion) to others (net deposition).

We propose that the erosion controlling processes, other than cross-field transport, can be measured or calculated in our experiment. Namely, the ionization profile of the sputtered material is measured from plasma-excited atomic emissions. The parallel forces / acceleration on ions can be measured through the Doppler shift of ion spectroscopy viewing parallel to B (Fig. 3). Additionally, the parallel friction and pre-sheath potential forces can be calculated from the measured plasma and pre-sheath parameters [Stangeby]. The gyro-motion/temperature of the ions can be measured directly from ion spectroscopy Doppler broadening transverse to the magnetic field. With these measurements as inputs into a near-surface transport code (e.g. WBC [Brooks 2002], DIVIMP [Stangeby 1992]), the cross-field transport can be inferred by matching the measured E/R profile, since it is the remaining free parameter.

We can demonstrate the feasibility of this technique through a simple example. The parallel transport time, $\tau_{//}$, back to the surface for an atom ionized in the plasma is largely determined by the pre-sheath accelerating electric field, $e\,E \sim T_e / \lambda_{ion}$ where T_e is the plasma electron temperature in eV and λ_{ion} (cm) is the plasma species ionization MFP. One can estimate $\tau_{//}$ (μs) ~ 1.4 ($L_{//}\ \lambda_{ion}\ M_{ion} / T_e)^{1/2}$ where $L_{//}$ (cm) is the initial parallel distance of the ion creation from the surface, and M_{ion} (amu) is the ion's mass. So for the example of carbon material in our helicon plasmas (Section 2.2), we expect a minimum $\tau_{//}$ ~ 3-5 μs when $L_{//} \sim \lambda_{ion} \sim a_{plasma}$. We can estimate the longest perpendicular transport time scale, $\tau_\perp$, from Bohm diffusion ($D_{Bohm} \propto T/B$) to be $\tau_\perp \sim a^2/D_{Bohm}$ ~ 10 μs for B~0.05 T [Hollmann 2001]. Thus under almost all cases $\tau_{//} \sim \tau_\perp$, meaning perpendicular

transport will sufficiently "compete" against parallel transport, making our measurement of net E/R a sensitive gauge of cross-field transport.

The true strength of this research proposal lies in its flexibility. One can vary experimental parameters affecting cross-field transport, and simultaneously measure those effects through the E/R pattern using the in situ ion beam analysis. As seen from the example above we can strongly vary the sensitivity of the E/R to cross-field transport through judicious scans of plasma density, magnetic field and target material. In particular the large range of densities available in operating the helicon plasma source allows for a large parameter scan, even while maintaining a constant magnetic field. Conversely, measurement of the cross-field transport magnitude as the magnetic field strength is varied can strongly inform one of the fundamental transport processes (e.g. diffusive vs. convective). While it is clear that our plasmas will not exactly reproduce fusion edge plasma condition (primarily due to the low B), these results will be highly relevant for fusion PSI. First, recent reports have shown marked similarity in plasma transport between confinement devices and low-B linear plasma devices [Antar 2001, Hollmann 2001]. Secondly, a greater knowledge on the diagnosis and controlling E/R mechanisms for fusion relevant materials (C, Mo. W) will be gained. Thirdly, these experiments would serve as rigorous benchmarks for the numerical transport codes used in fusion research. Lastly, it is hoped that if the underlying transport mechanisms can be uncovered with these experiment and analysis, then the extrapolation (in B) to fusion edge plasmas will be credible.

The focus of this experiment is the E/R pattern rather than response of the material to hydrogen plasmas. Therefore we can use the higher densities available from argon plasma operation. Another experimental possibility is the use of upstream impurity injection (to artificially increase $L_{//}$ in a sense) while measuring the deposition pattern of the injected species on the target (Fig. 8). Finally, the use of a target surface titled away from normal to the plasma will allows us to increase our ability to diagnose smaller spatial scale E/R patterns that will occur in high density plasmas. In this case, the ion beam spot size is minimized by making the target normal to the ion beam (Fig. 8), while the target's E/R pattern is "stretched" by the obliquely incident plasma.

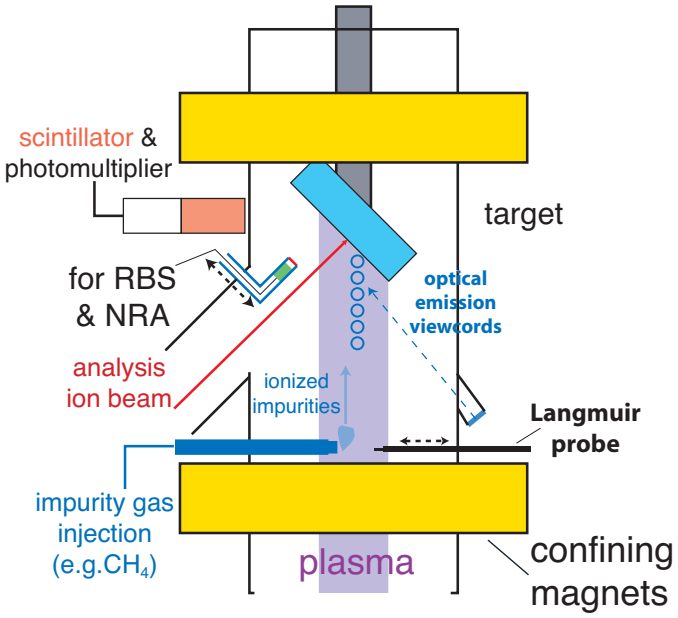

Fig. 7 *Experiment using 45 degree target inclination and/or upstream impurity injection high spatial resolution.*

4.2. ***Film deposition growth with hydrogenic trapping***

The trapping of tritium (T) fuel in deposit layers appears to be a serious threat to the operation viability for burning plasma experiments, particularly those that use carbon-base materials [Federici 2001]. At the same time, carbon provides the most robust plasma-facing material for the fusion environment. Unfortunately there is a lack of basic understanding on the rate and location T trapping in confinement devices. For example, the startling T trapping results from the JET tokamak D-T campaign, nearly half of the injected T was found in carbon deposits in hidden regions of the divertor [Coad 2001], remain largely unexplained [Brooks 2003]. This lack of understanding arises both from the difficulties of diagnosing E/R patterns, the root cause of the T trapping, and the complexities of carbon chemical erosion and hydrocarbon transport.

We propose to measure the dynamics of hydrocarbon film deposition and hydrogenic trapping caused by plasma erosion and transport using in situ ion beam analysis. Carbon targets will be exposed in hydrogenic plasmas of various densities (helicon source). Ion beam analysis (Section 3.1) will be used to measure simultaneously the growth of carbon films and hydrogenic content in the films. The measurement will be spatially resolved across the surface exposed to the main plasma column and to surface regions outside the plasma column (see for example Fig. 7). Ion beam analysis is a particularly critical diagnostic tool to bring to this problem. Optical emission spectroscopy is unsuitable in the cold (T_e < 2 eV) plasma regions where the films will likely occur, i.e., outside the main plasma column in our experiment, or in hidden divertor regions in confinement experiments. Also optical spectroscopy techniques cannot measure most of the hydrocarbon molecules (volatiles, radicals and molecular ions) that dominate the near-surface E/R pattern for carbon in cold hydrogenic plasmas. However the emissions of highly dissociated HC molecules (such as CH and C_2) will be monitored with our spectroscopy system.

Real time analysis of the hydrocarbon film growth allows us to scan a range of parameters important in carbon chemical erosion and HC transport, namely: target surface temperature, plasma and atomic flux, and H isotopes (H vs D). Additionally the presence of non-carbon dopants, which are expected to be present in confinement devices, can be detected by IBA and their effect on hydrogenic trapping measured.

4.3. Dynamics of H implantation and plasma refueling from transient plasma bombardment

Confinement plasmas are primarily fueled by the release of hydrogenic species from the wall. The H wall recycle flux is one to two orders of magnitude larger than the injected gas quantity controlled by the experimentalist. Also, the inventory of hydrogen in the saturated near-surface region of the wall is at least 100 times greater than the particle inventory in the plasma volume. It is understood that with constant H plasma bombardment, the wall material reaches saturation and an equilibrium is established in which the received H plasma flux is returned as hydrogenic molecules [Stangeby]. However, the reality is that the plasma flux to wall surfaces is rarely constant, but rather arrives transiently. At the fast time scale (< 1 ms), it has been measured that the plasma density flux is extremely intermittent, particularly in plasma regions far from the confined core plasma [LaBombard 2001, Antar 2001]. A particularly extreme example of this intermittent plasma flux occurs during ELM edge instabilities. On longer time-scales

(t > 10 ms), the time-averaged plasma flux also varies strongly with global parameter changes, particularly line-averaged plasma density and confinement mode. In fact it has been measured that the wall provides the majority of plasma fuelling and lack of density control after the transition from a low to a high confinement mode in the DIII-D tokamak [Jackson 1992]. However there is little fundamental understanding on how plasma-facing materials release H species due to these plasma transients.

We propose to measure the dynamic response of fusion materials regarding the absorption and release of hydrogen isotopes due to plasma transients. The experiments will be primarily carried out with the pulsed plasma gun (operated in H or D) since it most closely reproduces the fusion edge plasma transient conditions (n_e ~10^{13} – 10^{14} cm^{-3}). Experiments will be carried out on the candidate fusion materials of carbon, molybdenum and tungsten. Real-time, depth-resolved hydrogenic profiles will be measured in the sample near-surfaces (~ 100 nm) as a function of time from the plasma pulse using IBA.

Of particular interest is the development of fast IBA profiling techniques for studying the H dynamics. We propose to obtain this capability by using ERD with high-energy ion beams of the same elements as the material under exposure (C, Mo, W) for H and D detection (see Fig. 9 for the example of C materials). This exploits the fact that the forward recoil cross-section increases strongly (~Z^4) as the incoming ion's nuclear charge Z. Thus the sensitivity is greatly improved over the usual He (Z=2) beam. Secondly, since we are essentially implanting material particles themselves into an already highly amorphous material, we are able to use higher incident beam current before strongly perturbing the surface. Furthermore, beam rastering can be used to avoid overheating. This higher beam current (> 1 μA) then also increases our sensitivity and time resolution. As an example, based on a previous He ion ERD experiment on hydrogen saturated carbon surface [Green 1986] we expect ~3x10^4 counts / 10 nm H layer / μC of incident 2.5 MeV carbon beam ions. Therefore, H and D profiling seem feasible on the 10 ms time scale of interest in these experiments with a carbon beam current ~ 1 μA, which is well within the capability of our accelerator system.

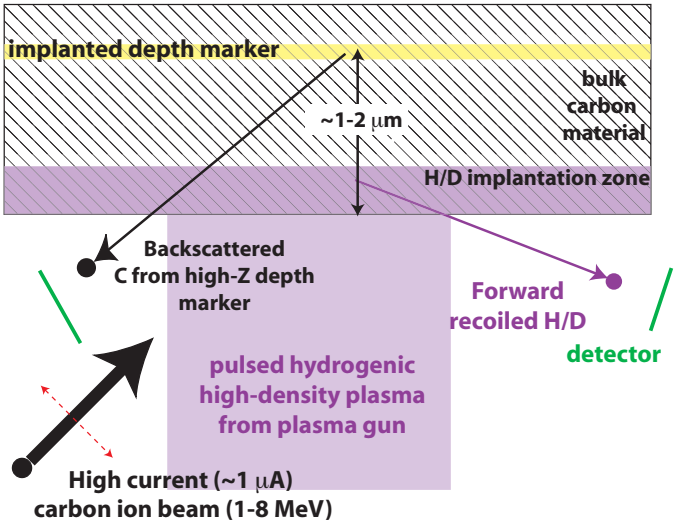

Fig. 8 *Schematic of carbon material ion beam analysis for transient plasma exposure to hydrogenic plasmas. The incident carbon ion beam is used for net erosion/deposition measurement by RBS of a previously implanted depth marker and for rapidly measured hydrogenic depth profiles using ERD.*

For isotope discrimination (H vs. D) we will use IBA techniques such as NRA (^{3}He beams for D detection) or particle-induced gamma-ray emission (^{15}N beams for H detection with 1 nm depth resolution). For carbon material exposure, net erosion

measurements using C ion beam RBS from implanted high-Z depth is also available (Fig. 9).

5. Three-year Research Schedule & Budget Justification

First year

This year will necessarily focus on the design work and installation of the experimental facility. An appropriate graduate student and thesis subject will be identified. We will focus on the following tasks:

- Design and fabrication of vacuum components, magnetic field coils and helicon plasma source
- Commission plasma vacuum system on accelerator beam line.
- Test and calibrate proposed IBA techniques on samples exposed to fusion plasmas.

Second year

We will begin plasma operation and physics experiments. Priority will be given to the graduate student thesis topic.

- Troubleshoot the IBA diagnosis running simultaneous with plasma exposure
    - Verify the detector protection scheme.
    - Install and calibrate spectroscopy equipment.
- Begin physics experiment
    - Gather data on carbon E/R patterns for transport modeling.
    - Produce and diagnose hydrocarbon films for hydrogenic retention studies.

Third year

We plan to begin full exploitation of the experimental facility:

- Finish experiment(s) and analysis for thesis topic.
- Purchase and install plasma gun source.
    - Test high speed IBA for H diagnosis
- Expand E/R test to high-Z refractory metals.

We propose a funding level for the research project of approximately $150,000 per year over three years for a total request of $458,625.

The uniqueness of the research topics envisioned for this project make it highly appropriate for graduate student research. We propose to develop and support a Ph.D. level research project. The work will be directed and supervised by the Principal Investigator with the equivalent of 0.5 months salary support.

Professional technical and engineering support is requested at part-time level (~$20,000 / year). This is primarily for initial design and construction of the plasma

facility and routine operation of the ion accelerator. A subcontract to NEC (National Electrostatic Corp) is also included for bi-annual accelerator maintenance.

The initial major equipment costs lie in the purchase and construction of the plasma vacuum (chamber and pumping), magnetic coils, magnet power supplies, and helicon plasma source. These are minimally needed to begin plasma operation. Plasma and optical emission spectroscopy diagnostics are purchased and added in the second year and the full biasing/cooling capabilities will be added to the sample manipulator. The plasma gun and associated power supplies will be added in the third year along with a possible upgrade in power or RF frequency for the helicon source.

The requested travel expenses will primarily support travel of the PI and graduate student to report results at domestic scientific conferences. Materials and supplies will cover miscellaneous cost associated with operating the plasma facility (e.g. plasma gases, target preparation, IBA detectors, etc.)

6. Summary

A new experimental plasma facility is proposed to study the dynamics of plasma-surface interactions. The unique feature of the facility is its ability to measure the surface characteristic using in situ ion beam analysis techniques. The design philosophy of the facility is to combine well-established plasma technology, plasma diagnosis and ion beam surface analysis techniques to provide a unique tool in studying plasma-surface interaction dynamics. As a result, we expect to be able to address many of the outstanding edge plasma transport and PSI issues in magnetic confinement research. The facility will also be a generically useful tool for plasma science and plasma-surface interaction research.

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Biographical information

Dr. Dennis Whyte is Assistant Professor of Engineering Physics at the University of Wisconsin – Madison. He obtained his undergraduate degree in Engineering Physics from the University of Saskatchewan in 1986 and his Ph.D. in Applied Physics from the Universite du Quebec in 1992. His doctoral thesis concerned the use of laser-ablated thin films as a particle transport diagnostic technique in tokamak plasmas.

From 1992 to 2002 he conducted research on the DIII-D tokamak National Fusion Facility, first as a post-doctoral fellow and recently as a research scientist for the University of California – San Diego. Dr. Whyte was the experimental coordinator of DiMES (Divertor Material Evaluation Studies) on DIII-D and and a principal investigator of the PISCES (Plasma Interactions with Surface Component Experimental Station) device at UCSD. He is presently a member of the DIII-D Research Council.

Dr. Whyte is an acknowledged expert in the field of plasma-surface interactions and on issues regarding the design and operation of material surfaces in burning plasma experiments. These issues include the suppression of erosion in detached plasmas, the diagnosis and control of chemical erosion through wall conditioning, the flux dependence of carbon chemical erosion yield, the importance of first wall erosion, and the diagnosis of lithium liquid sputtering. He is a member of the SOL /Divertor International expert group for the International Tokamak Physics Activity (ITPA). Dr. Whyte has over 100 peer-reviewed publications on nuclear fusion research topics such as plasma and impurity spectroscopy, erosion of plasma-facing surfaces and tritium retention. Recently, Dr. Whyte was a member of an international team an that published an extensive, invited review on plasma-surface interactions [Nuclear Fusion **41** (2001) 1751] .

Facilities and Resources

The facilities and resources at the University of Wisconsin - Madison are ideally suited for the proposed project.

UW-Madison purchased the National Electrostatic Corporation (NEC) 1.7 MV tandem ion accelerator from Agere Systems (Lucent Technology) in October 2002. The accelerator has been moved from Murray Hill, NJ to UW-Madison and is being re-installed and commissioned there. Accelerator operation is expected to begin in Spring 2003. The laboratory housing the accelerator is sufficiently large and equipped (e.g., power feeds, water cooling) for the additional plasma experiment, as well as for the existing implantation beam lines. The NEC headquarters are located in the Madison, WI area making NEC involvement in re-commissioning and maintenance of the accelerator relatively straightforward.

UW-Madison faculty and staff have extensive expertise in constructing and operating plasma facilities. In particular, Profs. N Hershkowitz and J. Scharer are experts on helicon plasma sources. The plasma gun source was developed by G. Fiksel of UW-Madison. In addition a significant collection of surplus plasma equipment and diagnostics is available to our experiment.

UW-Madison is a current member of the international ADAS consortium, which gives it access to the collisional-radiative atomic physics rate calculations need for spectroscopy analysis [Summers 1994].

Report of current and pending support

There is no external support for the research at present.