1 Introduction

Necessary Background

The high heat, particle, and radiation fluxes that will be imposed on the plasma facing components (PFCs) of a future fusion reactor create a harsh environment for materials. This unique environment drives an increased need for understanding the dynamics of plasma surface interactions (PSI) for the advancement of fusion research. Many competing processes cause the removal and redeposition of surface atoms, and the complicated mechanisms for each (such as physical and chemical sputtering, redeposition, recycling) make understanding the dynamics of PSI an intriguing challenge.

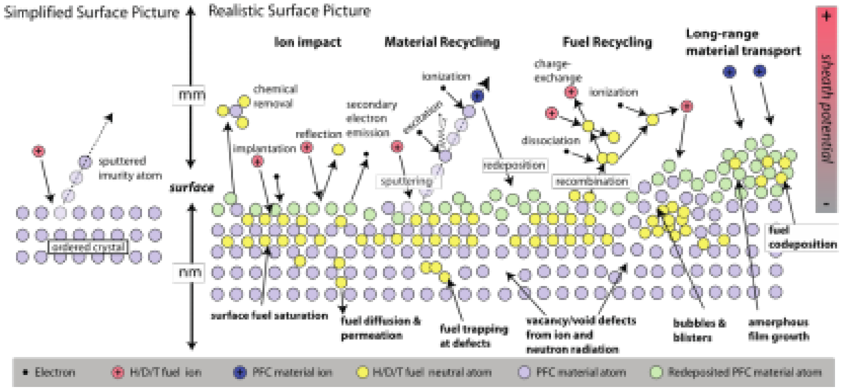


Figure 1: Diagram of various PSI mechanisms showing the numerous, complex reactions that are simplified by the typical sputtering model.[11]

Figure 1 illustrates the complexity of the PSI that govern the surface morphology of PFCs. These complex processes result in the movement of material through both erosion and redeposition. Erosion will both result in material loss (necessitating replacement) and the introduction of impurities into the plasma (resulting in worse energy confinement). Redeposition results in a surface with changed material properties, such as thermal conductity, surface binding energy, and phase[5]. Developing techiniques for the measurement of the dynamics of plasma-exposed surfaces will give a more complete understanding of future fusion research.

What you will do

Why you will do it

The introduction provides a brief but helpful technical background to answer the questions:

What you will do?

Why will you do it?

It might be a good idea in this introduction to split the background and the questions **what** and **why** into separate paragraphs

2 Background

2.1 AIMS

Current methods & technical details

The Accelerator-Based In-Situ Materials Surveillance (AIMS) diagnostic was developed and used at the end of the FY12 Alcator C-Mod campaign. AIMS uses a compact radio frequency quadrupole (RFQ) accelerator in combination with a neutron and gamma detectors to induce and measure nuclear reactions in the inner divertor in between shots on C-Mod. By analyzing surface composition on a shot-to-shot basis, AIMS produced the first in situ data which described the evolution of both the deposited boron layer and the implanted plasma particles (deuterium)[7].

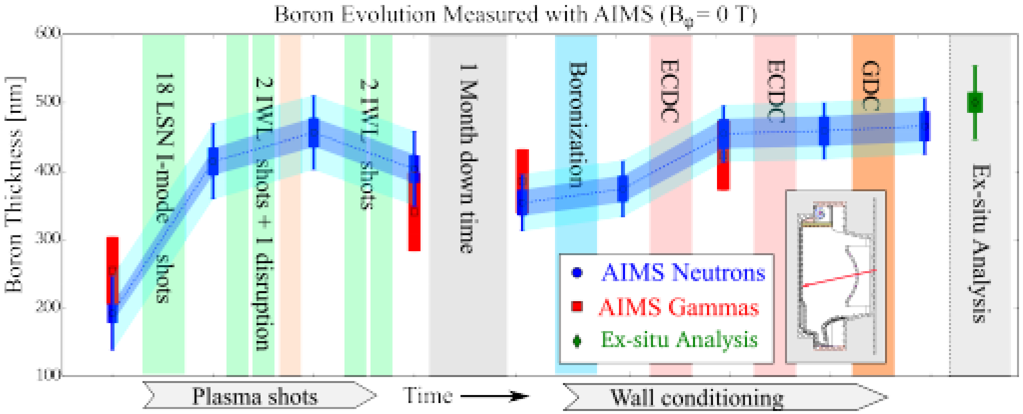


Figure 2: Evolution of boron thickness over several different C-Mod shots[4].

Preview of the proposal

The AIMS FY12 campaign was successful in demonstrating the possibility of using in situ IBA to studying divertor surfaces between shots. Much more science is possible, both via the expansion of the current diagnostic capabilities and through the formulation of more. The installation of a new RF system, the presence of a scintillating tile in the inner divertor, and new detector capabilities will allow for expansion and verification of the data already acquired.

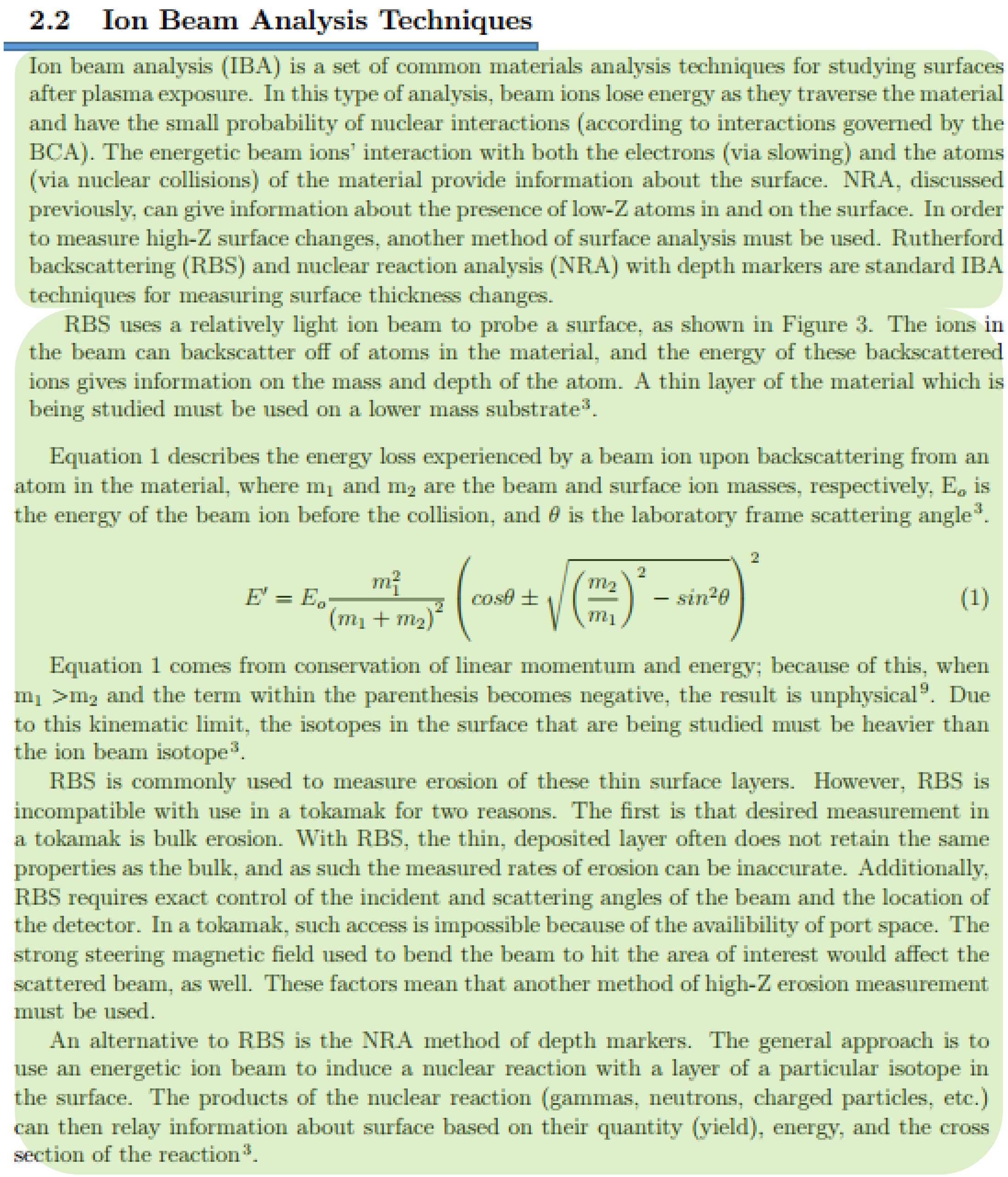
More background and methods

..but there are limitations

Which can be overcome by this method described next

In addition to continuing the science already explored with AIMS, new anaylis can be added to the diagnostic. Nuclear reaction analysis (NRA) and the ^{11}B(d, pγ)^{12}B reaction was used to obtain the boron erosion and redeposition results. While this data is useful for understanding the changing surface of the divertor, it does not give information about the change in the bulk molybdenum of the divertor tiles. This information cannot use the same NRA method of studying the surface because the Coulomb barrier precludes nuclear reactions between high-Z elements and a ~1 MeV deuterium beam. This means another method of IBA is necessary to measure this bulk erosion.

Clear continuity from last sentence describing how limitations are currently addressed



2.2 Ion Beam Analysis Techniques

Ion beam analysis (IBA) is a set of common materials analysis techniques for studying surfaces after plasma exposure. In this type of analysis, beam ions lose energy as they traverse the material and have the small probability of nuclear interactions (according to interactions governed by the BCA). The energetic beam ions' interaction with both the electrons (via slowing) and the atoms (via nuclear collisions) of the material provide information about the surface. NRA, discussed previously, can give information about the presence of low-Z atoms in and on the surface. In order to measure high-Z surface changes, another method of surface analysis must be used. Rutherford backscattering (RBS) and nuclear reaction analysis (NRA) with depth markers are standard IBA techniques for measuring surface thickness changes.

RBS uses a relatively light ion beam to probe a surface, as shown in Figure 3. The ions in the beam can backscatter off of atoms in the material, and the energy of these backscattered ions gives information on the mass and depth of the atom. A thin layer of the material which is being studied must be used on a lower mass substrate[3].

Equation 1 describes the energy loss experienced by a beam ion upon backscattering from an atom in the material, where m_1 and m_2 are the beam and surface ion masses, respectively, E_o is the energy of the beam ion before the collision, and θ is the laboratory frame scattering angle[3].

$$E' = E_o \frac{m_1^2}{(m_1 + m_2)^2} \left(cos\theta \pm \sqrt{\left(\frac{m_2}{m_1}\right)^2 - sin^2\theta} \right)^2 \qquad (1)$$

More technical background on current methods

Equation 1 comes from conservation of linear momentum and energy; because of this, when $m_1 > m_2$ and the term within the parenthesis becomes negative, the result is unphysical[9]. Due to this kinematic limit, the isotopes in the surface that are being studied must be heavier than the ion beam isotope[3].

RBS is commonly used to measure erosion of these thin surface layers. However, RBS is incompatible with use in a tokamak for two reasons. The first is that desired measurement in a tokamak is bulk erosion. With RBS, the thin, deposited layer often does not retain the same properties as the bulk, and as such the measured rates of erosion can be inaccurate. Additionally, RBS requires exact control of the incident and scattering angles of the beam and the location of the detector. In a tokamak, such access is impossible because of the availibility of port space. The strong steering magnetic field used to bend the beam to hit the area of interest would affect the scattered beam, as well. These factors mean that another method of high-Z erosion measurement must be used.

An alternative to RBS is the NRA method of depth markers. The general approach is to use an energetic ion beam to induce a nuclear reaction with a layer of a particular isotope in the surface. The products of the nuclear reaction (gammas, neutrons, charged particles, etc.) can then relay information about surface based on their quantity (yield), energy, and the cross section of the reaction[3].

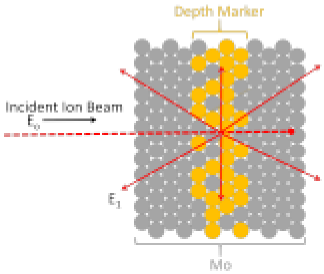


Figure 4: A schematic of the kinematics of NRA. This example shows an implanted layer which produces radiation under ion bombardment.

More technical background

..but there are still more limitations

..so some preview of proposal

Typically, depth markers utilize a cross section resonance; that is, a sharp increase in the cross section at a certain energy (see Figure 5). By scanning the energy of the incident ion beam, the resonance can be found. This allows determination of energy loss in the surface, which translates to the thickness of material that the ion beam passed through before reaching the depth marker[3]. However, the RFQ is a single-energy beam, which does not allow for this energy-scan methodology. A modified version of this technique would be required for use with the RFQ.

Some technical background needed in the proposal

In order to avoid the difficulties of energy scanning, and to reduce measurement error, a new technique for using depth markers is proposed. Instead of doing an exact calculation of cross section based on yield, the ratio of two yields (and thus cross sections) can be used to find the energy loss of the ion beam. Two such imagined cross sections might be as seen in Figure 6. If the equation for γ-yield is

$$N_\gamma = \frac{d\sigma}{d\Omega}(E)\frac{I_D t}{e}\Omega dn\varepsilon \tag{2}$$

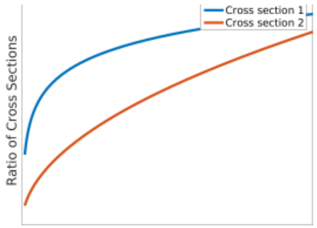


Figure 6: Two possible cross sections and their energy dependences.

where N_γ is the number of counts under the γ peak, $\frac{d\sigma}{d\Omega}(E)$ is the differential cross section, $\frac{I_D t}{e}$ is the number of deuterons incident on the target, Ω is the solid angle of the detector, d is the thickness of the target, n is the number density of the target, and ε is the detector efficiency.

Taking the ratio of $N_{\gamma 1}$ and $N_{\gamma 2}$ allows all of the beam and detector variables to cancel, leaving

$$\frac{N_{\gamma 1}}{N_{\gamma 2}} = \frac{\frac{d\sigma}{d\Omega_1}(E)}{\frac{d\sigma}{d\Omega_2}(E)} \tag{3}$$

This removes much of the error due to detector and beam factors, and results in a direct way to find the energy loss in the surface above the depth marker, as illustrated in the figure below:

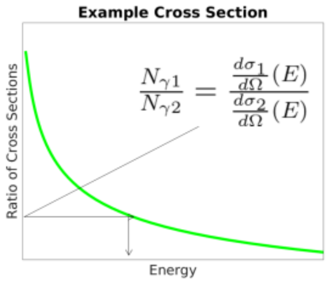


Figure 7: An example of how the proposed method of ratios would work with N_γ data.

However, in order to make this technique possible, the cross sections used must have a ratio which is monotonic to deuteron energy. This allows each value for the ratio to have a unique deuteron energy at which it can occur. Preferably, the ratio will also have a large slope with respect to energy, in order to have a higher energy resolution, and thus higher depth resolution.

The background section provides a relatively concise (~3 pages) understanding of the current methods and most importantly the limitations in current approaches. The need for new work is clear.

Since this prospectus does not include an objectives section, hints of the proposal are interspersed into this section. In general an objectives section is also recommended to either introduce or summarize the key objectives that are going to be discussed in the proposal section.

3 Research Proposal

General
What you will do

The work proposed for this thesis is to continue developing the AIMS diagnostic, both via improvements to the hardware that may allow more low-Z surface analysis in the FY16 Alcator C-Mod campaign, and through developments of a new method of high-Z, bulk surface monitoring with depth markers.

3.1 Further AIMS measurements on C-Mod

Specific
What you will do

Further AIMS tests in the FY16 Alcator C-Mod campaign will allow further exploration of the capabilities of such an in-situ diagnostic. Improved beam quality due to extensive upgrades of the alignment and RF system will allow better data resolution. These upgrades, along with a new detector reentrant tube, will decrease the necessary time for measurements. Increased accuracy of cross section measurements from the DANTE system will also give AIMS results greater accuracy. All of these changes, in addition to the ability to look at different tokamak operating regimes during the new campaign, will allow AIMS to intorduce new information about the in-situ effects of plasmas on tokamak surfaces.

3.2 Diagnostic development

In order to develop the depth marker technique, several steps will have to be taken, as described below.

3.2.1 Identification of depth marker isotopes and cross section measurements

The isotope used as the depth markers must be low-Z ($Z \leq 10$) in order to have a reasonable cross section for interaction with a 900 MeV deuteron beam (based on Coulomb repulsion). Additionally, the isotope must not be elsewhere in C-Mod, and have a cross section for interaction identified in the literature. A review of the literature for available cross sections, including Elekes et al.[6] will be required for this step.

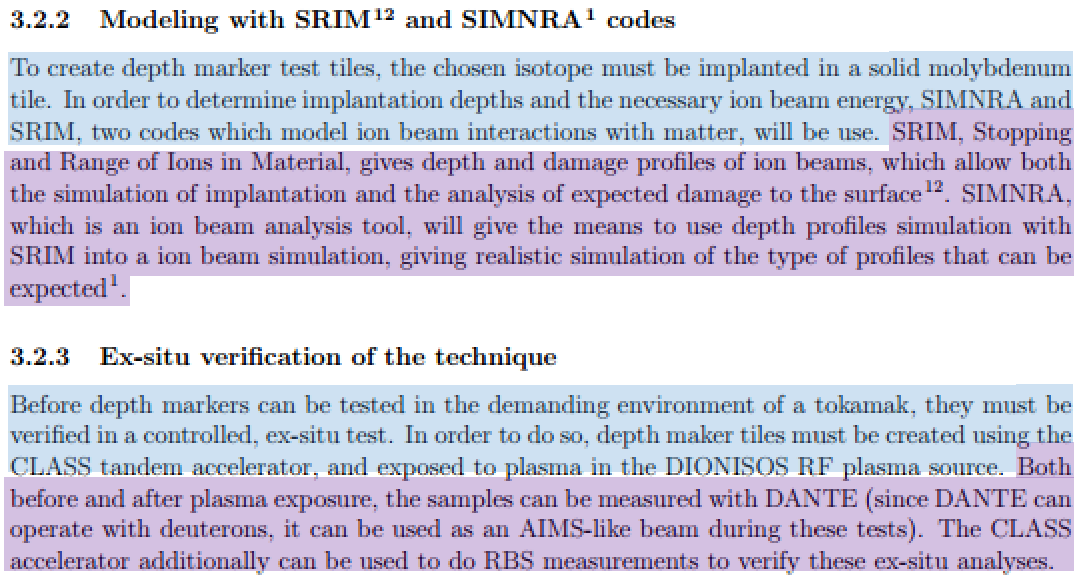
Once possible cross sections are identified, the exact dependencies on deuteron energy and angular placement of detectors must be resolved. Even though cross sections have been being classified for decades, many cross sections have gone unmeasured, or are only measured at a few angles and energies. This derth of knowledge makes particle-induced gamma emission (PIGE) studies like AIMS impossible without additional cross section measurements. Indeed, the International Atomic Energy Agency (IAEA) deemed the lack of information severe enough to create a coordinated research program to fund the generation of such data[2]. Results from the program such as Elekes et al.[6] and Sziki et al.[10] will aid in the determination of useful cross sections, but do not have full energy and angular resolution.

Specific
background
needed for…

In order to proceed with depth marker measurements, or indeed all of the AIMS diagnostic efforts, a more complete database of deuterium cross sections must be generated using the CSTAR facility at MIT. The DANTE 2 MeV tandem accelerator and the angular array of γ-detectors located at this facility in a shielded vault allow for the determination of deuterium cross sections in a safe environment. These results will both add to the database of deuterium cross sections and allow the AIMS depth marker study to proceed.

…Specific
What you will do

Specific
What you will do



3.2.2 Modeling with SRIM[12] and SIMNRA[1] codes

To create depth marker test tiles, the chosen isotope must be implanted in a solid molybdenum tile. In order to determine implantation depths and the necessary ion beam energy, SIMNRA and SRIM, two codes which model ion beam interactions with matter, will be use. SRIM, Stopping and Range of Ions in Material, gives depth and damage profiles of ion beams, which allow both the simulation of implantation and the analysis of expected damage to the surface[12]. SIMNRA, which is an ion beam analysis tool, will give the means to use depth profiles simulation with SRIM into a ion beam simulation, giving realistic simulation of the type of profiles that can be expected[1].

Specific
background
needed

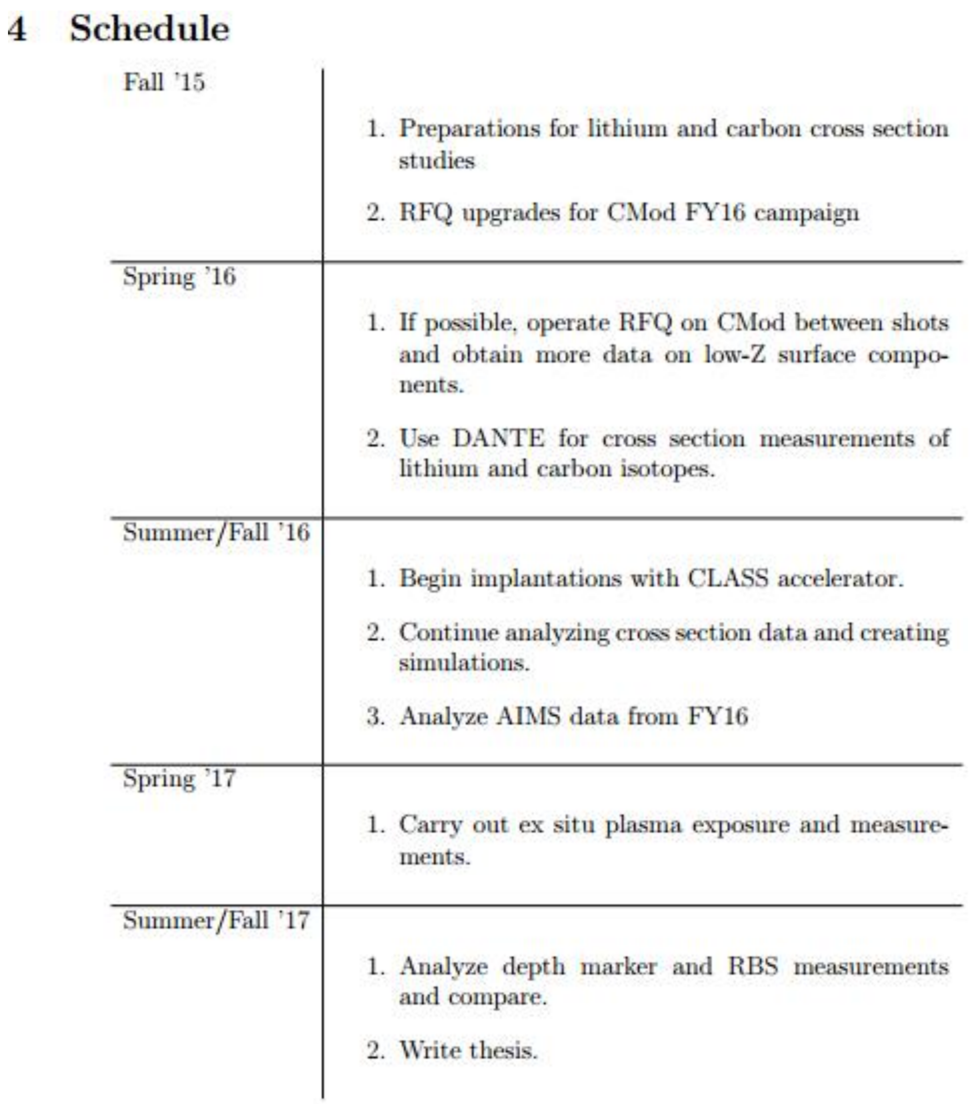
Specific
What you will do

3.2.3 Ex-situ verification of the technique

Before depth markers can be tested in the demanding environment of a tokamak, they must be verified in a controlled, ex-situ test. In order to do so, depth maker tiles must be created using the CLASS tandem accelerator, and exposed to plasma in the DIONISOS RF plasma source. Both before and after plasma exposure, the samples can be measured with DANTE (since DANTE can operate with deuterons, it can be used as an AIMS-like beam during these tests). The CLASS accelerator additionally can be used to do RBS measurements to verify these ex-situ analyses.

Specific
background
needed

The proposed work section is nice and short providing both a general description of the work to be done, as well as specific descriptions of the work to be done. Background is provided where necessary, and where it would not be appropriate in the background section. However, the background section provides the heavy lifting in terms of necessary knowledge for the proposal.



4 Schedule

Fall '15	1. Preparations for lithium and carbon cross section studies 2. RFQ upgrades for CMod FY16 campaign
Spring '16	1. If possible, operate RFQ on CMod between shots and obtain more data on low-Z surface components. 2. Use DANTE for cross section measurements of lithium and carbon isotopes.
Summer/Fall '16	1. Begin implantations with CLASS accelerator. 2. Continue analyzing cross section data and creating simulations. 3. Analyze AIMS data from FY16
Spring '17	1. Carry out ex situ plasma exposure and measurements.
Summer/Fall '17	1. Analyze depth marker and RBS measurements and compare. 2. Write thesis.

Clear actionable tasks are given for each semester of work.

If possible, time structured “deliverables” should be described to help assess whether the project is on track while you are progressing. Clear measurement of success or failure would be helpful.

5 Course Requirements

Course	Requirement	Semester	Credits	Notes
22.11	Core	Fall '12	6	22.101 credit
22.12	Core	Fall '12	6	22.101 credit
22.611	Area of Specialization	Fall '12	12	
22.105	n/a	Fall '12	12	
22.62	Area of Specialization	Spring '13	12	
22.70	Area of Specialization	Spring '13	12	
22.13	Core	Spring '14	6	
22.14	Core	Spring '14	6	
22.16	Core	Spring '14	6	
22.15	Core	Fall '14	6	
3.21	Major	Spring '15	12	
22.74	Major	Fall '15	12	
22.73	n/a	Spring '16	12	
21W.035	Minor	Spring '16	12	Undergraduate course
21W.778	Minor	Fall '16	12	Undergraduate course
21W.737[J]	Minor	Fall '16	12	Undergraduate course

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