External Proton Beam Analysis of Plasma Facing Materials for Magnetic Confinement Fusion Applications

by

Harold Salvadore Barnard

Submitted to the Department of Nuclear Science and Engineering in partial fulfillment of the requirements for the degree of Master of Science in Nuclear Science and Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2009

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Abstract

A 1.7MV tandem accelerator was reconstructed and refurbished for this thesis and
for surface science applications at the Cambridge laboratory for accelerator study
of surfaces (CLASS). At CLASS, an external proton beam set-up was designed and
constructed to perform in-air ion beam analysis on plasma facing divertor tiles from
the Alcator C-Mod tokamak. A Particle Induced Gamma Emission (PIGE) technique
was developed for boron depth profiling. In addition, Particle Induced X-ray Emission
(PIXE) was implemented and used for a comprehensive study of poloidal tungsten
migration in the C-Mod divertor.

A novel PIGE technique was developed for measuring depth profiles of boron de-
position on C-Mod tile surfaces. Boron (B) is regularly deposited on C-Mod tiles
to improve plasma performance. This technique is therefore useful for studying the
interaction of B with plasma facing components (PFC) to develop a better under-
standing of the effects of B in Alcator C-Mod. The technique involves taking multiple
PIGE yield measurements of a single sample while changing the beams path-length
through the air to vary the energy of the beam incident on the sample. A numerical
code was written to deconvolve boron depth profiles from these gamma yields by
exploiting the sharply peaked cross section of the $^7\text{Be}\left(p,\alpha\gamma\right)^4\text{Be}$ resonance reaction. Simulations demonstrate that this code converges to the expected results. Prelimi-
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verified the feasibility of this technique.

An external PIXE ion beam analysis study was conducted to measure campaign
integrated, poloidal tungsten (W) migration patterns in the C-Mod divertor. Eroded
W from a toroidally continuous row of W tiles near the outer divertor strike point
was used as a tracer to map W erosion and redeposition onto a set of Mo and W tiles
that covered the poloidal extent of the C-Mod lower divertor which were removed
following the 2008 experimental campaign. These tiles were examined for W using
external Particle Induced X-ray emission (X-PIXE) analysis; a highly W sensitive ion
beam analysis (IBA) technique in which a characteristic x-ray emission is induced from a material surface as it is exposed to an external proton beam, produced by the electrostatic tandem accelerator. With a set of systematic high spacial resolution measurements (≈ 3mm resolution), complete poloidal profiles of W redeposition have been constructed. These profiles indicate W transport and redeposition of up to $1.5 \times 10^{21} \text{atoms/m}^2$ (14nm of equivalent W thickness) in several regions including the outer divertor, the inner divertor, and inside the private flux region. In addition to the W results, PIXE allowed for indirect measurements of spatially resolved boron profiles and direct measurements of titanium, chromium, and iron.

A comprehensive description and explanation these PIGE and PIXE studies and their results are presented.

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Chapter 1

Introduction

1.1 Fusion Energy

For the last half century scientists have sought to use controlled nuclear fusion of Deuterium (D) and Tritium (T) as an energy source. Harnessing the energy from the fusion reaction of these hydrogen isotopes is very enticing because it has the potential to be used as a large scale, nearly inexhaustible, clean energy source. Initiating, confining, and sustaining such a reaction however, is an extremely complex physics and engineering challenge.

From a fundamental physics standpoint, controlled fusion is a very desirable energy source because the energy density of the fuel is enormous (17.6 MeV/fusion or 360 billion Joules per gram of DT) [11]. Fusion is also advantageous in that, a fusion reactor would produce a very small environmental impact. DT fusion produces Helium, a completely inert gas, and neutrons as byproducts. Though the neutrons produce some radioactive byproducts from the activation of structural materials, only a small amount of relatively short lived waste would be produced, which is a considerable advantage over a fission reactor fuel cycle. Deuterium fuel is also extremely plentiful and is a relatively inexpensive fuel that can be extracted from water. Tritium, is not found naturally because of its short half life but it can be generated in tandem with fusion from the reaction of neutrons with lithium, another plentiful element [11]. Despite the benefits of fusion, realistically, a fusion reactor for electri-
cal production may be several decades away. There are however many experiments around the world, exploring various aspects of fusion energy.

There has been considerable progress toward magnetic fusion energy (MFE) devices with machines called tokamaks. Tokamaks confine high temperature plasmas using strong magnetic fields and plasma currents to stabilize and counteract the plasma’s tendency to expand due to its kinetic pressure. These devices are toroidal and use a static toroidal magnetic field, on the order of several Tesla, generated by external coils in combination with a plasma current which must be driven inductively or by other means (RF, neutral beams, etc.). In principle, if the plasma particles and energy are confined properly, the plasma can be heated to temperatures in excess of 10keV, thermonuclear fusion can begin to occur at an appreciable rate. At these temperatures, a significant fraction of the nuclei collide with enough to energy to fuse before escaping from the confined plasma. This results in a highly exothermic process called thermonuclear fusion.

Tokamaks with inductively driven currents have played a central role in the magnetic fusion efforts and have been the most successful devices in terms of high temperature and energy confinement. They are, however, inherently non-steady state, pulsed devices. They typically operate in pulses on the order of a few seconds in length which is scientifically useful because the pulses are very long compared to the timescales of most plasma phenomena. For “tokamak-like” MFE devices to be practical energy sources, their operation must approach steady-state. There are many critical issues that must be addressed to achieve steady state. In addition to improving our understanding of the dynamics of fusion plasmas, major advances must be made in many areas including non-inductive current drive, efficient tritium breeding, and disruption mitigation. Another very important issue and the topic of this study, is the need to understand the complicated, dynamic interactions between the plasma and its surrounding materials, referred to as plasma surface interactions (PSI).
1.2 Plasma Surface Interactions

In any real laboratory plasma, confinement is imperfect, and plasma particles inevitably diffuse out of the plasma and come in contact with the walls of their containment vessel. These particles can take part in a variety of interactions with the surface which can damage the surface and can have a profound effect on the plasma. Some particles maybe implanted in the surface leading to issues such as fuel retention. Particles from the surface of the plasma facing components (PFC) can also be removed and enter the plasma due to sputtering. This can result in erosion of PFCs and the introduction of impurities into the plasma which, are both unfavorable for tokamak operation. Another effect is the redeposition of sputtered particles. This process along with erosion can dynamically change the geometry of plasma facing surfaces [35]. An effective method to mitigate these issues in tokamaks has been to periodically deposit thin films of low-Z materials such as boron on PFCs. These films resulting from the "boronization" process absorb vacuum impurities such as oxygen, and act as a sacrificial layer that prevents PFC erosion. As a result, boronization has been shown to dramatically improve tokamak core plasma performance by reducing impurity radiation [23].

1.3 Ion Beam Analysis

Ion beam analysis (IBA) refers to a collection of techniques used for probing the surface and near-surface properties of a material. IBA involves the irradiation of samples of material with an ion beam with energy on the order of several MeV and the spectroscopy of radiation produced by the resulting reactions. For example, techniques used in PFC research often include Rutherford Backscattering Spectroscopy (RBS), Particle Induced X-ray Emission (PIXE), Nuclear Reaction Analysis (NRA), and Particle Induced Gamma Emission (PIGE).

Beams in the several MeV range can penetrate to depths of 10s of $\mu m$ into solid materials. Since many of the processes effecting PFCs such as boronization, erosion,
deposition, and other plasma phenomena all occur on depth scales similar to the beams penetration depth, IBA techniques are well suited for the study PFCs.

IBA is commonly performed in vacuum but can also be performed on samples in air if the beam passes through a vacuum tight exit window, usually several $\mu m$ thick. Such beams are referred to as external beams and are used to simplify and expedite handling of large samples. In this study, external PIXE and PIGE have been used for PFC surface analysis.

1.4 Motivation for Thesis

All magnetic fusion devices must have a first wall that comes in contact with the plasma. This wall is exposed to very severe thermal conditions and constantly interacts with energetic plasma particles. PFCs in the first wall must therefore be designed considering the implications of geometry as well as the material's thermal, nuclear, and plasma interaction properties. Bulk properties of PFC materials, such as heat transfer and resistance to radiation damage are important and are currently being studied independently. The surface processes however, such as erosion and fuel retention, are highly coupled with the dynamics of the plasma and are not very well understood. The interactions of the plasma with the PFC surfaces dramatically effect everything from energy confinement to particle inventory, and inevitably, the plasma performance. It is therefore, very important to develop techniques to study and understand the processes that occur at the surface of PFCs.

Ion beam analysis techniques such as PIXE, PIGE and RBS have been used extensively for PFC studies and have proven very effective [32]. Prior to 2006 the MIT fusion program did not have the facilities to perform IBA on materials from Alcator C-Mod. To develop these IBA capabilities on site Cambridge Laboratory for Accelerator Study of Surfaces (CLASS) was set up beginning in the fall of 2006. The accelerator used in CLASS is a 1.7 megavolt tandem accelerator that was reconstructed and refurbished for the CLASS facility between 2007 and 2009. A considerable portion of this thesis project involved the reconstruction of this accelerator, and after its
completion in the spring of 2009, IBA techniques were available for surface analysis including PIGE and PIXE.

PIGE analysis has applications for measuring low-Z elements on Alcator C-Mod. C-Mod relies on low-Z PFC surface coatings of boron to improve performance by preventing high-Z (Mo) impurities from PFCs from entering the core plasma. Measuring boron on C-Mod PFCs and studying erosion and redistribution of boron in surface layers can identify the locations of erosion, and could potentially be useful to optimize the boronization technique or to understand mixing of boron with molybdenum at the surface. It was therefore, useful to develop PIGE technique for boron Depth profiling.

PIXE analysis also has applications for measuring tungsten and other medium to high Z elements in C-Mod. Since tokamak divertors experience very high heat and particle fluxes the ability to measure the redistribution of high-Z PFC materials in these regions is useful. Tungsten has been identified as a candidate material for future MFE devices because of its resilience to plasma erosion. To study the merits of W as a PFC, a row of tungsten tiles were installed in C-Mod at one poloidal location for the 2007 and 2008 experimental campaign. Measuring the migration of this tungsten has interesting implications for determining net tungsten erosion rates and studying high-Z impurity transport. It was therefore useful to examine tiles in the C-Mod divertor using PIXE analysis. Such PFC studies will contribute to our knowledge base on plasma facing materials and could potentially inform decisions about the design of new MFE devices.
Chapter 2

Background

Plasma facing components (PFC) in tokamaks are exposed to very harsh conditions including high mechanical stress, high heat loads, exposure to energetic particles, and radiation damage. Materials that are resilient under all of these conditions are desirable. Unfortunately, there are no materials that are ideal under all of these conditions simultaneously. There are a variety of different materials that have been used in present experiments and will likely be used in future MFE devices. The most commonly used materials for high heat flux regions are high-Z refractory metals like tungsten and molybdenum or low-Z materials such as carbon.

Many reactor studies have regarded tungsten as the most favorable candidate first wall material because of its thermal properties, low fuel retention, and its resistance to radiation damage and activation [23]. It also has the highest melting point (3422°C) of all metals. High-Z metals like tungsten are also advantageous because they have very low plasma sputtering rates. However they are more detrimental to energy confinement than low-Z materials when they are eroded and enter into the plasma due to line radiation. There has generally been less experimental experience with tungsten and other high Z-materials than there has been with carbon [23].

Carbon is another very common PFC material and is used in devices like DIII-D, JET, and ASDEX Upgrade. Carbon is extremely resilient when exposed to high transient heat fluxes and has good thermal and mechanical properties at high temperatures, but, since its chemical properties allow it to form hydrocarbons with the
hydrogenic fuel, it has high fuel retention characteristics and relatively high erosion rates. This study focuses on molybdenum and tungsten PFCs because they are the predominant materials used for Alcator C-Mod.

2.1 Plasma Facing Components in Alcator C-Mod

The plasma facing first-wall in Alcator C-Mod is primarily made from molybdenum TZM alloy tiles (0.05% Ti, 0.08% Zr, > 99.2% Mo). These tiles, which have dimensions ≈ 2.5cm × 2.5cm, are fastened to the stainless steel vacuum vessel and are closely packed. Molybdenum is a refractory metal with a high melting point (2623°C). Though Mo is not suitable for fusion reactors or DT burning devices because of its susceptibility to neutron activation, it is still useful as a substitute for W in short pulsed devices. This is because Mo has similar thermal properties to W but is less expensive and easier to machine [23].

For the 2007 and 2008 campaigns, some tungsten tiles were added to C-Mod to evaluate its properties as a PFC in regions of high heat and particle flux. They were installed in one toroidally continuous row on the outer divertor at/near the location of strike point. An added benefit resulting from the installation of these W tiles is that they can be used to study campaign integrated transport. Since the W tiles are located at only a single poloidal location and are toroidally symmetric, the eroded W conveniently works well as a tracer to study tungsten migration. An image of the W tiles and a diagram of their location is shown in figure 2-1.

2.1.1 Divertors and Limiters

Plasma particles and energy cannot be perfectly confined and will diffuse out of the plasma. As a result, the plasma will interact with the walls of the device, often in ways that are non-uniform and difficult to predict. To deal with these problems, tokamaks use structures such as limiters and divertors that are designed to intercept the outer edge of the plasma and define the geometry of the plasma’s interaction with the plasma facing surfaces.
Figure 2-1: (Left) Image showing a segment of the outer divertor with a toroidally continuous row of W tiles. (Right) Illustration of the poloidal location of tungsten divertor tiles.

Limiters are typically a flat surfaces that directly intercept the edge of the plasma. Ions that diffuse into magnetic flux tubes that intercept the limiter collide with the surface, transfer most of their energy and are often neutralized. This defines the shape of the plasma and removes particles that reach the plasma edge [27].

Most modern tokamaks, such as C-Mod, use divertors. In a diverted plasma an additional coil modifies the magnetic topology such that the poloidal cross section of the plasma is pinched off at a null point, causing the outer surface of the plasma called the scrape off layer, to be directed into a structure called the divertor, shown in figure 2-2. In the divertor, the magnetic field intercepts the divertor’s surface, causing the ions confined to field lines in the scrape off layer to collide with the surface of the divertor. This allows particles in the scrape off layer to be removed as the ions become neutralized when they strike the divertor and are no longer confined by the magnetic field. Being free from confinement, they can then be pumped out of the vessel by vacuum pumps such as turbo pumps and/or cryo-pumps.

Divertors are necessary in MFE reactors to sufficiently thermalize and remove helium exhaust from the plasma. In addition, there are two basic plasma physics reasons why modern tokamaks use diverted plasmas. The first is that, under the right conditions, diverted plasmas operate in an enhanced confinement regime, called H-
Figure 2-2: Poloidal cross section of Alcator C-Mod: This illustration shows divertor structure circled at the bottom and the outer wall which is roughly the shape of the limiters that protects components such as RF Antennae.

H-mode operation allows for a dramatic improvement in plasma performance because it can increase the energy confinement by up to a factor of two due to a complicated process that leads to an anomalously steep pressure gradient at the plasma edge. The other benefit is that diverted plasmas can reduce the thermal loads on the PFCs surfaces by spreading out the heat over a larger surface area. Diverted plasmas can operate in the "conduction limited" regime which allows the temperature of the plasma at the divertor surface to be much lower than at the plasma edge, decreasing power loads and sputtering [28].

The materials in the divertor, especially at the divertor strike point, experience a very high heat and particle flux (as high is $10^{20} - 10^{24} m^{-2} s^{-1}$) of ions with energies of 10s-100s of eV. These high particle fluxes may cause impurities to be sputtered...
into the plasma, and also may implant plasma particles in the surface [36]. Both implantation and sputtering can potentially be problematic for steady state fusion devices. In pulsed devices like C-Mod the divertor is coated with a thin layer of boron (boronization) to mitigate the problems that arise from sputtering and erosion of divertor surfaces.

2.2 Boronization

Many experiments with high-Z PFCs have demonstrated that conditioning PFCs by depositing boron (boronization) or other low-Z elements such as beryllium or lithium, improves tokamak plasma performance. This is attributed to improved energy confinement due to a reduction in radiative losses from sputtered metallic impurities that originate from PFCs[29]. In C-Mod, the boron acts as a sacrificial layer that prevents erosion of the Mo. Since the boron has a much lower nuclear charge \((Z = 5)\) than molybdenum \((Z = 42)\), boron impurities in the plasma are usually fully ionized in the plasma core, so line radiation from atomic transitions causes minimal radiative cooling. Mo ions, however, are generally not fully stripped of their electrons, even at thermonuclear temperatures. This allows Mo ions to strongly radiate in the core plasma through atomic transitions, dramatically reducing energy confinement [23].

The improvements due to boronization have been demonstrated on Alcator C-Mod by direct comparison between plasma shots with and without boron films present. When all of the boron was removed from the PFCs for the 2005 experimental campaign, the molybdenum impurity fraction during plasma pulses was observed to be \(n_{Mo}/n_e \leq 0.1\%\). When the walls were boronized, the molybdenum fraction \(n_{Mo}/n_e\) was decreased by a factor of 10-20 causing considerably higher confinement times and \(H_{89P} \leq 2\) [29].

In C-Mod boronization is accomplished through plasma deposition using a helium-diborane \((He + D_2B_6)\) plasma. The plasma is produced in a toroidal field that is RF heated \(f_{RF} = 2.45GHz\) at the electron cyclotron resonance frequency. The resonance region is then swept across the divertor and the walls by varying the toroidal
field to deposit a layer of boron in the desired regions [24].

Boronization is highly successful, but it degrades rapidly as plasma shots eroded the boron. This appears to be caused by rapid erosion of a small area and is strongly effected by RF heating [10]. A more detailed study of boron films could therefore be useful for understanding boron erosion and for optimizing the boronization process. Further study of boron erosion and redeposition could also have implications for particle transport in the plasma and the mixing of B with Mo on PFC surfaces.

2.3 Erosion and Transport of PFC Materials

If measured PFC erosion rates in tokamaks are extrapolated to steady state, it becomes immediately clear that erosion and transport of PFC materials is a very serious issue for long pulse MFE devices. For example, graphite divertor plates from the DIII-D tokamak have shown erosion rates of up to $4\text{nm/s}$ which would correspond to $\sim12\text{cm/exposure year}$ [33]. Such erosion rates are unacceptable because PFC thickness is limited to $<1\text{cm}$ for sufficient heat conduction in a MFE reactor.

2.3.1 High-Z Erosion Studies

There have been numerous IBA studies of high-Z erosion and transport that have been conducted on Alcator C-Mod and other devices including JET, ASDEX Upgrade, DIII-D [33], and JT-60 [37]. These experiments were done using IBA techniques, most commonly: Rutherford Backscattering Spectroscopy (RBS), Particle Induced X-ray Emission (PIXE), and nuclear reaction analysis (NRA).

An example of an erosion measurement is a study by Wampler, et al [34] in which net Mo erosion rates measured directly using RBS. This was achieved by embedding chromium marker layers at a known depth beneath the surfaces of Mo tiles before they were installed in C-Mod. After one run campaign they were removed and RBS was used to determine the change in depth of the marker layer. As a result, a net erosion of $150\text{nm}$ was observed (over 1090 plasma shots) at the outer divertor strike point and was less elsewhere [34].
Redeposition patterns have also been experimentally observed. In a recent study by Y. Ueda, et. al. [37], tungsten redeposition patterns on carbon tiles were observed in JT-60U. Neutron activation and energy dispersive X-ray (EDX) spectrometry were used for measuring the total W embedded within the carbon surfaces. X-ray photoelectron spectroscopy (XPS) was also used to measure depth profiles. The results showed substantial poloidal migration of W from the outer divertor to parts of the W facing surface of the divertor dome (≈ 3 × 10^{21} \text{m}^{-2})\), the inboard surface of the divertor dome (≈ 2 × 10^{22} \text{m}^{-2}), and the inner divertor (≈ 8 × 10^{22} \text{m}^{-2}) [37].

In the JT-60U study, the W tile array spanned only ≈ 10° of the toroidal angle so W did not toroidally encircle the divertor. As a result, toroidal measurements showed that deposition at the outer divertor was concentrated close to the toroidal region surrounding the W tiles [37]. In C-Mod however, the W tiles are toroidally continuous. This significantly reduced or eliminated toroidal asymmetries in the in both tungsten erosion and deposition. This toroidal symmetry made it possible to perform a comprehensive study of tungsten migration in C-Mod which is a major topic of this study.
Chapter 3

Accelerator

Tandem accelerators have been instrumental in advancing the field of nuclear physics and are very useful for studying materials. The term, 'tandem' implies that there are two successive linear accelerators that use the same power supply. Negative ions are injected into the first stage and are accelerated toward the positive high voltage (HV) terminal. The ions are then stripped of some of their electrons by nitrogen gas that is injected inside the HV terminal (carbon foils can also be used in other designs). The now positive ions are then accelerated away from the HV terminal through the second stage, then exit the accelerator.

The accelerator used in this study is a 1.7 MV Tandetron™ tandem accelerator designed by General Ionex Inc. that was reconstructed and refurbished for the Cambridge Laboratory for Accelerator Study of Surfaces (CLASS). Tandetrons are designed to accommodate most low energy ion beam analysis (IBA) techniques which are typically used for studying materials. The accessible energies and beam currents are well suited for nuclear reaction analysis (NRA), Rutherford Backscattering Spectroscopy (RBS), Elastic Recoil Detection (ERD), and Particle Induced X-ray Emission (PIXE) [12]. A photo of the accelerator is shown in figure 3-1.
Figure 3-1: Photo of the 1.7 MV tandem accelerator in the CLASS facility

3.1 Accelerator Components

3.1.1 Ion Sources

The Tandetron has two ion sources: a cesium sputtering source (fully operational) and duoplasmatron source (still under construction). The cesium sputtering source can produce negative ions from most elements (with the exception of noble gases) through cesium sputtering of a solid target followed by electron charge exchange with neutral cesium. The duoplasmatron source is designed to produce negative helium ions by extracting ions from a helium plasma which are then negatively ionized through charge exchange with lithium vapor.

Cesium Ion Sputtering Source

The cesium sputtering source can produce negative ions from most elements that can exist in solid state, with low vapor pressure. The negative ions are produced by a several step process involving sputtering and charge-exchange.

The ion are produced from a cylindrical target made from (or containing) the species of interest. The target is biased with $-3\, kV$ and bombarded with Cesium
(Cs$^{1+}$ ions). The Cs is first evaporated from liquid Cs in a chamber heated to ~150°C. The vapor is then thermally ionized by an resistive heater. Cs ions sputter particles from the target while Cs vapor accumulates on the surface of the target as a thin layer. The sputtered particles are usually positive ions or neutral atoms and undergo one or more charge-exchange interactions with the solid Cs at the surface to become negative ions. These negative ions are then extracted from the source by a -15kV potential, after which, they leave the source towards the accelerator [13]. Currently, the cesium sputtering source is operational and is being used to produce $H^-$ beams from titanium hydride ($TiH_2$) targets for experiments requiring proton beams. A typical negative ion spectrum from a copper target is shown in figure 3-2.

![Negative Ion Spectrum from Copper Target](image)

Figure 3-2: A typical negative ion spectrum from the cesium sputtering source using a copper target.

**Duoplasmatron Source**

The duoplasmatron source is designed produce negative helium ions. The source electro-statically ionizes neutral Helium ($He$) gas by thermal electron from a heated filament that are accelerated by a several kV potential. The $He^+$ ions are accelerated by a 15 – 20kV extraction potential and pass through a section of the source called the lithium charge exchange canal which filled lithium vapor. As the $He^+$ ions pass through the lithium, the charge exchange cross section is sufficiently high that enough
$He^+$ ions will undergo two charge exchange events with the lithium vapor that $> 10 \mu A$ of negative $He^-$ current can be produced [14].

### 3.1.2 Electrostatic Focusing

As the beam emerges from the ion source it is not well collimated and has a divergence angle of roughly $1^\circ$. Since the inner diameter of the acceleration column is $< 1 cm$ and beam path between the source and the accelerator is several meters, focusing is required to prevent substantial beam loss. In the Tandetron, this is accomplished with an electrostatic Einzel lens. To produce the focusing effect, the Einzel lens creates an axisymmetric E-field between a wire mesh grid at a high voltage ($\sim 5kV$) and two co-linear cylinders at ground potential. This design creates an E-field geometry, shown in figure 3-3, that causes no net acceleration and has a radial component that causes focusing.

![Diagram of the E-field geometry in the electrostatic Einzel lens which cause a focusing effect on negative ions. $+V$ is the applied voltage, $\hat{z}$ is the beam axis, and $\hat{r}$ is the radial direction](image)

Figure 3-3: Diagram of the E-field geometry in the electrostatic Einzel lens which cause a focusing effect on negative ions. $+V$ is the applied voltage, $\hat{z}$ is the beam axis, and $\hat{r}$ is the radial direction.
3.1.3 Acceleration of Ions

The accelerator uses a high DC voltage to accelerate the ions. The high voltage is created by a feedback stabilized RF supply powering a sulfur-hexafluoride ($SF_6$) insulated Cockroft-Walton charging network. The power supply is adjustable, and generates a very stable, steady-state terminal voltage of up to $1.7\text{MV} \pm 200\text{V}$ which is connected directly to the acceleration sections of the accelerator (referred to as acceleration columns).

The tandem design uses two acceleration columns joined by an ionization section which is connected directly to the high-voltage terminal. The design allows the accelerator exploit the ionization of accelerated negative ions by an electron stripping medium (such as nitrogen gas) to convert negative ions, accelerated in the first section, to positive ions which are then accelerated in the next section. This increases the effective acceleration potential of the power supply by a factor of two for singly charged ion species. The tandem accelerator concept is shown schematically in figure 3-4 and described in table 3.1.

![Figure 3-4: Schematic describing the tandem accelerator concept](image)

3.1.4 Magnetic Ion and Energy Selection

A large electromagnet is used to select the desired ion species to be injected into the accelerator. This magnet is referred to as the low energy (LE) magnet. After acceleration, a second magnet called the high energy (HE) magnet, is used to steer
Negative ions are produced by an ion source.

The desired ion species are selected and injected toward terminal by low energy magnet.

Negative ions are accelerated toward the (positive) high voltage terminal.

Electrons are stripped from ions by \( N_2 \) gas that is injected at terminal.

Ions are now positive and accelerate away from the HV terminal to reach a final energy \( E_i = (Z_i + 1) \cdot V_{\text{terminal}} \) where \( Z_i \) is the final charge state of the ion species.

The ion beam is focused by the magnetic quadrupole lens.

Desired Ion species/charge-state are steered into beam line towards the experiment.

<table>
<thead>
<tr>
<th>Table 3.1: Basic process of ion acceleration in a tandem accelerator</th>
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<tbody>
<tr>
<td>Step</td>
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<td>7</td>
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</table>

the high energy ion beam to select the desired ion beam charge state and direct it into the proper beam-line.

**Ion Species Selection**

The LE magnet is used much like a mass/charge spectrometer. From the Lorentz force on the charged particle \( F = qv \times B \), the bending radius \( R_B \) in a uniform magnetic field is given by equation 3.1.

\[
R_B = \frac{\sqrt{2mE}}{qB_0}
\]  

(3.1)

Where \( B_0 \) is the magnitude of the magnetic field, and \( q,m,E \) are the particle's charge, mass, and kinetic energy, respectively (SI units).

The ion source has a constant extraction potential \( E_o \) such that each ion has an energy of \( qE_o \) \((q = -e)\). Since the magnet current \( I_m \) is proportional to the magnetic field, assuming a fixed \( E_o \), the expression for \( R_B \) results in relation 3.2.

\[
I_m \propto \sqrt{\frac{m}{q}} \quad \rightarrow \quad \frac{I_m}{I_{m0}} = \sqrt{\frac{m}{m_0}}
\]  

(3.2)

Where \( m,q \) are the particles' mass and charge respectively. This relationship is useful because it allows the accelerator operator to identify and select the desired ion species simply by varying the magnet current. Using the second relationship, if one
ion species can be identified (such as $H^-$, the lightest ion usually present), the rest of the ion species in can be identified.

**Energy Selection**

The HE magnet is used for bending the beam of high energy ions so that they are directed into the correct beam line to the desired experiment. This is necessary since ionization in the $N_2$ stripper creates a spectrum of charge states, leading to populations of ions of different energies. From the geometry of the magnet and the angle of beam deflection $\theta_B$ from the axis of the accelerator, is given by equation 3.3.

$$\sin(\theta_B) = \frac{d_o}{R_B} \rightarrow \sin(\theta_B) = \frac{qB_o d_o}{\sqrt{2mE}}$$

(3.3)

Where $d_o$ is the length of the magnet in the direction of the incident beam, $R_B$ is the bending radius, $B_o$ is the field, $q, m, E$ are the particle’s charge, mass, and kinetic energy, respectively (SI units). For tandem accelerators the final energy $E$ of the accelerated ion depends on the initial charge state $Z_{(-)}$ (which is essentially always $-1e$), the final charge state $Z_{(+)}$ of the ion, and the high voltage terminal potential $V_o$. Equation 3.3 can be rewritten for the tandem accelerator account for the charge state dependence of $E$, shown in equation 3.4. From this equation the convenient scaling rule (3.5) is given to determine the charge state/energy of the ion selected by the HE magnet, assuming the LE magnet selects a single ion species (with $Z=-1e$) by mass. Ions of a single mass and charge state can therefore be selected after acceleration to produce the desired mono-energetic beam.

$$\sin(\theta_B) = \frac{\sqrt{eB_o d_o}}{\sqrt{2mV_o}} \left( \frac{Z_{(+)}}{\sqrt{Z_{(+)}} + Z_{(-)}} \right)$$

(3.4)

$$I_m \propto \frac{\sqrt{m \cdot V_o \cdot (Z_{(+)} + 1)}}{Z_{(+)}},$$

(3.5)
3.1.5 Magnetic Focusing

A magnetic quadrupole lens is used to focus the beam after it is accelerated. Though quadrupoles cause more aberrations than an axisymmetric electrostatic lens, they are necessary because the required voltages would be much too high to electro-statically focus the high energy beam. Quadrupole lenses use two focusing sections, each with two magnets with four pole pieces that produce a magnetic quadrupole field, shown in figure 3-5. The second section is the same as the first except rotated by 90°.

![Figure 3-5: Quadrupole field viewed along the beam axis, \( \hat{z} \).](image)

In the two side quadrants of the quadrupole lens, the particle trajectories bend radially inward in the first section causing a focusing effect, and then are slightly defocused because of the second section as shown in figure 3-6. The defocusing effect is less pronounced in the second section due to the B-field gradient. The ions are focused by the beam in a stronger part of the field and travel radially inward where the defocusing field of the next section is weaker.

The opposite process occurs in the top and bottom quadrants but still produces the same effect. The particles are defocused by the first section (quad 1) and move
3.2 Accelerator Upgrades

While refurbishing the accelerator, several systems were upgraded or replaced to improve the accelerators operation and out of necessity:

3.2.1 Recirculating Cooling System

Many of the accelerators components require water cooling including the turbo pumps, steering magnets, and beam-line components. Refrigerated water is piped into the lab
from the building’s recirculating chilled water system. The system however, is very old and the water is often discolored and filled with particulate matter (such as flakes of rust). The debris could potentially cause clogs to form if it were piped directly into the accelerators hardware. To avoid this problem, a new cooling system was built which has a self contained recirculating cooling loop for the accelerator which transfers its heat to the chilled water system through a heat exchanger.

### 3.2.2 Improved $N_2$ Gas Stripper control

At the high voltage terminal when the two accelerator tubes join, it is necessary to inject a small amount of gas (dry nitrogen) to strip the electrons from the negative ions to produce positive ions for the second acceleration stage. The stripper gas inflow and outflow due to pumping, will reach an equilibrium with a constant average density. This density is proportional to the probability that an electron will be stripped from the negative ion. Since too much gas leads to vacuum degradation and electric breakdown and too little causes insufficient stripping, fine control of the stripper gas flow is advantageous for maximizing the stripping efficiency.

The original design used a flow valve mounted on to the stripper section of the accelerator. This valve was controlled by a knob that turned a metal rod which passed through a swagelock fitting, then to a ~2m nylon rod that turned the valve. The swagelock fitting made a very poor feed-through, so it was necessary to replace it with a high pressure feed-through that can be rotated with little friction. Currently, the flow can be adjusted manually by rotating the feed-through, however, in the future, this feed-through can be adapted to a stepper motor and controlled remotely if necessary.

### 3.2.3 Centralized Controls

The accelerators controls have been centralized so that most major accelerator components including the sources, HV supply, steering magnets, and beam lines can be operated from the accelerator control station. The accelerators original design had
one control rack for the HV supply and beam alignment, and a two source control
racks with power-supplies and controls for each of the ion sources, but did not have
the hardware to operate the experiments remotely. To centralize all of the controls
the three original racks were set up in the same location and an additional rack was
added for controlling the beam line hardware remotely. A list of the list of new
hardware added in the beam-line control rack is give by table 3.2.3.

<table>
<thead>
<tr>
<th>Beam-line Control Rack</th>
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<tbody>
<tr>
<td>1 6 channel controller for pneumatic beam-line hardware such as gate valves and Faraday cups</td>
</tr>
<tr>
<td>2 ±1000V power supplies for x and y electrostatic steerers</td>
</tr>
<tr>
<td>3 18 channel BNC patch panel for routing signals from the experiments to the control center</td>
</tr>
<tr>
<td>4 Digital data logging oscilloscope for recording data and using beam profile monitor</td>
</tr>
<tr>
<td>5 Nuclear instrumentation module (NIM) bin and space for additional equipment</td>
</tr>
</tbody>
</table>

Table 3.2: A list of new hardware for remotely controlling beam-lines and experiments.

All of the hardware in the new rack is routed internally to a patch panel on the HE magnet table. A photo of the control center is shown in figure 3-8.

### 3.2.4 Improved Interlocks

The accelerator was designed with a built-in interlock system that disables the appropriate systems when the necessary conditions for vacuum, cooling, air pressure, arcing, or stripper-gas are not satisfied. The original design did not however have a radiation interlock or interlocks for the experiments on the beam lines.

Two alarmed radiation monitors with Geiger-Mueller detectors were installed; one at the high energy end of the accelerator, and the other behind the control racks at the low energy end. These radiation monitors have an interlock relay that was wired into the circuit that shuts down the high voltage supply. Because of this modification, if a radiation hazard arises, the lights and alarms will warn the operator, and in addition, the high voltage supply will shut down, preventing further radiation exposure.
The new interlock system connected for the beam-lines allows for six interlock chains to be connected to the an interlock that closes the first gate-valve at the high energy end of the accelerator. If any of the of the interlock chains on the beam-lines or experiments are broken, or if the radiation alarm is activated, the gate valve will close preventing any beam from reaching the experiments. Since this interlock allows the ion beam to be contained without shutting down any major components or power supplies, the operator does not need to restart or re-adjust the accelerator.

3.2.5 Sputter Source Alignment

Prior to its repair, the sputter source (figure 3-9) had several severe alignment problems. The misalignments caused the beam trajectory to deviate from the axis of the injector beamline enough that it inhibited proper electrostatic steering focusing, producing beams with negligible currents. The most significant misalignment was between the source and the extraction electrode. This problem arose because the two flanges on either side of the insulator were not concentric; their centers off by 1.8 \( \text{mm} \). Since the components in the source require alignment tolerances of \( \pm 25 \text{ \mu m} \),
correcting the misalignment was absolutely necessary.

![Diagram of the internal components of Cs sputtering source.](image)

Figure 3-9: Diagram of the internal components of Cs sputtering source.

This was accomplished by redesigning the extraction electrode such that its position could be adjusted relative to the source. The source was then mounted on a rotary table on a milling machine and was reassembled with each part aligned using a dial indicator to within the required tolerances. The second misalignment was between the source and electrostatic Einzel lens. For the lens to focus properly it is critical that the beam pass through the center. The beam however did not pass through the center and could not be adjusted because source was rigidly mounted to the lens. This problem was solved by replacing a rigid section of beamline between the source and lens with vacuum bellows with compression bolts to correct the angular misalignment. The final alignment was made by trial and error by mounting a piece of aluminum foil in place of the lens grid, observing the location of the discoloration from the beam spot, and then adjusting the angle of the bellows. After the sources alignment was complete, the beam could be focused through the injector aperture (~ 0.5 cm diameter) with greater than 90% transmission efficiency.
3.3 Radiation from the Accelerator

Linear accelerators like the Tandetron that operate with a static acceleration potential in the low MeV range, can produce ionizing radiation, particularly X-rays. These X-rays can be generated as stray high energy electrons are absorbed and from electron excitation. In the Tandetron, these sources of radiation are mitigated with lead shielding and by electron suppression using permanent magnets in the ion sources and a slightly helical E-field in the acceleration columns. Radiation can also produced within the experimental setups at the end of the beamlines either intentionally for IBA measurements or unintentionally, therefore, proper calculations must be made to determine which precautions should be taken for each experiment.

Bremsstrahlung Radiation

In some linear accelerators, bremsstrahlung radiation can be a problem when free electrons are inadvertently accelerated by high voltage components such as the HV terminal in the accelerator, or the ion extraction components in the sources. When these high energy electrons collide with internal parts of accelerator, they slow down rapidly and cause bremsstrahlung (or braking) radiation. The Tandetron however, has specially designed acceleration tubes to eliminate this problem. The disks that make up the acceleration tubes have off-axis cut-outs which are arranged such that each disks is rotated by several degrees with respect to the adjacent disks. As a result, a static electric field for acceleration is created between these disks which has a slight helical component due to the asymmetry. This has only a small effect on the ions because of their large mass and averages to zero over the length of the accelerator. Electrons in the tubes however, move along trajectories that move them far enough away from the acceleration path so that they collide with the walls of tubes before they can gain enough energy to cause a high-energy bremsstrahlung radiation hazard. The resulting radiation is at sufficiently low in energy that it is stopped by the accelerator’s pressure vessel (~ 1 inch thick steel).
X-Rays from Ionization

When ionization occurs in the gas stripper region of the high-voltage terminal, some X-rays are produced by subsequent atomic transitions. To shield this radiation, the gas stripper (inside the accelerator tank) is wrapped with a ~ 1/8 inch thick layer of lead.

Electron Suppression in Sources

Both ion sources require voltages of up to 30 KV. These voltages, in principle, can accelerate electrons and cause a bremsstrahlung x-ray hazard. However, both sources have strong permanent magnets built into the 15–30 kV extraction sections. The magnetic field from these magnets alters the electrons trajectories enough that they collide with the inner walls of the source before being accelerated, thus eliminating the radiation hazard.

Radiation from Experiments

The accelerator documentation states that the accelerator has been designed so that it will produce radiation levels that are lower than ”accepted non-occupational levels” [12], so no measurable radiation is expected from the accelerator or the ion sources. This has been verified with a portable Geiger counter. There are also two alarmed Geiger-Mueller (GM) radiation detectors that are turned on the by the main breaker that powers the accelerator, so it is highly unlikely that there will be any serious radiation hazards from the accelerator that would go undetected.

Significant radiation can, however, be produced in experiments due to beam-target interactions, so it is necessary to calculate the expected radiation levels for each new experiment and verify these predictions with the appropriate detection equipment. For external beams, the largest danger is the direct exposure to the beam, which can have a range as high 10 cm in air. Direct exposure must be avoided because it will cause burns. In addition, the beam can deliver doses greater of $10^7$ rad/s over a region the size of the beam spot to depth of 10s-100s of μm in skin [2]. Backscattered ions
can be an issue but are much less significant than direct exposure. Backscattered particles can be completely avoided by keeping a distance of greater than the beams range ($\gtrsim 10 - 15\text{cm}$). Another issue for an external beam is the radiation produced by reactions in the sample and in the air. To make an estimate for the radiation production or activity $\alpha [\text{Bq}]$, all of the the relevant cross sections $\sigma_t [\text{m}^2]$ are averaged over the beam’s energy range then multiplied by the maximum beam ion current $I_{max}/Z\text{e} [\text{s}^{-1}]$, the range $R_{max} [\text{m}]$ at the maximum energy, and the target particle densities $n_t [\text{m}^{-3}]$, as shown in equation 3.6.

$$\alpha = n_t \cdot \left( \frac{I_{max}}{Z\text{e}} \right) \cdot \sigma_t \cdot R_{max}$$  \hspace{1cm} (3.6)

Using this method, the radionuclide production rates were calculated for the most significant nuclear reactions induced by a proton beam in air. The results are shown in table 3.3. For a typical external proton beam used in PIGE boron measurements, these reactions produce an activity of $\alpha = 1.43 \cdot 10^5 \text{Bq}$ from prompt gamma emission and an activity of $\alpha \sim 1.5 \cdot 10^5 \text{Bq}$ from accumulated radioactive nuclides (from 1 hour of operation). This activity is small and is well below acceptable limits. Further calculations and measurements of radiation produced from Mo, B, and W targets are described in chapters 5 and 6.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate [nuclides/s]</th>
<th>$Q_{\text{reaction}} [\text{MeV}]$</th>
<th>$\tau_{1/2}$</th>
<th>$Q_{\text{decay}} [\text{MeV}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{O} (p, \gamma)^{17}\text{F}$</td>
<td>$1.43 \cdot 10^5$</td>
<td>0.600</td>
<td>64.49 sec</td>
<td>2.761</td>
</tr>
<tr>
<td>$^{14}\text{N} (p, \gamma)^{15}\text{O}$</td>
<td>$1.51 \cdot 10^3$</td>
<td>7.297</td>
<td>122.24 sec</td>
<td>2.754</td>
</tr>
<tr>
<td>$^{12}\text{C} (p, \gamma)^{13}\text{N}$</td>
<td>$8.47 \cdot 10^2$</td>
<td>1.943</td>
<td>9.965 min</td>
<td>2.220</td>
</tr>
</tbody>
</table>

Table 3.3: Nuclide production rates for a $2\text{MeV}$, $100\text{nA}$ proton beam passing through kapton then stopping in air. This represents an activity of $\alpha = 1.43 \cdot 10^5 \text{Bq}$ from prompt gamma emission and an activity of $\alpha \sim 1.5 \cdot 10^5 \text{Bq}$ from accumulated radioactive nuclides for a typical external proton beam used in PIGE boron measurements (from 8 hours of operation).
4.1 External Beam

There are a variety of Ion Beam Analysis (IBA) techniques that are well suited for studying Plasma Facing Component (PFC) surfaces. IBA is typically conducted in an evacuated chamber. However it is possible to set up a beamline where the beam passes through a thin vacuum tight exit foil (or window) so it can irradiate samples that are in air, at atmospheric pressure. This is referred to as an external beam. The most important benefit of external IBA for the study of PFCs is that samples can be repositioned or changed very quickly and easily. Samples can be arbitrarily large because they are not limited by a vacuum chamber. The most notable disadvantages however, are the increased uncertainty in the incident energy due to straggling from the window and the air and inaccuracies in the sample position. In addition there can be increased background radiation causing a decrease in signal to noise ratio [2].

The capability for handling large samples is particularly useful for studying PFCs such as divertor tiles from C-Mod because each section is large in size and contains tens or hundreds of $\sim 2\text{cm} \times 2\text{cm}$ tiles. Since no vacuum chamber or pump-down time is required, many individual tiles or even sections of the divertor or limiters can be repeatedly repositioned and analyzed quickly. This allows hundreds of measurements to be made in a matter of hours. Such fast throughput makes analysis with high spacial resolution possible as well as analysis aimed at measuring macroscopic trends
from tile to tile. A drawing of the beam line for external IBA is shown in figure 4-1 and descriptions of some of its components are given in Section 4.3.

Figure 4-1: A drawing of the beam line used for external ion beam analysis. The numbers correspond to the following components: (1,6) vacuum gate valves, (2,3) y and x electrostatic steerers, (4) insertable Faraday cup, (5) beam profile monitor, (7) beam aperture/window assembly. (8) turbo pump.

4.2 Window Design

When designing a beam window there are several issues that must be considered. (1) The window must be thick enough and mechanically strong enough to maintain vacuum on one side with atmospheric pressure on the other. (2) The window must be thin enough that ion beam loses as little energy as possible as it passes through. (3) The energy lost by the beam must also be dissipated by the window to prevent it from melting. All of these conditions must be simultaneously satisfied by choosing a
suitable window material and properly choosing maximum beam current and window dimensions. Beryllium foil was first considered, followed by DuPont\textsuperscript{TM} Kapton\textregistered polyimide film because of its availability and successful implementations in previous external beam experiments [2].

Beryllium (Be) is commonly used for X-ray window because of its low absorption due to its low atomic number. Ions, such as protons, lose most of their energy through small-angle coulomb scattering from electrons. Be has a low atomic number ($Z = 4$) and thus a low electron density for a metal. The resulting low stopping power for protons and other charged particles combined with its high melting point of $1287^\circ C$ make Be desirable for exit foils.

Kapton\textregistered is a polymer made by DuPont. It is designed for many applications and is commonly used in electronics. It is particularly useful because of its ability to maintain its mechanical and electrical properties over a wide range of temperatures (-269$^\circ C$ to 400$^\circ C$). It can also withstand higher radiation doses than most other polymers [9]. After the following analysis was performed, Kapton was chosen as the preferred exit foil material.

4.2.1 Mechanical Properties

In order make a vacuum tight window of minimal thickness, it is often necessary to choose a film that is thin enough that atmospheric pressure causes it to exceed its yield strength and plastically deform. It is typically difficult to accurately model thin films that are plastically deformed so it would considerable effort to rigorously optimize the window geometry. It is not necessarily advantageous to push mechanical limits of the window, because beam heating will undoubtedly change the properties of the exit foil and radiation damage will eventually degrade the its strength. There are a variety of materials that can be used to make windows that are typically less than 10$\mu m$ thick and several millimeters in diameter [2]. It also possible make larger diameter windows by supporting the foil with a solid metal or carbon mesh with a high void fraction.

For this study a 1/8\textsuperscript{th} inch (3mm) diameter aperture was used with an unsup-
ported, 7.5µm Kapton exit foil. This geometry was chosen based on the minimum available Kapton thickness and conservative, rough estimates of the maximum window diameter. The foil supporting aperture was made with a rounded edge to minimize the curvature of the foil to reduce the shear stress at the edges. The structural integrity of this window was then verified experimentally with a vacuum pump.

4.2.2 Nuclear and Atomic Properties

Beryllium

Beryllium (Be) foil is essentially one single isotope, $^9Be$. Generally this means that there will be fewer possible reactions that contribute to the background noise in the detector such as $Be_4^9(p, \gamma)B_5^{10}$. This is only partly beneficial because, after the beam exits through Be, it then passes through the air which is composed of most the same elements that are present in Kapton.

beryllium also has a neutron producing reaction $^9Be(p, n)^9B$. This reaction has minimum threshold energy of $\sim 2MeV$. The CLASS facility cannot provide adequate neutron shielding, so if a Be window is used the energy of beam energy must be kept below 2 MeV to avoid neutron production shown in figure 4-2 [31]. This effectively puts a limit on the beam penetration depth into the sample that is much lower than the limit due the accelerators maximum voltage.

Kapton

Kapton is a polymer with a the chemical formula $C_{22}H_{10}N_2O_5$. Therefore Kapton can produce background radiation from particle induced reactions of carbon, hydrogen, nitrogen and oxygen. Some possible interfering reactions are shown in table 4.1. None of these elements however, produce neutrons at energies below the maximum energy for protons in the Tandetron, 3.4MeV [22]. Fortunately these background reactions tend to be negligible compared to the boron reaction used in this study.
Figure 4-2: The cross section of this beryllium (p,n) reaction shows that will the Be window will begin to produce neutrons when the proton energy exceeds 2 MeV [31].

<table>
<thead>
<tr>
<th>Proton-Gamma Reactions</th>
<th>Q [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\text{C} (p, g) \text{N}_7^{13}$</td>
<td>1.943</td>
</tr>
<tr>
<td>$^7\text{N} (p, g) \text{N}_7^{14}$</td>
<td>7.551</td>
</tr>
<tr>
<td>$^7\text{N} (p, g) \text{O}_8^{15}$</td>
<td>7.297</td>
</tr>
<tr>
<td>$^7\text{N} (p, g) \text{O}_8^{16}$</td>
<td>12.127</td>
</tr>
<tr>
<td>$^8\text{O} (p, g) \text{F}_9^{17}$</td>
<td>0.600</td>
</tr>
</tbody>
</table>

Table 4.1: These reactions can occur in Kapton and potentially interfere with external proton beam IBA measurements [22].

4.2.3 Energy Loss in Window

It is important to minimize the amount of ion energy that is lost in the window to ensure that ions are able to exit the window with sufficient energy to be useful for IBA. The rate of energy loss of ions as they pass through a material depends on the material’s stopping power $S \equiv -dE/dx$. $S$ is dependent on many factors, most importantly: the energy of the ions, the ion species, and the composition of the target material. To determine loss of ion energy, the stopping power vs. energy data $S(E)$ was generated by code by James Ziegler called ”Stopping and Range of Ions in Matter” (SRIM2008) [38]. This $S(E)$ data was used to calculate the energy of an ion beam as it passes through the window by integrating equation 4.1 in 1-dimension
over position, where i is the index of a grid location, \( x_i \).

\[
E_{i+1} = E_i - S(E_i) \cdot (x_{i+1} - x_i) \tag{4.1}
\]

Using this method a plot was generated for beryllium (figure 4-3) and Kapton (figure 4-4) for several ion species that could be potentially useful measuring or profiling boron, hydrogen or deuterium.

![Energy Loss of 3 MeV Ions in Beryllium](image)

Figure 4-3: A plot of the calculated energy loss in beryllium as a function of distance for ion species that are relevant for measuring boron and hydrogen.

The predicted energy loss profiles shown in figures 4-3 and 4-4 are a clear indication that only proton (\( H^+ \)) beams can efficiently pass through \( \sim 10\mu m \) of either window material. Since it is difficult to make windows thinner than \( \sim 5\mu m \), external beams at energies less than 3MeV are limited to \( H^+ \) beams and possibly \( \frac{2}{3}He^+ \) (for fuel retention studies). Both Be and Kapton show comparable beam energy loss, though Kapton causes slightly lower energy loss.
4.2.4 Thermal Properties

The beam window must be able to dissipate the thermal energy deposited in its bulk from the proton beam as it passes through. Thermal damage is most likely reason for acute window failure (aside from accidental puncturing by the experimenter). The amount of heat deposited in the window is roughly proportional to the beam energy and current. Since the rates for reactions used in IBA are proportional to the beam current, it is advantageous to design the window to withstand the highest beam currents possible in order to improve count rates in the detector and the signal to noise ratio. Since the window is very thin, even though the total power deposited is typically less than 0.1 watts, the power density is high enough that the window can potentially heat up and melt. Since the the beam power from Cs sputtering source can greatly exceed the windows thermal limitations, it is necessary to determine an upper bound on current passing through window to prevent thermal failure.

To determine the thermal operating limits for beam energy and current a conductive model was used for beryllium because of its high thermal conductivity. Kapton
however, has a very low thermal conductivity, making convective heat transfer dominant for heat dissipation. As such, a numerical model that includes conduction and convection was used to model Kapton.

**Conductive Model for Beryllium**

Beryllium has a high thermal conductivity (270 Wm$^{-1}$K$^{-1}$) which means a significant amount of its heat is lost by conduction to the supporting aperture. Therefore, a conservative estimate for the maximum beam current and energy was determined by calculating the maximum temperature of the window by assuming the window is only cooled by conduction. There are two situations that are important to consider: (1) If the beam is defocused and is larger than the window, heating will be approximately uniform. (2) If the beam is well focused and is smaller than the diameter of the window, as shown in figure 4-5, the heating will be localized and the beams current profile becomes important.

In both of these situations, heat conduction is governed by the heat equation 1-D cylindrical heat equation 4.2. Where $T = T(r, t)$ is the temperature, $k$ is the thermal conductivity, $\dot{q}(r)$ is the power density deposited by the beam [16].

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\dot{q}(r)}{k} = 0$$

(4.2)

For the defocused beam, the heating is approximately uniform and the supporting aperture at the edge of window is room temperature $T_\infty$. The solution in this case is very simple; the temperature profile is parabolic and the maximum temperature is given by equation 4.3, where $\dot{q}$ is the power density deposited by the beam [16].

$$T_{\text{max}} = \frac{\dot{q}R^2}{4k} + T_\infty$$

(4.3)

The situation for a focused beam is slightly more complicated. In this case the boundary conditions, shown in figure 4-5. The region $r < a$ is heated by the ion beam which is depositing thermal energy with a power density $\dot{q}(r)$, the region $a < r < b$ is not heated, and the interface $r = b$ is at ambient temperature. For the region
a < r < b, where beam heating is negligible ($\dot{q} = 0$), equation 4.2 can be solved for the temperature $T$ in dimensionless form to given equation 4.5. Where $T_b$ is ambient temperature at the edge of the window, $k$ is the thermal conductivity of the window, and $\langle \dot{q} \rangle$ is the average power density deposited by the beam [16].

\[
\frac{T - T_b}{T_a - T_b} = \frac{\ln(r/b)}{\ln a/b} \quad \text{for } a < r < b
\]  

(4.4)

where: 

\[T_a = T_b + \frac{\langle \dot{q} \rangle a^2}{2k} \ln(b/a)\]

For region $r < a$ the solution to the heat equation 4.2 is dependent on the choice of heating profile $\dot{q}(r)$. The heating profile depends on three factors shown in equation 4.5.

\[\dot{q}(r) = S_w(E_i) \cdot j(r)\]  

(4.5)

Where $E_i$ is the energy per ion in the beam, $S_w(E_i) = -\frac{dE_i}{dx} \text{[eV/m]}$ is the stopping power of the window material, and $j(r)$ is the beam current density $[A/m^2]$ profile.

Since the incident beam is mono-energetic to within $\pm0.01\%$ and $S_w(E_i)$ is approximately constant in the thin window, the shape of the heating profile depends on the current profile of the beam. For this thermal model, a parabolic beam current profile shown in equation 4.6 was used because it is a reasonable approximation of the actual beam and it results in simple solutions to the heat equation 4.2.

\[j(r) = \frac{2I_o}{\pi a^2} \left(1 - \left(\frac{r}{a}\right)^2\right)\]  

(4.6)

Where $I_o$ is the total beam current, and $r$ is the radial coordinate. Using this current profile...
profile 4.6, the heat equation 4.2 can be solved for the region $r < a$. The solution is given in dimensionless units in equation 4.8.

$$\frac{T - T_\infty}{T_o - T_\infty} = \frac{1}{3a^4} \left( r^4 - 4a^2 r^2 + 3a^4 \right) \tag{4.7}$$

where: $T_o = T_\infty + \frac{3}{8 \cdot \pi} \left( \frac{I_o \cdot S_w(E_i)}{k} \right)$

The results of this calculation are plotted as temperature profiles $(T - T_\infty)$ in a Be exit foil from a 100nA, 2MeV ion beam, shown in figure 4-6. From this result, it is apparent that the heating from 100nA beam can be safely dissipated if the beam is not highly focused.

Figure 4-6: Plot of the calculated temperature profiles $(T - T_\infty)$ in a Be exit foil from a 100nA, 2MeV ion beam. This calculation the beam profile is parabolic and assumes heat loss is dominated by conduction.
4.2.5 Thermal Model for Kapton

Kapton has a very low thermal conductivity (0.37 $Wm^{-1}K^{-1}$) [9] compared to Be and most other metals. Since heat conduction is poor in Kapton, the dissipation of the heat deposited by the beam is dominated by convection by the air on the surface of the window.

To model the thermal properties of the Kapton window, a 1-D (cylindrical) thermal relaxation code was written to calculate the radial temperature profile of the window for a given beam energy and current. The code first calculates the beam power absorbed by the window. Then, from an initial temperature profile, it iteratively redistributes and dissipates the heat among the radial locations $r_i$ by conduction, radiation, and convection. As the system approaches equilibrium, the time steps increase so that the simulation converges to steady state. The code essentially iterates equation 4.8 in time until it relaxes an equilibrium solution.

$$q_{beam} = q_{conduction} - q_{convection} = \frac{\partial}{\partial t} U_{\text{internal}}$$

$$\dot{q}_i V_i + k \left( A_{i(-r)} \frac{T_i - T_{i-1}}{r_i - r_{i-1}} + A_{i(+r)} \frac{T_i - T_{i+1}}{r_i - r_{i+1}} \right) - h A_i (T_i - T_\infty) = \rho c V_i \frac{\partial T}{\partial t} \quad (4.8)$$

Like many thermal modeling problems, however, it is difficult to accurately determine the heat transfer coefficient $h$. $h$ coefficients are usually determined from experimentally derived correlations because they can vary over a wide range based flow conditions and geometry. Depending on the conditions, $h$ for air can vary as much as an order of magnitude within the range $10 - 100 \, W/(m^2K)$. To accommodate this large range, 10 $W/(m^2K)$ was used in the calculations to make a conservative estimate. The results of this calculation are shown in figure 4-7. These results suggest that a Kapton window can survive steady state exposure to 100$nA$ of beam current at 2$MeV$ if the beam is not highly focused.

A 7.5$\mu m$ Kapton exit foil was implemented and used with 1 – 2$MeV$ beams up to $> 100nA$ for $> 50$ hours without thermal failure. This experimental result validated predictions from the model and the window design. In addition, to accommodate
higher currents, a 1/8 inch compressed-air line was added to actively cool the exit foil from the bottom.

![Temperature Profiles of Kapton Exit Foil for Various Ion Beam Radii](image)

Figure 4-7: Plot of the calculated temperature profiles $(T - T_\infty)$ in a Kapton exit foil from a $100nA$, 2MeV ion beam. This calculation done using a heat transfer coefficient $h = 10 \, W/(m^2K)$ and assuming gaussian beam profiles with full width half maxima of $0.3, 0.7, 1.0, 1.3, 1.7[R/R_o]$ where all $R_o$ is the exit foil radius. The beam currents were normalized such that $100nA$ was incident on the window.

### 4.3 Beam-line Instrumentation

Many applications require the beam to be focused or aimed properly at a sample target (in this case an exit foil/aperture). This requires several instruments; an X-Y steerer, a Faraday cup, located in the beam line for rough beam alignment, and a magnetic quadrupole lens and, possibly, a beam profile monitor for focusing and the final alignment. Instruments for precisely measuring beam current are also necessary for proper normalization of measurements.
Beam Profile Monitor

The beam profile monitor (BPM) that is used is an instrument made by National Electrostatics Corporation. It consists of a helical wire mounted on a $\sim 20$ Hz rotary drive (such that the axis of rotation is perpendicular to the beam). As the wire rotates, it passes through the beam. Since it is helical, part of each cycle provides a horizontal sweep and part produces a vertical sweep. When energetic particles in the beam collide with the surface of the wire, secondary electrons are emitted and absorbed by a cylindrical collector. Since the secondary electron emission measured by the collector is proportional to the local beam current, as the wire sweeps through the beam in both directions due to its helical shape, the collector signal can be used to measure X and Y profiles in real time [6]. These profiles are useful for measuring shape of the beam in order to determine its shape and extrapolate the location its focal point after quadrupole focusing.

It should be noted that, for all of the external beam measurements the BPM was not necessary because the beam alignment could be determined and maximized by directly measuring of beam current with an external Faraday cup.

Faraday Cup

A Faraday cup is a fairly simple device that is used for directly measuring beam current. It is essentially a micro-ammeter that is connected to a metal cup, that can be inserted into the path of the ion beam. The cup is positively biased (or surrounded by a negatively biased enclosure) to capture the secondary electrons that are emitted as the cup absorbs the ions from the beam. There is one Faraday cup built into the beam line that can inserted with a pneumatic actuator. It is used for rough alignment of the beam and to measure the beam current incident on the window. Since some of the beam clipped by the outer edge of the aperture before passing through the window, there is also second cup that can be placed on the end of the external beam aperture. This will be used for measuring the beam current that passes through the window so the data can be normalized to beam current that absorbed by the sample.
4.3.1 Beam Current Measurement

The beam current from the source can vary by > 10% over the course of an hour. Since X-ray and Gamma emission are proportional to the number of ions incident on the sample, it is necessary to take beam current measurements for each experiment to normalize the data. For PIGE and PIXE analyses, the spectra from the unknown samples are compared to known standards, therefore the current measurements must be consistent and proportional to the actual current, but do not require absolute calibration. A more detailed description of the data normalization is given in Section 5.5.

Though collection of ions with a Faraday cup is a simple process, accurate measurement of beam current can be difficult due to secondary electron emission. When energetic ions strike the surface of a solid, a large number of low energy secondary electrons are emitted from the surface, often several per incident ion. For positive ion beams this increases the magnitude of the measured current and does the opposite for negative ion beams. Secondary electron emission also depends on the energy of the incident ions and varies with target material, so steps must be taken to ensure that the current can be measured repeatably.

The most desirable way to mitigate this problem is to suppress the secondary electrons with a negatively biased cage (10 – 100V). This bias voltage effectively repels the emitted electrons back into the surface so they do not produce a spurious current signal. This method is used in for the Faraday cup in that is inserted before the ions are injected into the accelerator.

When geometric constraints prevent the use of a biased structure surrounding the target, the target itself can be biased with a positive voltage to have the same effect. Unfortunately, biasing the IBA samples for external IBA was not found to be a viable method because secondary electron emission from the exit foil and electrons liberated from ionization of the air are attracted to the biased sample, thus perturbing the measurement. This makes absolute current measurements very difficult.

Instead, relative current measurements are used and the need for absolute calibra-
tion removed by normalization to a known target. For PIXE analysis, the aperture supporting the exit foil was electrically insulated from the beam line and the current was measured from the backside of the aperture with a charge digitizer, which integrates that collected current. Since the beam is mono-energetic and fluctuations in the steering magnetic field are negligible, the beam’s position relative to the aperture were negligible. This provided a consistent way measure a current that is both proportional to the total beam current from the accelerator and to current incident on the sample. For PIGE analysis the current was too high for the charge digitizer, so instead, the beam current was measured before and after each PIGE measurement and averaged. This method was verified experimentally by repeated measurements of known target samples.

4.4 Photon Detection and Spectroscopy

IBA measurements are generally made by exposing a sample to an ion beam then counting the scattered or emitted particles with an energy analyzing detector. The features in the energy spectrum can then be correlated to specific properties of the sample. Photon counting measurements are made with a detector that ”absorbs” the photon energy and converts it into an electronic signal (usually a current pulse). The signal is typically amplified then converted to voltage pulses that are counted by a multi-channel analyzer (MCA) [20]. Different detectors must be used depending on the energy range of the photons. Detectors that are relevant to this study are described in the following sections.

4.4.1 Gamma Detectors

For PIGE analysis, using \((p, \gamma)\) reactions, it is necessary to detect the gamma-ray photons that are produced within the irradiated samples. Since each \((p, \gamma)\) reactions produces photons with an energy that is characteristic of the reaction, it is also necessary to discriminate between photon energies. All gamma detectors stop photons by the same basic processes. At low energies below several MeV photoelectric
absorption dominates whereby each absorbed photon is absorbed by single electron creating a high energy (or fast) electron; this is the preferred interaction for photon detection because it produces a distinct peak in the energy spectrum. For medium energy photons $3-7\text{MeV}$, Compton scattering dominates whereby photons inelastically lose energy to electrons, producing background continuum in the spectrum. And with high energy photons the dominant process is pair-production, the spontaneous creation of an electron-positron pair. In addition to the full absorption photo peak, pair-production also produces two peaks with energies that are $0.511\text{MeV}$ and $1.022\text{MeV}$ due to the escape of positron-electron annihilation photons. As the energy of the gammas increases they are less likely to be absorbed. This means that the efficiency of the detector usually decreases as the gamma energy increases [20].

After the photons are absorbed their energy must be converted to a measurable signal. This can done through the scintillation process where fast photo-electrons (and positrons) deposit their energy by scintillation medium which converts the energy to low energy photons. In inorganic scintillators, this occurs because the fast particle cause a number of bound electrons in the valence band of the scintillation crystal to be excited to the conduction band. Each electron-hole pair then migrates until it de-excites and emits a low energy photon that is detected by a photomultiplier tube. Common scintillation crystals include Sodium Iodide (NaI) or Bismuth Germanate (BGO) crystals [20].

There are also solid-state semiconductor detectors. The most common are high purity germanium detectors which are large, semiconductor devices that convert the absorbed photon energy directly into a current pulse.

**Sodium Iodide NaI(Tl)**

Sodium iodide (NaI) detectors are the most common scintillation detectors available. NaI detectors use a NaI crystal doped with Thallium which is optically coupled to a photo multiplier tube. Over all, NaI scintillators have the highest light output of all commonly available gamma detectors, and have moderately good energy resolution.
Bismuth Germanate

Bismuth Germanate (BGO) detectors are another type of scintillation detector. BGO has a lower light output than NaI. However, because of Bismuth’s high nuclear charge (and thus higher electron density), BGO has greater ability to stop and detect high energy photons than NaI. This significantly improves BGO detection efficiency for photons with energies greater than 3-5 MeV.

High Purity Germanium

High purity Germanium (HPGe) detectors are semiconductor devices that have extremely precise energy resolution which makes them excellent for discriminating photo peaks from reactions that nearly overlap in energy. They are less convenient to use because they must be operated at cryogenic temperatures. They are also more difficult to manufacture with large detector volumes so they generally have a smaller active volume than scintillators and therefore have lower detection efficiencies.

4.4.2 Gamma Detector Selection

A NaI(Tl) detector was chosen over BGO for the experiments primarily because of its availability. A HPGe detector was also available but since the energy resolution of NaI is adequate for discriminating boron peaks, the high energy resolution of HPGe would be of little benefit and the lower detection efficiency would be detrimental.

4.5 X-Ray Detection

For X-ray detection for PIXE analysis, the options are limited to Lithium drifted Silicon detectors Si(Li) and intrinsic Germanium (IG) detectors. Lithium doped Germanium Ge(Li) detectors have been used in the past but have largely become obsolete after the introduction of Si(Li) and IG detectors. All of these detectors are semiconductor devices that absorb X-ray photons and produce a number of electron-hole pairs that is proportional to the photons energy. They also must be operated at cryogenics
temperatures and are usually cooled by liquid nitrogen or thermoelectric coolers [5].

Si(Li) detectors are commonly used for PIXE analysis because their detection efficiency is fairly constant between 5 – 20 keV and decreases sharply for higher and lower energies [18]. This range can vary based on detector’s design because the lower bound is set by the thickness of the protective beryllium window, and the upper bound is set by the detector’s size. These detectors are well suited for PIXE analysis of medium to high Z elements because K-shell X-rays for elements with atomic number $20 < Z < 50$ and L-shell X-Rays for elements with $Z < 50$ fall within the detectors energy range [18]. A Si(Li) detector was used in the experiments because it was available and a because of its beneficial characteristics for PIXE analysis.

IG detectors are smaller, but essentially identical to the HPGe detectors used for gamma detection, described in section 4.4.2. They have a higher detection efficiency than Si(Li), especially at higher energies and have a range that extends into the $> 100keV$ range. This additional range is not necessarily useful for PIXE and may have additional Compton background interfering with the lower range [5].

### 4.6 Detector Geometry

There are three major factors that influence the design of photon detection and spectroscopy experiments: detector efficiency, attenuation, and solid angle. Detector efficiency varies considerably between detectors. Gamma detectors generally have their highest efficiency in the $\sim 100keV$ range which decreases with increasing energy. With X-ray detectors, particularly Si(Li), the efficiency is reasonably constant, roughly in the range $5 – 20 keV$ and lower at other energies [18]. The efficiency of the detector dictates which detector can be used for the analysis technique. Since detectors vary significantly in shape and size, the selection also effects the geometry of the experiment.

Attenuation must also considered. As photons pass through matter, their intensity will be attenuated exponentially, given by equation 4.9 where $\mu/\rho$ (a function of energy) is the mass attenuation coefficient of the material, $\rho$ is the mass density, and
\( x \) is the thickness of the material.

\[
I(x) = I_0 e^{-\frac{\mu}{\rho} \cdot \rho x}
\]  

(4.9)

Solids that obstruct the path of photons between the source and the detector can decrease the intensity of the measured photons by orders of magnitude. Figure 4-8 shows some relevant mass-attenuation coefficient data from NIST [8], converted to photon absorption mean free paths for materials with their normal solid densities and air at sea level. There is a large variation in attenuation for different energy ranges, this makes attenuation significant for PIGE analysis but extremely important for PIXE analysis.

![Photon Mean Free Paths for Solid Materials and Air](image)

Figure 4-8: Photon absorption mean free paths for PFC relevant solid materials and air.

The solid angle, \( \Omega \equiv \int d\Omega \), subtended by the detector is also important. Gamma and X-ray emission are usually isotropic for IBA purposes and, since the beam spot
is small, the intensity decreases as $1/r^2$, it generally helps to place the detector as close as possible while avoiding obstructions especially for PIXE analysis and for measurements of photons with low intensity.

4.6.1 PIGE Geometry

Most experimentally useful PIGE reactions have cross sections in the milli-barn to barn range ($10^{-27} - 10^{-24} cm^2$). For the accelerator’s typical beam current range, PIGE emission is relatively small compared to the Compton scattering continuum and the background radiation levels. This makes maximizing the detector solid angle very helpful.

It is also helpful to minimize attenuation, however, since photons in the $\sim MeV$ range tend to have mean free paths in the $mm - cm$ range in solids, it is not necessarily a requirement that the photons be perfectly unobstructed, especially if avoiding obstructions comes at the expense of decreasing the solid angle.

A detection geometry that is useful for measuring the total boron on a sample is shown in figures 4-9 and 4-14, where the detector is placed beside the beam exit window so that the gamma rays from the beam-target spot are not obstructed. This geometry is especially useful because changing or moving the sample does not change the detection geometry. Another geometry, for PIGE depth profiling is shown in figures 4-10 and 4-15, where the detector is placed behind the tile. This in-line geometry is very useful for PIGE depth profiling. Since the beams energy depends on its path length through the air, if the tile and the detector are placed on a translational stage, the sample can be moved towards and away from the beam window to change the energy without changing the detection geometry. This allows many measurements to be taken at different energies while keeping the detection geometry consistent without adjusting and retuning the accelerator controls. This geometry causes some loss of signal due to attenuation but it is has only a moderate effect. If the tile is $\sim 1cm$ thick the $(p, \gamma)$ photons from boron will pass through with a $\sim 50\%$ loss of intensity, where as nearly all lower energy X-rays and gamma-rays will be absorbed. The transmission of photons as a function of energy is shown in figure 4-11.
Figure 4-9: PIGE Detection geometry: This geometry is useful for taking multiple PIGE measurements on many samples while keeping detection geometry and normalization consistent.

### 4.6.2 PIXE Detector Geometry

PIXE experiments usually are designed specifically for measuring average elemental concentrations in surface layers because PIXE cross sections vary smoothly with energy.

X-ray detectors, having $\sim 1 cm^2$ detection areas, are generally much smaller than gamma detectors. They can therefore be placed closer to the X-ray source or beam spot on the sample allowing measurement over a large solid angle. This is not entirely necessary because X-ray production cross sections are very high compared to PIGE cross section, often 10s or 100s of barns as shown in the next chapter in figure 5-2. Since the cross section is so large, the detector does not need to be placed close to measure sufficient X-ray counts. It is still beneficial however, because, if the beam current is high and the detector is far away, sufficient X-rays can be detected, but there will be more gammas produced. These gammas will contribute to a Compton background that can interfere with the X-ray measurements. It is therefore, beneficial...
Figure 4-10: In-line PIGE Detection geometry: This geometry is useful for PIGE depth profiling because it enables the experimenter to vary the beam energy at the tiles surface by changing the beam path-length through the air, while keeping detection geometry and normalization consistent.

to place the detector close to the sample and run the accelerator at lower beam current (~ 1 nA).

X-rays with energy ~ 10 keV typically have a mean free path on the order of several \( \mu m \) in solids, as shown in figure 4-8. It is absolutely necessary to avoid obstructing the path of the X-ray photons between the sample and the detector. A convenient and commonly used geometry to accomplish this is by using a 45° angle of beam incidence and a 45° detection angle, as shown in figure 4-9. A photo of the actual beamline set-up used for the PIXE measurements is shown in figure 4-13.
Figure 4-11: Transmission of gamma photons through a 1cm thick molybdenum tile sample: This illustrates that ~ MeV photons can pass through C-Mod tiles with only moderate attenuation whereas ~ keV photons are almost completely absorbed.

Figure 4-12: PIXE Detection geometry with 45° ion beam incidence and 45° detection angle: This geometry is used for PIXE measurements of average elemental concentrations in surface layers.
Figure 4-13: A photo of the PIXE analysis set-up with $45^0$ ion beam incidence and $45^0$ detection angle. (1) The sample positioning stage allows the sample to be moved vertically and horizontally with respect to the proton beam. (2) A Si(Li) detector is used for measuring proton induced X-rays. (3) The external beam aperture is surrounded by a guide to keep the detection geometry consistent.
Figure 4-14: A photo of the PIGE analysis set-up with normal ion beam incidence and 45° detection angle. (1) The external proton beam passes through the exit foil into the sample. (2) A tile sample is placed in the path of the beam (tile not shown). (3) A NaI detector measures gamma emission from the tile surface.
Figure 4-15: A photo of the PIGE analysis set-up with in-line detection geometry.  
(1) The external proton beam passes through the exit foil into the sample. (2) A tile sample is clamped in place, in front of the detector. (3) A NaI detector measures gamma emission from the tile surface. (4) The detector and tile are mounted on a translation stage allowing the beams path-length to be varied without changing the tiles position relative to the detector.
Chapter 5

Theory and Analysis

5.1 PIGE Analysis Overview

Particle Induced Gamma Emission (PIGE) is an IBA technique that can be used to determine the quantity and distribution of elements in the surface of a material with the proper nuclear data, modeling, and measurements. PIGE analysis utilizes an ion beam to induce characteristic nuclear reactions in a target material. Ion beams of several MeV can readily penetrate the Coulomb barrier for light nuclei making PIGE most effective for detecting light elements with $Z < 30$. Most of these elements have appreciable $(\rho, \gamma)$ cross sections at energies less than 10 MeV [30]. PIGE is therefore useful for measuring low-Z elements on PFCs such as Boron. Since many reactions from low-Z nuclei are sharply peaked (resonant reactions), elemental depth profiling is also possible using measurements at multiple energies.

5.2 PIXE Analysis Overview

Particle Induced X-ray Emission (PIXE) can also be used for quantifying the elements that compose a material. PIXE analysis makes use of the characteristic X-rays that are produced from the ionization and the subsequent atomic electron transitions. The most tightly bound electrons in the first principle energy level are referred to as K-shell electrons, and, similarly, the second, and third principle energy levels are the
L, M... etc. shells. Ionization of these inner shells leads to a reordering of the atomic electrons to fill the vacancy. X-rays produced from transitions to the lowest energy K-shell are the highest in energy, and the next highest are the L transitions, then M, etc. Since the higher energy X-rays are easier to detect because they penetrate into X-ray detectors with less attenuation, the K transition and often the L transition, are the most relevant for PIXE analysis. For low Z elements, the K transitions are too low in energy to be measured by most X-ray detectors. Therefore, PIXE is most useful for detecting medium to heavy elements ($Z \gtrsim 20$) [15].

PIXE analysis is performed almost exclusively with lithium drifted silicon Si(Li) detectors. These detectors generally have a detection efficiency that is constant between 5 and 25 keV and very low efficiency outside of this range. The relevant interactions must therefore produce X-rays within this range.

5.3 PIGE and PIXE Reaction Cross Sections

The probabilities of energetic particle interactions are tabulated in the form of a cross section $\sigma(E)$. Cross sections have units of area, commonly the Barn ($1b \equiv 10^{-28} m^2$) and are dependent on the energies of the interacting particles in their center of mass frame. Cross sections are convenient because the probability $P$ of a reaction per incident particle can be calculated using the relation $P = n_t \cdot \sigma \cdot dx$ for energetic particles passing through stationary target particles with density $n_t$.

5.3.1 Resonant Nuclear Reactions

When a target material is bombarded with energetic particles, those particles can be absorbed by or scattered from the target nuclei. When an incoming particle is absorbed, the resulting nucleus is usually in an excited state which decays by emitting a $\gamma$-photon and/or another particle (proton, neutron, alpha, etc). The cross sections of these reactions depend on the reacting species and on the kinetic energy of the interacting particles. Resonant nuclear reactions have a cross section $\sigma(E)$ that is sharply peaked at a resonance energy $E_r$. 

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Lighter elements tend to have nuclear reactions that can be induced by relatively low energy ions because their low nuclear charge causes the nucleus to have a weaker Coulomb barrier. Elements with $Z < 30$ commonly have resonant proton induced gamma emission (PIGE) or $(p, \gamma)$ cross sections with resonance energies less than 3MeV which are useful for PIGE analysis.

Reaction probabilities are also tabulated as a quantity referred to as the astrophysical S-factor, commonly with units $[eV \cdot b]$. The S-factor $S(E)$ is related to the cross section $\sigma(E)$ by an exponential fitting function given by equation 5.1 and the Sommerfeld parameter given in equation 5.2.

$$\sigma(E) = S(E) \exp \left(-\frac{2\pi\eta}{E}\right)$$  \hspace{1cm} (5.1)

$$\eta = \frac{Z_1Z_2e^2}{\hbar\nu} = 0.1575Z_1Z_2 \left(\frac{A}{E}\right)^{1/2}$$ \hspace{1cm} (5.2)

Where $E$ and $Z_i$ are the energy [MeV] and charge numbers [e] of the interacting particles, respectively and $A$ is the reduced mass of in AMU. The S-factor is usually a smooth function of energy and has a functional form that is derived from the Coulomb barrier tunneling probability for colliding charged particles. Because of its smoothness and its physical relevance, the S-factor can be used to make reasonable extrapolations for charged particle induced nuclear reaction cross sections to energies where no data is available [1].

There are several $p, \gamma$ reactions that can be induced by protons with energy less than 3.4 MeV, accessible with the 1.7 MV Tandetron.

$^{10}\text{B}(p, \alpha\gamma)^7\text{Be}$

Perhaps the most useful for boron detection on C-Mod tiles is the $^{10}\text{B}(p, \alpha\gamma)^7\text{Be}$ reaction. Typically this reaction is not used for B detection because of interfering reactions with other low Z-elements. However, since B constitutes the vast majority of low-Z deposition in C-Mod, this reaction works well for Mo PFCs. $^{10}\text{B}(p, \alpha\gamma)^7\text{Be}$ has a very large cross section relative to other boron reactions and is dominant in the gamma spectrum even though natural B is only 20% $^{10}\text{B}$ and 80% $^{11}\text{B}$. In addition
it produces gamma photons with energy $h\nu = 429\text{keV}$ which are low enough in energy to be in the range where the NaI detection efficiency is the highest. The width of the peak is broader than other resonant boron reactions, however it is still narrow enough for boron profiling. Cross section data for this reaction is shown in figure 5-1 [7]. There are several other similar reactions including $^{11}\text{B}(p,\alpha\gamma)^7\text{Be}$ and

![Cross Section for $^{10}\text{B}(p,\alpha\gamma)^7\text{Be}$](image)

Figure 5-1: Cross section data for the $^{10}\text{B}(p,\alpha\gamma)^7\text{Be}$ reaction ($h\nu = 429\text{keV}$) measured by R.Day and T.Huus [7].

$^{11}\text{B}(p, p'\gamma)^8\text{Be}$ that have resonances in the several MeV range. These reactions can be advantageous for various reasons including avoiding interfering reactions, however they are not as convenient as the $^{10}\text{B}(p,\alpha\gamma)^7\text{Be}$ reaction because their cross sections are smaller by a factor of $\sim 100$.

$^{11}\text{B}(p,\gamma)^{12}\text{C}$

This reaction has been used in the past for IBA detection of Boron. The cross section for this reaction has is peaked at several resonance energies ($E_r = 163, 675, 1390\text{keV}$). Most notably, the resonant peak at $E_r = 1390\text{keV}$, is very broad (1270 keV width), but has a relatively small cross section even at resonance ($\sigma_r = 0.053mb$). This reaction yields several relatively high energy gammas, $h\nu = 4.43, 12.80$, and $17.23\text{MeV}$ [30]. Its resonance is broad enough that the cross section will be approximately constant over the expected thickness of the boron. This characteristic allows the total
amount of boron to be measured without varying the accelerator’s energy. However, its small cross section combined with the low detection efficiency of high energy gammas makes this reaction more difficult to observe than the $^{10}\text{B}(p, \alpha\gamma)^7\text{Be}$ reaction.

### 5.3.2 X-Ray Production Cross Sections

The X-Ray production interactions that are relevant for PIXE analysis are the result of ionization of tightly bound electrons, and the subsequent radiative atomic transitions that fill the vacancy. Since this mechanism is different from the gamma emission process, PIXE cross sections generally have a considerably different shape and magnitude than the sharply peaked resonant reactions that are common in PIGE analysis. The shape of the X-ray production cross sections is a direct result of the kinematics of particle impact ionization because the radiative transitions do not occur until after ionization takes place. The X-ray production cross section is still considerably different than the ionization cross section for the corresponding electron shell due competing electron transitions and interactions. A number of different cascades of transitions can often occur fill the a single electron vacancy, each yielding different energy photons. For example, a tungsten L ionization can lead to transitions of electrons from the M, N, or O shells (where K is the lowest principal energy level [innermost atomic shell], L is the next higher principle energy level, then M,N,O...).

This tungsten L ionization produces at least three distinct X-ray peaks with different magnitudes which are designated by the shell where ionization took place and the shell where the electron originated that filled the vacancy ($M \rightarrow L \equiv L_\alpha$ or $N \rightarrow L \equiv L_\beta$ and so on). There are also competing interactions that can fill the vacancy. Auger electron emission and Coster-Kronig electron emission often compete with X-ray emission making the total X-ray production considerably lower than the ionization rate [18]. Since X-ray production rates cannot typically be calculated analytically (due to the complexity of the atomic structure and the competing interactions), they are usually determined experimentally or with computational models. Figure 5-2 shows the proton induced X-ray production cross sections for elements that are observed on C-Mod tiles.
Figure 5-2: A plot of relevant cross sections for PIXE analysis of C-Mod tiles: This data is necessary for quantifying tungsten on molybdenum tiles as well as molybdenum on tungsten tiles. See citations for sources of cross section data [19], [4], [25].

5.4 Modeling Ion Beam Interactions With Matter

To extract meaningful information from IBA data, information about the ion beam’s trajectory as it passes through the sample material must be calculated. In particular, for depth profiling, the energy as a function of penetration depth \( x \) must be known. The beam’s trajectory is dependent on several parameters which are interrelated: the atomic densities of the matter’s constituent elements \( n_j(x) \), the incident ion beam energy \( E_b \), and current \( I_b \), and the ion stopping, \( S(E) \equiv -dE/dx \).

The physical situation causes several of these functions to be implicit functions of each other. As the ion beam passes through the material it loses energy at a smooth continuous rate due to small angle scattering off electrons. This slowing down rate is characterized by the stopping \( S(E, \rho_j(x)) \) at a rate that is dependent on the energy of the beam and the density of each atomic species \( j \). Since the densities \( \rho_j \equiv m_j \cdot n_j(x) \)
of the elements that make up the target material are generally functions of position x, the ion stopping $S(x, E)$ of the target material can be calculated using Bragg’s Rule shown in equation 5.3.

$$S(E)_{\text{total}} = \sum_i \left( \frac{1}{\rho} \frac{\partial E}{\partial x} \right)_i \cdot \rho_i$$ (5.3)

The energy of the beam at a depth x depends on the initial energy of the beam $E_b$ on the sample and implicitly depends $S(x, E)$ and is given by the following integral (5.4):

$$E(E_b, n(x)) = E_b - \int_{x(E_b)}^{x} S(x', E(x')) dx'$$ (5.4)

### 5.4.1 Beam Energy Calculations

To study proton induced reactions, it is necessary to determine or predict the energy of the beam as it interacts with the sample. The Tandetron produces an effectively mono-energetic beam with an energy that is set by the operator. The beam however loses energy as it passes through the window (as described in section 4.2.3), the air, and the sample. The energy loss in these regions must be quantified so that the proper beam energy and cross sections can be used to interpret gamma yields.

The energy loss of the beam was calculated numerically using theoretical and experimental proton stopping data. The stopping data for Kapton ($H_{25.64} C_{56.41} N_{5.13} O_{12.8}$) is given in figure 5-3 and the stopping data for dry air ($C_{0.02} O_{21.08} N_{78.43} Ar_{0.47}$) is given by figure 5-4. Using the stopping data for Kapton and dry air, the energy of a proton as a function of its distance traveled can be calculated numerically. The proton energy-trajectories were calculated for several different initial energies and two available Kapton thicknesses. These calculations are shown in figure 5-5 for 7.5$\mu$m (0.3mil) Kapton and figure 5-6 for 12.5$\mu$m (0.5mil) Kapton.
Figure 5-3: A plot of stopping data for protons in Kapton. The theoretical data was calculated using SRIM2008 [38], and the experimental data was provided by E. Rauhala, et al [26].

Figure 5-4: A plot of stopping data for protons in dry air. The data was calculated using SRIM2008 [38]
Figure 5-5: A plot of the calculated energy-trajectories of protons as they pass through 7.5\(\mu m\) (0.3mil) of Kapton (at 0cm) followed by 10cm of Air for 10 different initial beam energies. The vertical section of the curves at position 0 represents the energy loss of the beam in the exit foil and the sloped section represents the energy loss in air.

Figure 5-6: A plot of the calculated energy-trajectories of protons as they pass through 12.5\(\mu m\) (0.5mil) of Kapton (at 0cm) followed by 10cm of Air for 7 different initial beam energies. The vertical section of the curves at position 0 represents the energy loss of the beam in the exit foil and the sloped section represents the energy loss in air.
5.4.2 Calculating Gamma and XRay Yield

As the ion beam passes through the material the gamma yield $Y$ is dependent on the reaction cross section $\sigma(E)$ and can be expressed as an integral over the ion beams range, given by equation 5.5.

$$Y(E_b,n(x)) = \Phi \cdot \int_0^{R(E_b)} n(x)\sigma(E)dx$$

Where $R(E_b)$ is the ion beam range, $\sigma(E)$ is the cross section of the reaction, and $\Phi = \frac{I_b}{eZ_i} \cdot \Delta t$ is the ion fluence which can be expressed in terms of experimental parameters: the beam current $I_b$, time elapsed during exposure $\Delta t$ and the ion charge $eZ_i$.

Since the probability that the reaction will occur is energy dependent, given by the cross section $\sigma(E)$, the yield can be equivalently represented as an integral over the beam particles' energy as they slow down, weighted by the reaction cross section as shown in equation 5.6.

$$Y(E_b,n(x)) = \Phi \cdot \int_{E_b}^{0} \left[ \frac{n(x)\sigma(E)}{-S(x,E)} \right] dE$$

Though equations 5.5 and 5.6 can be used to mathematically describe the gamma yield for PIGE experiments, they generally cannot be integrated analytically. This is because the ion stopping $S(x,E)$ is simultaneously dependent on position $x$ and energy $E$ which are implicit functions of each other. Numerical integration is, therefore, necessary and is described in section 5.6.1.

5.5 Data Processing and Normalization

Proper calibration is necessary because the count rates in these experiments are dependent on a number of factors and experimental parameters some of which can vary in time.
5.5.1 Normalization

Absolute calibration is often not possible because many aspects of IBA experiments such as detection efficiency, losses due to attenuation, and other geometric effects, cannot be easily determined. This issue is further complicated because many of these effects, including detection efficiency, are energy dependent. This makes relative measurements necessary.

When taking measurements, all of the beam parameters are roughly constant except for the beam current due to fluctuations in the ion source. These fluctuations are usually fairly small (< 5%) during a 100 second experiment, but over the course of 10s or 100s of measurements, the beam current can often drift by a factor of two or three. Since the current \( dq/dt \) varies throughout the measurement and the number of reactions is directly proportional to the total number of incident ions \( q/e \), the total charge must be integrated and used to normalize the data. For PIGE measurements, this was done by averaging over multiple Faraday cup measurements, and for PIXE measurements, this was done with a charge digitizer connected to the aperture supporting the beam exit-foil. Since the detectors generally have a small but finite amount of 'dead time' as they are processing each absorbed photon, the charge collected must be scaled so that it reflects the total charge collected by the sample when the detector was active. This is done by multiplying collected charge \( Q \) by the ratio of the detector live time \( \tau \) to the real time \( t \).

The most convenient normalization for both PIGE and PIXE are thick target yield measurements of known sample targets. Since the experimental parameters are the same between the samples and the standard and the composition of each standard is known, dividing the yields from each sample by the yield from the standard will cause the unknown experimental constants to cancel. The normalized yield \( \tilde{Y} \) used for comparing and analyzing data is given by equation 5.7.

\[
\tilde{Y} = \left( \frac{N_1}{Q_1 \cdot \frac{q}{t_1}} \right) / \left( \frac{N_0}{Q_0 \cdot \frac{q}{t_0}} \right)
\]  

(5.7)
5.5.2 Error Analysis

The data collected in IBA experiments are essentially counting measurements where each count is an independent, random event. The random error can therefore, be calculated using Poisson statistics. As such, each measurement of $N$ counts has a standard error of $\sigma = \sqrt{N}$ and each source of error must be added in quadrature [21].

The equation for estimating the measurement uncertainty in the normalized X-ray yields is given in a general form in equation 5.8 where $N_{1,0}$ are numbers of counts, $Q_{1,0}$ are particle fluences, and $x_{1,0}$ are the distances of the samples from the beam window.

$$
\Delta \tilde{Y}^2 = \sum_i \left( \frac{\partial \tilde{Y}}{\partial \alpha_i} \right)^2 \cdot \Delta \alpha_i^2, \quad \alpha_i \equiv \{N_1, N_0, Q_1, Q_0, x_1, x_0\} \quad (5.8)
$$

Since all of the quantities of that contribute to the normalized yield $\tilde{Y}$ have a multiplicative relationship, as given by equation 5.7, it is more convenient to calculate the fractional uncertainty in the form $\Delta \tilde{Y}/\tilde{Y}$. The fractional uncertainty in the number of counts $N$ comes directly from Poisson statistics is proportional to $1/\sqrt{N}$. The largest source of uncertainty (up to 5% but often lower) is the charge $Q_{1,0}$ normalization. This was determined by observing the differences in yields between identical normalizations measurements of Mo tile standards. Another source of uncertainty is positioning of the sample. The precision of the sample positioning can is expected to have an uncertainty of a fraction of a millimeter. Variations in position slightly changes the beam energy which changes the range and the average cross section. If the positioning uncertainty is assumed to be $\Delta x = 0.2\text{mm}$, the contribution of $\Delta x$ is small, but non-trivial. The uncertainties in $t$ and $\tau$ could also be considered, but they are accurate to within a fraction of a percent and are likely to be negligible. The total uncertainty, based the quantities just described, are combined in equation 5.9.
which gives the fractional uncertainty in \( \bar{Y} \).

\[
\frac{\Delta \bar{Y}}{\bar{Y}} = \left[ \frac{1}{N_1} + \frac{1}{N_0} + \left( \frac{\Delta Q_1}{Q_1} \right)^2 + \left( \frac{\Delta Q_0}{Q_0} \right)^2 + \left( \frac{C_z \cdot \Delta x_1}{N_1} \right)^2 + \left( \frac{C_z \cdot \Delta x_0}{N_0} \right)^2 \right]^{1/2}
\]

\[
C_x \equiv \frac{\partial N}{\partial x_{tile}} \approx \left( \frac{dN}{dE} \right) \cdot \left( \frac{dE}{dx} \right)_{air} \approx \left( \frac{n \tilde{\sigma}}{\bar{S}_{Mo}} \right) \cdot \tilde{S}_{air}
\]

5.6 Numerical Methods for PIGE Analysis

5.6.1 Gamma Yield Calculation

To calculate the gamma yield for a specified material density profile, equation 5.5 must be integrated. This expression can be numerically integrated over the position \( x_i \) coordinate using the following method, described by equations 5.11, 5.12, 5.13, and 5.14.

\[
x[i + 1] = x[i] + dx
\]

\[
S[i] = \sum_j \left( \frac{1}{\rho} \frac{\partial E}{\partial x} \right)_j \cdot m_j \cdot n_j[i]
\]

\[
E[i + 1] = E[i] - S[i] \cdot dx
\]

\[
Y_k[i + 1] = Y_k[i] + n_k[i] \cdot \sigma_k(E[i]) \cdot dx
\]

First, the initial beam energy \( E_b \), the cross section \( \sigma(E) \) and the mass density \( \rho_j(x) \equiv m_j \cdot n_j(x) \) of the elements is specified. The stopping power \( S(x, E) \) is dependent on the particles’ energy and the target material so the total stopping \( S[i] \) must be recalculated at every value of \( x_i \), using the tabulated stopping data \( \partial E/\rho \partial x \) [38] for each element in the material (equation 5.12). Next, the energy is calculated using the \( S[i] \) (Equation 5.13). The yield per incident particle \( Y_k[i] \) is calculated for the
cross section \( \sigma_k(E[i]) \) of reaction \( k \) (Equation 5.14).

To show the depth profile dependence of the gamma yield curves, gamma yields for the \(^{10}\text{B}(p, \alpha \gamma)^{7}\text{Be} \) reaction were calculated for boron layers of various thickness and for different profiles. The resulting gamma yield vs. energy curves for square, parabolic and half-Gaussian profiles are shown in figures 5-7, 5-8, and 5-9 respectively. The square profile, or step function, refers to a surface layer of solid B that ends abruptly at the thickness \( \tau \). For parabolic profiles, the functional form for the B depth profiles and their corresponding Mo profiles are given by equation 5.15 and half-Gaussian profiles in equation 5.16. \( \tau_p \) and \( \tau_g \) represent effective thicknesses that correspond B layer having the same total B as an equivalent step function B layer with thickness \( \tau \).

\[
\rho_B(x) = \rho_{B0} \cdot (1 - (x/\tau_p)^2) , \quad \rho_{Mo}(x) = \rho_{Mo0} \cdot (x/\tau_p)^2
\]  
\[
\rho_B(x) = \rho_{B0} \cdot \exp[-(x/\sqrt{2\tau_g})^2] , \quad \rho_{Mo}(x) = \rho_{Mo0} \cdot \exp[-(x/\sqrt{2\tau_g})^2]
\]  

Thick target yields for boron nitride (BN), shown in figure 5-10, were also calculated as a function of energy. BN thick target yields are useful because they can be easily measured experimentally and used as normalization standards. Since significant variation can be observed from the yield curves for different profiles, it is possible to deconvolve real boron profiles from gamma yield measurements.

### 5.6.2 Density Profile Fitting Algorithm for PIGE Data

In experiments, the total gamma yield can be measured for the reaction of interest. The gamma yield is the result of the probability of the reaction integrated over the beam’s range into the material. The yield is a function of beam energy and the density profile \( \rho_i(x) \), so in principle, the density profile can be deconvolved from multiple yield measurements, taken at different energies.

A common method to solve this deconvolution problem is by iteratively solving for a density profile that corresponds to a yield curve that best fits the data [30]. In general, the solutions to this problem are not unique. However, it is possible to
Figure 5-7: Calculated boron yields for boron layers with square (step function) profiles.

Figure 5-8: Calculated boron yields for boron layers with parabolic profiles.
Figure 5-9: Calculated boron yields for boron layers with half-Gaussian profiles.

Figure 5-10: Calculated thick target yield for Boron nitride (BN).
extract a realistic density profile from the data if the proper, physically reasonable boundary conditions, such as positivity, and an upper bound on density are imposed on the fitting algorithm [30].

The fitting algorithm developed for this study uses a constant/half-Gaussian fitting function with two degrees of freedom, $\tau$, $w$ shown in equation 5.17.

$$\rho(x; \tau, w) = \begin{cases} 
\rho_0 & \text{if } x \leq \tau \\
\rho_0 \cdot \exp\left[-\frac{(x-\tau)^2}{2w^2}\right] & \text{if } x > \tau
\end{cases} \quad (5.17)$$

This fitting function is a natural choice for the plasma deposited films. The constant represents the uniform deposition of the film on the surface, and the half-Gaussian represents the diffusion of film into the bulk of the surface.

$$\tau_i = \left\{\left(\tau_{N-1} - \frac{\Delta \tau}{\lambda_n}\right), \ldots, \left(\tau_{N-1} + \frac{\Delta \tau}{\lambda_n}\right)\right\}$$

$$w_j = \left\{\left(w_{N-1} - \frac{\Delta \omega}{\lambda_n}\right), \ldots, \left(w_{N-1} + \frac{\Delta \omega}{\lambda_n}\right)\right\} \quad (5.18)$$

$$\rho_{i,j}(x; \tau, w) = \begin{cases} 
\rho_0 & \text{if } x \leq \tau \\
\rho_0 \cdot \exp\left[-\frac{(x-\tau_j)^2}{2w_j^2}\right] & \text{if } x > \tau
\end{cases} \quad (5.19)$$

$$E(x + dx) = E(x) - \sum_i \rho_i(x) \cdot S_i(E(x)) \cdot dx \quad (5.20)$$

$$Y_{\text{calc}} = \int_0^{x_{\text{max}}} dx \frac{\rho(x)}{A} \sigma(E(x)) \quad (5.21)$$

$$\text{var} = \sum_k f(E_k) \cdot [Y_{\text{exp}}(E_k) - Y_{\text{calc}}(E_k)]^2 \quad (5.22)$$
The fitting algorithm essentially assumes a profile (5.19) with parameters \( \tau_o \) and \( w_o \) and tests points on an interval in the neighborhood of \( \tau_o \) and \( w_o \) in parameter space (5.18). For the next iteration a new interval is chosen that is centered about the parameters that provided the best fit for the data in the last iteration, with the minimum variance (5.22). With each iteration \( n \), the size of the interval decreases by a factor of \( \lambda^n \) allowing the code to converge to a solution.

5.7 Numerical Methods for PIXE Analysis

PIXE cross sections are slowly varying functions of energy above their lower energy threshold, so the analysis of PIXE data is focused on calculating correlation functions that relate measured X-ray yields to elemental concentrations or thicknesses of elemental films. This is done numerically, using similar methods to those for PIGE, described in section 5.6.1. The methods differ in the following two ways. The obvious difference is that X-ray production cross sections are used instead of PIXE cross sections. The second difference is that the attenuation must be accounted for in the calculations since the mean free paths of the X-ray photons are comparable to the beam penetration depths and are on the order of a few \( \mu m \). When attenuation is considered, an extra term is added to equation 5.5, resulting in equation 5.23.

\[
Y(E_b, n(x)) = \Phi \cdot \int_0^{R(E_b)} [n(x)\sigma(E) - \exp (-\mu(x) \cdot x)] \, dx \tag{5.23}
\]

\[
Y(E_b, n(x)) = \Phi \cdot \int_0^{R(E_b)} [n(x \cdot \sec(\theta_i))\sigma(E) - \exp (-\mu(x \cdot \sec(\theta_d)) \cdot x)] \, dx \tag{5.24}
\]

It also must be noted that, since there are 45° angles of incidence and detection, the depth in the material \( x \), and path length of the ions and photons \( x_p \) differ by a factor \( x = x_p \cdot \cos(45^\circ) \). In general, for arbitrary incidence angles \( \theta_i \) and detection angles \( \theta_d \), equation 5.23 should be modified to become equation 5.24. Numerical solutions to this integral equation with varied parameters such as \( n(x) \) and \( E_b \) can give insight
into the relationships between the X-ray yields and the elemental concentrations.

5.7.1 PIXE Sensitivity

X-ray production cross sections vary slowly with energy, so to zeroth order, the detection sensitivity for measuring an impurity should not vary greatly with the impurity depth. This is roughly true, however, the beam slows down in the material which decreases the cross section. In addition, the X-ray attenuation increases at greater depths. Both of these effects lead to a decrease in PIXE detection sensitivity as the depth of the impurity increases. This is important because PFCs in C-Mod are boronized weekly or even daily, so it is likely that at some locations, impurities such as tungsten are embedded layers of boron and be covered by up to several microns of B. This trend is demonstrated by the calculated result shown in figure 5-11 for PIXE detection sensitivity of tungsten embedded in bulk boron. For these calculations, sensitivity $\eta \equiv Y(x)/Y(0)$ is defined as the yield per atom at depth x, normalized to the yield per atom at the surface.

Since thermalized W ions do not penetrate more than a few nm into solid B or Mo, their location remains near the surface at the time of deposition. These deposited particles are subsequently buried in B from boronization. This will cause the PIXE measurements underestimate the quantity of deposited W.

5.7.2 PIXE Correlation Functions

After identifying a peak in the X-ray spectrum, the X-ray yield is obtained by integrating the peak area, subtracting the background, then normalizing to incident ion fluence. Thick target yields are also measured in the same way using pure, known samples. The yield $Y$ measured from unknown surfaces is then be divided by the thick target yield $Y_{tt}$ from the known sample, giving data in the normalized form $Y/Y_{tt}$.

To extract quantitative information from these measurements a correlation function must be calculated to relate the yield $Y/Y_{tt}$ to actual elemental concentrations.
or thicknesses. Since yields and thick target yields can be calculated by numerically solving equation 5.24, correlation functions can be generated by varying n(x). These correlations are essentially thin target yields that are calculated as a function of layer thickness, assuming uniform surface layers of different thicknesses. Correlations for measuring tungsten on molybdenum tiles (5-12), and molybdenum on tungsten tiles (5-13), are shown in the following figures.

Boron can also be estimated indirectly from PIXE measurements even though boron does not produce detectable X-rays. Since the surface films on C-Mod tiles are composed mostly of boron due to the frequent boronization process, the amount of boron on molybdenum tiles is measured from the suppression of the Mo·L X-rays. A correlation function for estimating boron thickness from the normalized Mo·L yield is shown in figure 5-14. Boron is much more difficult on tungsten however, because the L X-ray emission from the tungsten is several times higher in energy than the Mo·L emission and is therefore attenuated much less by the boron.
Figure 5-12: Plots of the tungsten thickness vs. X-ray yield normalized to the thick target yield for the tungsten bombarded with 1.5\textit{MeV} Protons. The figure on the right shows the same calculation as left except zoomed in on the relevant data for typical W thicknesses observed on C-Mod Mo tiles.

Figure 5-13: Plots of the molybdenum thickness vs. X-ray yield normalized to the thick target yield for the Mo bombarded with 1.5\textit{MeV} Protons. The figure on the right shows the same calculation as the left except zoomed in on the relevant data for typical Mo thicknesses observed on C-Mod W tiles.
Figure 5-14: (Left) Plot of the attenuated molybdenum L X-ray yield vs boron thickness for tiles bombarded with 1.5MeV Protons. (Right) A plot of the areal density (related to thickness) of the boron film vs the suppression of the molybdenum L X-ray yield.
Chapter 6

Experiments and Results

6.1 Overview

Refurbishment of the tandem accelerator was completed and the accelerator was used for PIGE and PIXE analyses. Preliminary results from PIGE analysis, described in section 6.3 demonstrated the feasibility of using PIGE for boron depth profiling. A PIGE depth profiling technique was implemented but not to the same degree as PIXE because of hardware availability.

The most complete results were achieved with PIXE analysis. PIXE spectra were measured at 160 poloidal locations on the surface of molybdenum and tungsten divertor tiles. From these spectra, shown in section 6.4.1, the quantities of plasma deposited tungsten, molybdenum, titanium, iron, and chromium were measured directly. Boron was also measured indirectly on molybdenum tiles by inferring the boron thickness from the suppression of the X-ray yield from the bulk Mo under the boron layer. These data were combined to construct poloidal profiles of the net plasma deposition of W, B, Cr, and Fe on Mo tiles and Mo deposition on W tiles.

6.2 Accelerator Performance

The accelerator and cesium sputtering source can now operate continuously and repeatably at or near the design's specifications. Nominal performance recorded in
### Table 6.1: Typical parameters for accelerator operation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable Run Time (1.5 MeV H(^+) beam)</td>
<td>8+ hours</td>
</tr>
<tr>
<td>Typical Vacuum Pressure</td>
<td>5x10^{-7} torr</td>
</tr>
<tr>
<td>Maximum Terminal Voltage(*)</td>
<td>1.4 MV</td>
</tr>
<tr>
<td>Maximum Proton Current</td>
<td>30 (\mu A)</td>
</tr>
<tr>
<td>Maximum Cu(^+) Current</td>
<td>15 (\mu A)</td>
</tr>
</tbody>
</table>

\(*\) The HV terminal supply is designed for 1.7 MV however the \(SF_6\) pressure in the accelerator tank is lower than the design pressure, so extra caution is required at high voltages.

The accelerator log is shown in table 6.2. As of the summer of 2009, the accelerator operates consistently and effectively for IBA. The accelerator was not benchmarked in excess of what was necessary for typical PIGE and PIXE measurements, so the accelerator is not necessarily limited to its demonstrated capabilities in table 6.2.

### 6.3 PIGE Experiment for B detection

#### 6.3.1 Simulation Results

Routine access to a NaI detector was limited, so some of PIGE results in this study are computational. After the implementation of the numerical code for deconvolving boron profiles was complete (described in section 5.6.2), another code was written to simulate data. This was used to determine if the boron profiling algorithm would converge to the correct profile starting from an initial guess that is different from the simulated profile. Data sets were generated for several different profile shapes by numerically integrating equation 5.6 for several beam energies, using the methods described in section 5.4. The energy intervals between simulated data points were chosen to correspond to experimentally achievable sample positioning precision (20 measurements with 1 – 2 \(mm\) spacing). To test for convergence, the initial guess for each profile was chosen to be substantially different from the profile used to generate the data.

The results of these calculations are shown in figures 6-1, 6-2, and 6-3. Figure 6-1 shows the result from a profile that is made up of constant that transitions into a half-
Gaussian (like the fitting function used in the profiling code). In this test the profiling code converged almost perfectly, as should be expected. The fit was close enough that the total calculated boron from the profile (a figure of merit for fit quality) was within 0.02%. Figure 6-2 shows the result from a parabolic profile. A parabola is similar to a Gaussian in the fitting function but has no direct correspondence. The result was therefore less precise than the previous experiment, but was still quite close, with 4.5% error in the total B areal density. Figure 6-3 shows the result from a profile that linearly decreases with depth. This profile is very different the profiling codes fitting function but the convergence is still reasonably good, with 2% error in the total B areal density.

6.3.2 Experimental Results

Preliminary PIGE measurements were made when only samples of molybdenum with thick boron layers were available (B thickness > beam penetration depth). These measurements were taken using the 'in-line' detection geometry shown in figures 4-10 and 4-15 using a 4” × 4” NaI detector. Each sample is placed close to the window and a measurement of the \(^{10}\text{B}(p,\alpha\gamma)^{7}\text{Be}\) gamma peak at 429 keV was made (over a ~ 100s) period. After each measurement the sample was moved back 1mm further from the window until the boron signal became indistinguishable from the background in the spectrum.

The first results are shown in figure 6-4. Four C-Mod tiles and a boron nitride (BN) sample were analyzed. The data indicate that the boron layers are thicker than the penetration depth of the beam because the boron yields continue to increase as the energy increases and no maxima are observed. Since BN is 50% atomic boron and has a higher stopping power than pure B, the B thick target yields from the samples are greater than twice of the yields at of the BN at every data point. This indicates that the surfaces of the tiles have a boron high B fraction.

The data sets from the tiles have a similar shape but do not overlap and vary in magnitude by ~ 20%. This is likely the result of poor current normalization because the source was not running very stably when these measurements were taken,
Figure 6-1: Profiling code results from simulated data with a profile that is a continuous function made up of a constant that transitions into a half-Gaussian. In this test the profiling code converged almost perfectly. (a) Shows the B and Mo profiles used to calculate the 20 simulated data points shown in (b). (c) Shows the resulting B and Mo profiles from the fitting routine, and (d) shows a comparison between the initial B profile to the fit B profile.
Figure 6-2: Profiling code results from simulated data with a profile that is parabolic. (a) Shows the B and Mo profiles used to calculate the 20 simulated data points shown in (b). (c) Shows the resulting B and Mo profiles from the fitting routine, and (d) shows a comparison between the initial B profile to the fit B profile.
Figure 6-3: Profiling code results from simulated data with a profile that is parabolic. 
(a) Shows the B and Mo profiles used to calculate the 20 simulated data points shown in (b). (c) Shows the resulting B and Mo profiles from the fitting routine, and (d) shows a comparison between the initial B profile to the fit B profile.
and the beam current was only measured before and after analysis of each tile (16 measurements). This was insufficient to accurately measure the total proton fluence. Though normalizations are off by an estimated 10 – 20%, within each set of data the measurements maintain an approximately constant ratio between the yield data and the BN yield.

A more recent result is shown in figure 6-5. While installed in C-Mod, this tile was exposed to severe plasma conditions which caused the surface to melt. The boron profile for this tile was interesting because it provides information about the mixing of B with Mo as a result thermal damage. The same basic procedure was used on this tile, except with better normalization techniques. Since a charge digitizer was not available for the high beam current, the proton fluence was determined by measuring the current before and after each measurement at each position, with a digital nano-ammeter. In addition, a normalization measurement was made with a thin (∼ 200\(\mu\)m) slice of BN in front of the analyzed face of the tile at the minimum distance from the window (10mm), corresponding to the maximum energy (\(E_b = 1.68\ MeV\)) used in this experiment. The data was then normalized to this BN thick target yield. Having this direct normalization to a BN thick target yield (measured from the same detection geometry as the experiment) allowed the data to be compared to a calculated yield curve with same normalization.

A comparison between the experimental data and the expected yield from a pure B layer is shown in figure 6-5. In the second plot in figure 6-5, the experimental data are shown with a calculated yield curve which assumes a thick layer of pure boron and uses the same normalization as in the experiment. The shape of the experimental data roughly matches the calculated shape, however the yields are significantly lower than the expected yield from pure B. This would suggest that the boron concentration in the tile surface is lower than pure boron.

Since an absolute beam energy calibration was not performed, there could also be some systematic error in the yield which could contribute to the offset between the curves. An example of this effect is shown by the \(\Delta E_o = \pm 5\%\) curves on second plot in figure
Since the B concentration appears to increase with depth, the fitting function used in the depth profiling algorithm described in section 5.6.2 cannot effectively match the data. However, information about the depth profile can be observed if the measured yield data are normalized to the expected yield from pure B (shown in the third plot in figure 6-5). This normalized yield data approximately represents the atomic fraction of boron at a depth that is related to the energy of the beam at the surface. From this data, it appears that tile has a B profile that increases with depth with an average boron fraction of \( \sim 70\% \) over the depths that were observed.

Since the cross section for \( ^{10}\text{B}(p, \alpha\gamma)^{7}\text{Be} \) is small when the beam energy is below 1 MeV, a measure of the effective penetration depth was calculated. The effective penetration was defined as the distance that the protons travel before slowing down to 1 MeV (assuming 70% B, 30% Mo). The yield data are plotted as a function of effective penetration depth in figure 6-6. Also shown is a plot of the \( ^{10}\text{B}(p, \alpha\gamma)^{7}\text{Be} \) cross section \( \sigma(x) \) as a function of depth for incident beam energies corresponding to energy used for each data point. The normalized yield vs. penetration depth is not explicitly a depth profile, however it represents a more complicated relationship between B concentration and B depth. Since the cross section curves \( \sigma(x) \) give the B detection sensitivity for each data point, in principle, a B concentration vs. depth profile can be deconvolved from the yield data.

6.4 PIXE Experiment

6.4.1 Spectra

The PIXE X-Ray Spectra were measured using a model LS60148 Lithium drifted Silicon detector Si(Li) from Princeton Gamma Tech and a PC with a multichannel analyzer for data acquisition. A beam of 1.5 MeV protons was used to induce X-ray emission from the tile surface. A 1.5 MeV proton beam (energy at the tile surface) was chosen because it has sufficiently high energy that the protons will penetrate \( \sim 5 \) \( \mu \text{m} \) into the surface before slowing down below the threshold energies of the relevant
Figure 6-4: Preliminary PIGE profiling data from C-Mod tiles with thick boron coatings and data from a boron nitride standard. Qualitatively, these data sets are consistent with the expected results from tiles with thick isotropic B layers.
Figure 6-5: Preliminary PIGE depth profiling data from a thermally damaged molybdenum C-Mod tile: The first plot shows the count rate data vs. the distance the beam travels through the air. The second plot shows the yield data vs. the predicted energy of the beam at the tile surface. This set of data is compared to the gamma yield curve calculated for pure B. The lower plot shows the experimental data normalized to the expected yield from pure B vs. the calculated energy of the beam at the tile surface. This provides an approximate measure of the B atomic fraction which varies with depth.
Figure 6-6: Analysis of a thermally damaged molybdenum C-Mod tile: The first plot shows the experimental data normalized to the expected thick target yield for pure boron. The effective penetration depth refers to the depth that the protons penetrate before the reaction cross section becomes small ($E < 1 \, MeV$). This does not directly show the depth profile but represents a relationship between the B concentration and depth. The second plot shows the PIGE cross section as a function of depth corresponding to the beam energy for each of the data points. These curves can be used to deconvolve the B depth profile from the data. (The cross section $\sigma(x)$ for the lowest penetration depth is on the lower left and the highest is on the right).
PIXE cross sections (shown in figure 5-2).

The spectra were measured at a total of 160 locations. The measurements were done in three groups corresponding to their locations in the lower divertor, shown in figure 6-7: the inner divertor tiles, the EF1 tiles (typically located in the plasma private flux region), and the outer divertor tiles. The spectra from each section are plotted in figures 6-8, 6-9, and 6-10. These plots contain the spectra from each spacial location and are plotted in an overlapping fashion by section. The vertical lines correspond to the characteristic X-ray transition energies for several relevant elements. These transition energies were acquired from measured and calculated data from the NIST physical reference data [17].

![Diagram of PIXE analyzed tiles](image)

Figure 6-7: A map highlighting the locations of the PIXE analyzed tiles in the lower C-Mod divertor: inner divertor region, EF1 region, and outer divertor region. The distances in \textit{mm} refer to position axes used in the plots of the PIXE data to indicate the locations of the measurements.

### 6.4.2 PIXE Yields

The spectra shown in section 6.4.1 were analyzed by summing the counts in each peaks and subtracting the background using the techniques described in section 5.5. The background subtracted yields from each peak were then normalized to the ion
charge collected during the measurement and normalized to the measured thick target yields from known samples (molybdenum TZM alloy, pure tungsten, and 316 stainless steel). These normalized yields \(Y/Y_t\) are useful because they can be correlated with net deposition of various elements. The calculation of these correlations are shown in section 5.7.2.

Distinct peaks from various elements can be identified in the spectra. The largest peak on all of the Mo samples is the molybdenum L peak which is used to calculate the boron deposition. Titanium is observed from plasma deposition and is present in 0.5 percent atomic fraction in the TZM molybdenum alloy that makes up the bulk of the tiles. A considerable amount of Chromium, Iron, and Nickel were also observed which likely originated from stainless steel components in C-Mod, such as the vacuum vessel. The X-ray yields for these elements are shown in figures 6-12, 6-13, and 6-14.

**Tungsten Measurement**

The measurement of tungsten deposition is a very important result because it both indicates the redistribution patterns of eroded W and provides a lower bound on the net tungsten erosion from the single row of W tiles. Three X-ray transitions from tungsten can be detected with the Si(Li) detector: the \(L_\alpha\), \(L_\beta\), and \(L_\gamma\). Of these transitions, only the first two produce sufficient counts to quantify tungsten deposition because \(L_\gamma\) yield is often near or below the the detection threshold. The \(L_\alpha\) yield is several times higher than the \(L_\beta\) yield which is several times higher than the \(L_\gamma\) yield. The \(L_\alpha\) would be ideal for measuring tungsten, if other impurities were not present. Unfortunately, Nickel is present from stainless steel, and Copper also appears to be present from other components in C-Mod, so the \(W \cdot L_\alpha\) yield is combined with the competing \(Ni \cdot K_\beta\) and \(Cu \cdot K_\alpha\) emission. Even if the \(Ni \cdot K_\beta\) reaction is subtracted from the \(W \cdot L_\alpha\) based on its expected yield from 316 stainless steel (inferred from \(Fe \cdot K_\alpha\)), there is still a measurable number of counts that originate from competing reactions. It is therefore important also to consider the \(L_\beta\) X-rays. Profiles of the net tungsten deposition as indicated by the \(W \cdot L_\alpha\) and \(W \cdot L_\beta\) emission are plotted in figures 6-15, 6-16, and 6-17. These measurements assume that the deposited material
### Areal Density Conversions

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass [amu]</th>
<th>Density [g/cm²]</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boron</td>
<td>10.2</td>
<td>2.34</td>
<td>$1 \text{nm} = 1.30 \cdot 10^{20} [m^{-2}]$</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>10.28</td>
<td>95.94</td>
<td>$1 \text{nm} = 6.45 \cdot 10^{19} [m^{-2}]$</td>
</tr>
<tr>
<td>Tungsten</td>
<td>19.25</td>
<td>183.84</td>
<td>$1 \text{nm} = 6.31 \cdot 10^{19} [m^{-2}]$</td>
</tr>
</tbody>
</table>

Table 6.2: This provides conversion factors relating layer thickness to areal density, assuming that B, Mo, and W form uniform layers with their expected elemental solid density.

Form uniform layers on the surface so they can be represented as effective thicknesses in [m] or as areal densities [atoms/m²]. Some conversions for relating thickness to areal density are provided in table 6.4.2.

#### Molybdenum Measurement

Since W deposition is observed on Mo tiles in the divertor, it is interesting to also measure the Mo deposition on the W tiles. Two W tiles exposed to one experimental campaign were available and were analyzed producing the spectra shown in figure 6-11. The spectra show that the $Mo \cdot L$ peak has a considerable amount of overlap the $W \cdot M_\alpha$ and $W \cdot M_\beta$ peaks on either side. Conveniently, the $W \cdot M_\alpha$ and $W \cdot M_\beta$ peaks are nearly identical for all of the spectra including the pure W sample. This made the background subtraction straightforward because the interfering peaks could be measured directly by subtracting the pure W spectrum. The correlation described in section 5.7.2 was applied yields measured from these spectra to give poloidal profiles of Mo deposition on the two W tiles, shown in figure 6-18.

#### Boron Measurement

Due to deposition from the boronization process, boron makes up the vast majority of the surface deposition in C-Mod. The boron decreases the beam energy and attenuates the emitted X-rays, resulting in a decrease in the Mo-L Yield. The amount boron deposition can be inferred from the suppression of $Mo \cdot L$ Yield using the correlation described in section 5.7.2. The results from the boron measurements are shown in figures 6-15, 6-16, and 6-17. Boron measurement is more difficult on the W tiles.
The W tile spectra, shown in figure 6-11, also demonstrate that there is no significant attenuation of the \( W \cdot L_\alpha \), \( W \cdot L_\beta \), and \( W \cdot L_\gamma \) peaks due to the boron on the surface. As such, it appears that boron that deposited on the W tiles is insufficient for PIXE detection.

### 6.4.3 Detection Limits

The minimum detection limits for tungsten depend strongly on the presence of other impurities. PIXE is extremely sensitive to tungsten, so on a surface with minimal impurities, as little as 1 \( nm \) of W can be detected. However, if there is a significant amount of Fe, Cr, and Ni on the surface, there is greater background noise within the energy range of the W peaks, causing the minimum detection limit to increase to \( \sim 10 \, nm \).

The PIXE measurements of boron on molybdenum are made indirectly by observing the suppression of the X-ray emission from Mo. The emission from Mo can be suppressed by any other impurity that is deposited on the surface, however the analysis assumes that only B exists on the surfaces because B makes up vast majority of the deposition. Since proton energy loss due to B relatively small, indirect PIXE measurements are relatively insensitive to B. From the empirical results, the minimum detectable B thickness was shown to be \( \sim 1\mu m \).
Figure 6-8: 1.5 MeV Proton PIXE Spectra from inner divertor Tiles, annotated with characteristic X-Ray data from NIST [17].

Figure 6-9: 1.5 MeV Proton PIXE Spectra from EF1 divertor tiles, annotated with characteristic X-Ray data from NIST [17].
Figure 6-10: 1.5 MeV Proton PIXE spectra from outer divertor molybdenum tiles, annotated with characteristic X-Ray data from NIST [17]

Figure 6-11: 1.5 MeV Proton PIXE spectra from two outer divertor tungsten tiles, annotated with characteristic X-Ray data from NIST [17]
Figure 6-12: Normalized X-ray yields from the inner divertor, for various elements identified on the spectra. The yields are plotted vs. the spacial location of the measurement. 0mm corresponds to the top of the inner divertor and 250mm corresponds to the bottom where the inner divertor meets the top of the divertor dome. The vertical lines represent the location of the tile edges and the colors represent the different regions of the tiles surfaces. Refer to figure 6-7 for the location of these samples.
Figure 6-13: Normalized X-ray yields from the divertor dome (EF1 tiles), for various elements identified on the spectra. The yields are plotted vs. the spatial location of the measurement. 0mm corresponds to the edge of the tile top of the inner divertor and 200mm corresponds to the bottom where the inner divertor dome meets the divertor floor. The vertical lines represent the location of the tile edges. Refer to figure 6-7 for the location of these samples.
Figure 6-14: Normalized X-ray yields from the outer divertor for various elements identified on the spectra. The yields are plotted vs. the spacial location of the measurement. 0mm corresponds lower edge of the outer divertor and 300mm corresponds to the bottom where the inner divertor dome meets the divertor floor. The vertical lines represent the location of the tile edges. Refer to figure 6-7 for the location of these samples. Refer to figure 6-7 for the location of these samples.
Figure 6-15: PIXE measurements of tungsten and boron deposition on the inner divertor tiles: The correlations described in section 5.7.2 were applied to the $W \cdot L_\alpha$, $W \cdot L_\beta$, and $Mo \cdot L$ X-ray emission data shown in figure 6-12 to generate poloidal profiles of the effective thickness of W and B vs. spacial location. Refer to figure 6-7 for the location of these samples.
Poloidal Profile of Tungsten and Boron Deposition on the EF1 Divertor Dome Tiles

Figure 6-16: PIXE measurements of tungsten and boron deposition on the EF1 divertor dome tiles: The correlations described in section 5.7.2 were applied to the $W \cdot L_\alpha$, $W \cdot L_\beta$, and $Mo \cdot L$ X-ray emission data shown in figure 6-13 to generate poloidal profiles of the effective thickness of W and B vs. spacial location. Refer to figure 6-7 for the location of these samples.
Figure 6-17: PIXE measurements of tungsten and boron deposition on the outer divertor tiles: The correlations described in section 5.7.2 were applied to the \( W \cdot L_\alpha \), \( W \cdot L_\beta \), and \( Mo \cdot L \) X-ray emission data shown in figure 6-14 to generate poloidal profiles of the effective thickness of W and B vs. spatial location. Refer to figure 6-7 for the location of these samples.
Figure 6-18: PIXE measurements of molybdenum deposition on two tungsten outer divertor tiles: The correlations described in section 5.7.2 were applied to the Mo-L X-ray emission spectra shown in figure 6-11 to generate poloidal profiles of the effective thickness of Mo vs. spacial location.
Chapter 7

Discussion and Conclusions

7.1 Discussion of PIGE Boron Measurements

In the PIGE profiling experiments, the boron measurements were successful. The simulated data, described in figures 6-1, 6-2, and 6-3 was used to verify the profiling code and showed promising results. The profiling code was able fit the simulated profiles to within several percent error. This means that if sufficiently accurate and properly normalized PIGE measurements are made, the depth profiling code can extract depth profiles. Though the PIGE profiling data is limited, the results closely resemble the results expected for deposition of thick boron layers. The first sets of preliminary data are shown in figure 6-4. These data were not properly normalized to the collected charge (±10 – 20%) so they did not overlap each other, however the yields for the tiles were greater than twice the yields from the BN which would be expected from a B layer because BN is 50% boron and causes the beam greater energy loss than B. In addition, each of these sets of measurements maintain an approximately constant ratio with the yield from BN. This result indicates that these tiles have isotropic layers of B that are thicker than the beam penetration depth.

A thermally damaged C-Mod molybdenum tile was also analyzed and yielded several interesting results. The surface of this tile was darkened and showed small ripples resulting from surface melting. A comparison of experimental data to the numerical models, shown in figure 6-5 and 6-6 show that the measured boron yields
were consistently lower than the calculated yield for pure B by \( \sim 30\% \). At lower end of the energy range, the measured B yield deviates even further from the than the calculated yield. This suggests that the boron concentration is low near the surface and increases with depth.

This result shows that the profile is anisotropic and demonstrates that information about the profile can be observed. The boron profiling algorithm, described in section 5.6.2, must be modified to accommodate such a profile because the algorithm assumes that the profile is a half-Gaussian and/or a constant function, neither of which can accurately fit a profile that increases with depth. These data however, still contain useful information about the relationship between B concentration and the B depth which, in principle can be deconvolved to determine a depth profile. Further study of tiles like this could have applications in studying how B and Mo mix on PFC surfaces when tiles are thermally damaged by the plasma.

The observation of both isotropic and anisotropic boron layers demonstrates that PIGE analysis is a viable method for diagnosing boron profiles. With further development of the profiling code and the implementation of absolute energy calibration methods, this technique has potential for being an effective and accurate method of boron depth profiling with an external beam.

### 7.2 Discussion of Tungsten Results

Tungsten migration due to erosion of W at the outer strike point has important implications for high Z impurity transport. The tungsten that is deposited in the divertor originates from a toroidally continuous row of tiles at one poloidal location in a high erosion region of the outer divertor. This effectively creates a toroidally symmetric tungsten source. Symmetry simplifies the analysis to two dimensions, allowing predictions to be made regarding the mechanisms that cause W migration.
7.2.1 Possible Mechanisms for Tungsten Transport

Tungsten is sputtered from the W tiles by plasma particles from the scrape off layer (SOL) which have temperatures of $> 10eV$. Though the vast majority of the particles in the SOL are deuterons $D^+$, they cannot contribute to sputtering because their energies are lower than the tungsten sputtering threshold due to their low mass relative. In addition to $D^+$, there is a considerable amount of boron, $B^{+1,+2}$... which is a major cause of W and Mo sputtering [23]. This W sputtering leads to redopisition which was studied using PIXE analysis. To summarize the results, a poloidal map of tungsten migration was created from all of the combined data and is shown in figure 7-2.

Outer Divertor

The largest deposition of tungsten was observed on two tiles directly below the tungsten tile. There was no detectable deposition more than $\sim 5$ mm above the W tile. This is likely the result of the geometric relationship between the flux surfaces and the outer divertor tiles. Since W sputtered at nearly any angle from the W surface has only line-of-sight access to flux surfaces that intercept poloidal locations below the point of sputtering, a large amount of the sputtered W will move downward. An illustration of this process is shown in figure 7-2. This process leads to a net downward transport of material along the outer divertor.

Net deposition of Mo is also observed on the W tile, as shown in 6-18. In addition, the trends in the deposition pattern match between the W tiles and the adjacent Mo tiles. The Mo deposition on the W tiles increases from the top of the tile to the bottom, then W deposition on the Mo continues to increase with a similar trend before reaching its peak near the bottom of the outer divertor. Since there appears to be a net transport of PFC material in the downward direction, it would seem that the highest Mo deposition should be towards the top of the W tile, which however, is not the case. This evidence would suggest that the erosion rate could be higher, on average, toward the top of the W tile, possibly due to the average location of
Figure 7-1: A complete map of tungsten migration in the C-Mod divertor summarizing of the PIXE tungsten measurements. Note: $10^{20} \text{atoms/m}^2$ of tungsten areal density is equivalent to 1.58\text{nm} of effective thickness.

The asymmetry in the Mo deposition on the edges of the W tiles is also interesting to note. Since the transport of material is mostly in the downward direction due to the geometry of the flux surfaces, it is more likely that Mo ions will gyrate into the gap above the W tile as it moves down along the flux surface. Whereas, it is less likely for a Mo ion to gyrate into the the gap below the W tile because the surface of the Mo ion can only make a fraction of it gyro orbit before it collides with the surface of the tile from which it was sputtered. This would explain the asymmetry in the
edge measurements.

Figure 7-2: Illustration of W redeposition on the outer divertor: When W is sputtered by incoming low Z ions from the SOL, it is highly probable that it will be re-ionized on a flux surface that intercepts a PFC surface below the sputtering location. The W follows this flux surface to the location of its deposition.

**Divertor Dome**

The divertor dome refers to the shelf-like structure that covers the EF1 coil. This part of the divertor is exposed almost entirely to a relatively cold plasma from the private flux region that is confined to flux surfaces that are outside of the separatrix. Unlike the SOL, these flux surfaces are not directly heated by the core plasma, so this region is colder \((T \sim 1eV)\) than the SOL and is referred to as the private flux region [3].

There are two distinct locations where tungsten is deposited on the divertor dome within the private flux region. A small amount of deposition is observed on the lower
half of the vertical surface and a larger amount is observed on the horizontal surface, close to the inner wall.

Figure 7-3: Illustration of W transport in the private flux region: tungsten is deposited on two regions of the divertor dome. The neutral W pass through the plasma and are deposited on the vertical surface of the divertor dome and W that is ionized in the private flux region is transported to the horizontal surface.

The deposition on the vertical surface is likely the result of sputtered neutral W particles that pass through the plasma and directly cross the gap between the outer divertor and the divertor dome. The upper half of the vertical surface of the dome subtends most of the sputtering solid angle. The deposition however, is nearly zero towards the top of this surface and increases toward the bottom. This could be the result of the angular variation in W ionization mean free path due to the flux surface geometry. For example, as shown in figure 7-4, W that is sputtered in at an upward angle travels a longer distance through hotter plasma in the common flux side of the separatrix than does a W particle that was sputtered at a downward angle.

There is a larger amount of deposition observed on the horizontal surface of the dome towards the inner wall which is the result of a different transport mechanism. This deposition likely results from W that is ionized within the private flux region,
Figure 7-4: Illustration of angular dependence of sputtered particles’ path-length through the SOL: A particle sputtered in a downward direction, travels a shorter distance, \( L_1 \), through the SOL than does a particle that is sputtered in the upward direction. Since \( L_1 < L_2 \), the ionization probability of a downward sputtered particle is lower, so it is more likely to reach the divertor dome.

as shown in 7-3. The sputtered neutral W particles that pass far enough through the plasma to cross the separatrix before being ionized will be free to migrate along the private flux surfaces to the top of the the divertor dome. This process could also be promoted by the \( E \times B \) drift as shown in the figure 7-5. In addition, the temperature gradient may cause a radial drift of particles across the separatrix, into the private flux region, further enhancing the deposition in the private flux region [3].

Since the plasma temperature is higher in the SOL and tends to be much lower in the private flux region, the temperature gradient creates a radial E-field due to the plasma potential gradient \( \sim \nabla T_e \). The radial E-field \( E_r \) and the toroidal B-field \( B_\phi \) cause a guiding center drift along the private flux surfaces in the poloidal direction toward the inner wall.
Figure 7-5: Illustration of the $E \times B$ drift in the private flux region: The Radial E-Field $E_r$, due to the temperature gradient, combined with the toroidal B-Field $B_\phi$ create the conditions for the ions to have a guiding center drift velocity $V_d$ along the private flux surfaces, moving them away from the outer divertor. This may lead to enhanced W transport and deposition on top of the divertor dome and on the inner divertor.

**Inner Divertor**

A large amount of tungsten is observed on the inner divertor. This W is concentrated on the lowest two tiles. This deposition is located near the inner divertor strike point, and may be the result of several processes. If the strikepoint frequently moves up above the these lower tiles, transport in the private flux region, as described in the previous section and in figure 7-5, would cause significant contributions to the deposition seen on the inner divertor. As shown in figure 7-6, it is also possible that some of the W that was eroded at the outer divertor and is either transported along the SOL around the outside of the plasma or diffuses out of the core plasma to be deposited at the inner divertor strikepoint. Both of these mechanisms are possible and depend on the strikepoint history. However, since tungsten has been consistently negligible in the core plasma, it is more likely that transport through the private flux region is the dominant source for deposition on the inner divertor.
7.2.2 Network Tungsten Erosion

From the tungsten deposition profile an estimate was made for the net tungsten erosion, $\Delta W$, assuming toroidal symmetry. This was done by summing the measured tungsten areal density, $\Phi_i$, and its corresponding area, $\delta A_i$, and then dividing it by the total area of the tungsten tile $A_w$ surface.

$$\Delta W \equiv \frac{\sum (\Phi_i \cdot \delta A_i)}{A_w}$$

$$\Delta W_{measured} = 58 \pm 3 \text{ nm}$$

With this method, shown in equation 7.1, the net tungsten erosion averaged over the surface is $58 \pm 3 \text{nm}$. This result represents a lower bound on the net tungsten erosion because it is possible that tungsten was transported elsewhere in C-Mod or was embedded deeper in the boron on the surface than was assumed in the analysis of the PIXE data. Since either of these effects would make the measurement lower than the actual net erosion, the real erosion must be equal to or greater than $58 \pm 3 \text{nm}$. 
Since this erosion is the result of 2000–3000 plasma shots, this net erosion corresponds to an erosion rate of roughly 0.02 – 0.03nm/s.

In a previous study by Wampler et al. [34] a net erosion of ~ 100nm of molybdenum was measured at the same poloidal location as the current position of the W tiles. This measurement was from a 1090 shot campaign, meaning that the equivalent Mo erosion rates is roughly 0.09 – 0.1nm/s. This shows that the erosion rate for tungsten appears to be several times lower than the erosion rates for molybdenum. This seems reasonable since W has a considerably lower sputtering yield than Mo, as shown in figure 7-7.

![Boron Sputtering Yields for Tungsten and Molybdenum](image)

Figure 7-7: Sputtering yields for boron ions incident on solid molybdenum and tungsten.

### 7.3 Discussion of PIXE Boron Measurements

Boron was also measured indirectly from the PIXE data. These results are shown in figures 6-15, 6-16, and 6-17. These measurements show interesting poloidal profiles of boron deposition which are consistent with physical intuition and appear to match trends that can be seen by visual inspection.

The inner divertor tiles are not toroidally uniform and are shaped to prevent
plasma erosion of the bolt holes where the tiles are fastened. The shape of these tiles are shown in figure 7-8. The boron deposition on surface (1) is significantly higher than the other two surfaces. Since this region protrudes the furthest into the plasma, it intercepts the highest particle fluxes. The boron in this region is higher than the other two regions and appears to be the result of deposition from B in the C-Mod plasma rather than directly from boronization. This would explain the lower net deposition on regions (2) and (3).

In regions where net plasma erosion and deposition are generally low, such as the middle of the divertor dome and the upper half of the outer divertor, the boron profile is reasonably constant around 2\mu m. This is likely from boron that accumulated from many boronizations.

It is also interesting to note that, at all of the regions where net W deposition is observed, boron is also observed with a similar profile, especially on the outer divertor and on the divertor dome. This would suggest that low-Z migration is caused by the same mechanisms as high-Z migration. This observation was also seen in a study by Y. Ueda, et al. [37].

7.4 Discussion of Deposition of Other Impurities

Titanium, Chromium, and Iron are also observed on many of the tiles. The Cr and Fe likely originates from stainless steel components such as the C-Mod vacuum
vessel and the Ti originates mostly from the Mo tiles which are made from the TZM alloy containing \( \sim 0.5\% \) Ti. In regions where net deposition of tungsten is observed, substantial deposition of Ti, Cr, and Fe are also observed. For tiles in regions of net erosion and in regions that do not experience significant erosion or deposition, there is little to no deposition of Cr and Fe. The Ti observed in these regions is nearly constant and is consistent with the measurements of the known TZM sample. These results suggest that the processes that cause the redeposition of W have a similar effect on lower-Z impurities that are present in the plasma.

7.5 Conclusions

The PIGE results have demonstrated the feasibility of profiling boron by means of varying the path-length of an external beam to gain spacial resolution. This technique requires further refinement, but has the potential to be a successful PIGE profiling technique. The technique could be improved by finding better methods for current integration and energy calibration. The analysis could also be improved by implementing more advanced fitting algorithms, such as stochastic methods, which are not constrained to specific fitting functions.

PIXE proved to be a very effective method for measuring trace amounts of tungsten deposition on PFCs. These measurements made it possible to observe campaign integrated tungsten migration. More in-depth analysis of the campaign averaged plasma conditions leading to these surface patterns will provide a more complete understanding of the of the data and will allow for more definite and conclusive explanations for the experimental observations.
Bibliography


