

Lithium PFC Characterization and Plasma Performance for LTX-beta

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Degree

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dedicated to my mother.

Acknowledgments

For the past few years everytime I was forced to think of finishing up, the phrase "hanuz dilli door ast"¹ would come to mind. The phrase was used by the 14th century poet Nizamuddin Auliya as a reply to a threat of execution sent by the Sultan of Delhi at the time, Ghyasuddin Tughlaq (while on a campaign in Bengal). Tughlaq lost his life in an accident on the way back, and was unable to carry his threat. I was afraid my thesis would meet the same fate as Tughlaq. Unlike Tughlaq however, my thesis had a lot of help.

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¹Old Persian - Literal translation, "Delhi is far away", often used to denote an unattainable goal.

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to wake up early the next day and go to work with a sense of purpose. I am grateful that theres two of us now.

Abstract

Lithium coatings on high-Z plasma facing components (PFCs) in the Lithium Tokamak eXperiment (LTX) led to flat temperature profiles. The flat temperature profiles were observed along with a hot low density edge, implying a broad, collisionless Scrape-Off Layer (SOL). Additionally, in-vacuo analysis of PFCs indicated that evaporatively deposited lithium coatings appeared to be oxidized, while the ability to achieve good plasma performance was retained. Theory attributes flat temperature profiles to low recycling walls, which was assumed to be due to hydrogen binding with elemental lithium to form lithium hydride. The presence of oxidized lithium, however, raises questions regarding the exact mechanism of hydrogen retention in LTX. To investigate these questions, a new Sample Exposure Probe (SEP) for detailed in-vacuo analysis of PFC samples was designed and commissioned for LTX- β . The SEP is equipped with a vacuum suitcase capable of transporting samples representative of LTX- β outer mid-plane PFCs under high vacuum to a stand-alone high resolution XPS system. Surface analysis using the SEP was performed with sufficient energy resolution to identify for the first time, the compounds that grow on evaporative lithium coatings inside a tokamak. This was the first demonstration that a vacuum suitcase can afford a solution that is simpler in design and affords more flexibility than building material characterization test stands for installation on a tokamak. The results indicate that Li_2O and LiOH are prime surface constituents of Li PFCs. Their presence substantiates the hypothesis that lithium oxide grows on elemental lithium before the growth transitions to lithium hydroxide for LTX- β like vacuum conditions. It is further indicated that Li_2O improves plasma performance in comparison to LiOH by both sequestering oxygen and increasing hydrogen retention.

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Chapter 1

Introduction

It is easy to make the case for more energy supply. There seems to be an undeniable link between human development index and modern energy consumed per capita; modern energy is energy from sources other than biomass [17]. It is also undeniable that the global energy demand has increased sharply over the last two hundred years (figure 1.1). Current estimates of global energy consumption [1] show that most of this demand is fed by coal, oil and natural gas today. In recent years, the demand for more energy has increased because of growth in developing countries that aspire to higher energy security. This is driven by the fact that most of the problems facing developing and under-developed economies, beginning from poverty to food or water scarcity and affordable healthcare, have energy solutions.

Electricity utilities classify the power they supply to grids in base and peak load. Base load is the minimum power being demanded by consumers over a 24 hour cycle, and peak load is the power demand over and above the base load. The present sources of energy that supply the base load requirements are non-sustainable, and will further aggravate the global warming problem if continued to be used. These need to be replaced by sources that are carbon neutral and can run continuously. Of all the various possible options, fusion is probably the most attractive because of abundant fuel reserves, low environmental impact and ability to supply base load. Assuming a deuterium-tritium (D-T) fuel cycle, fusion fuel reserves are bound by the availability of Li^6 which will be used to breed tritium. For fusion to provide energy at world consumption levels for the early twenty-first century, the known amount of Li^6 is projected to last somewhere around 20,000 years [2].

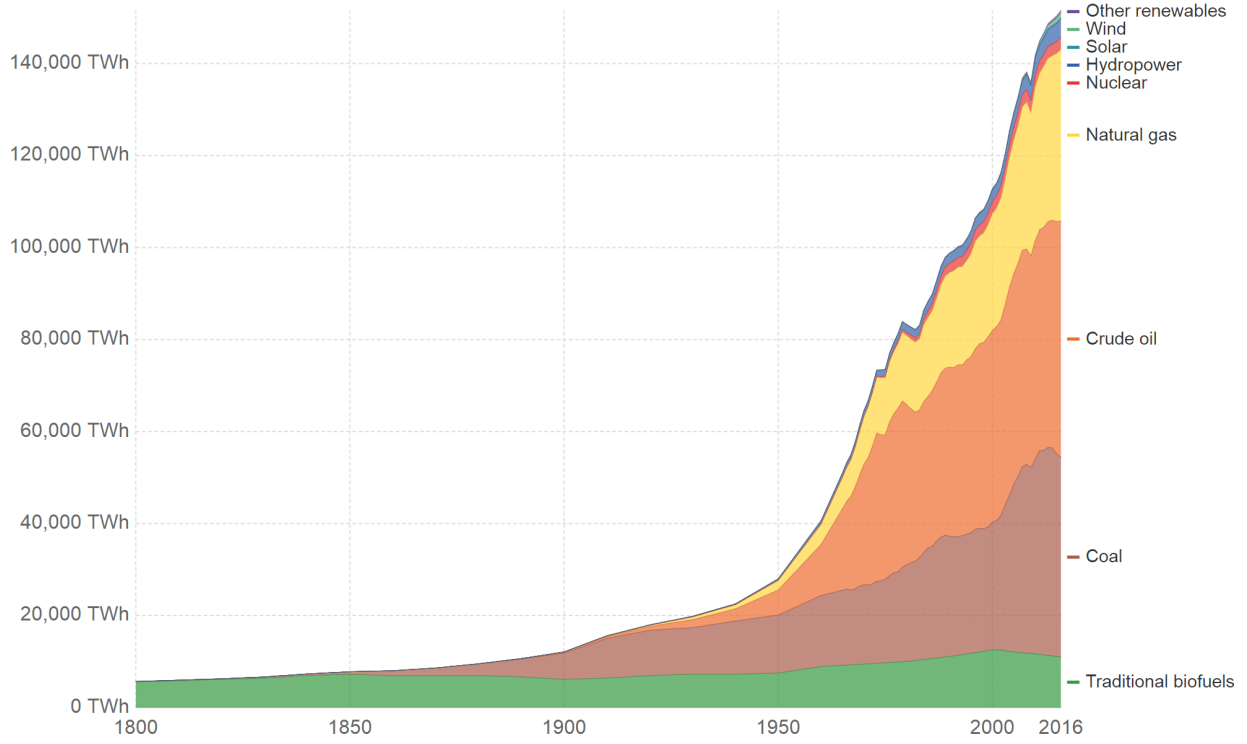


Figure 1.1: Sources of global energy consumption with time (in years) [1]

The fusion energy gain ratio (Q), defined as fusion power to input power, needs to be greater than 1 for a fusion energy source to be feasible, and closer to 100 for it to be practical. A figure of merit used to compare designs, called the triple product has the following constraint for $Q > 10$ (eqn 1.1) [18].

$$nk_bT\tau_E > 3 \times 10^{21} m^{-3} keVs \quad (1.1)$$

Here, τ_E is the energy confinement time, n is the plasma density, and k_bT is the plasma temperature in keV . The energy confinement time is further defined as the rate at which the confined plasma loses energy due to various processes. So the general problem is to confine a plasma hot enough to overcome coulomb repulsion for long enough times, such that the energy generated from fusion is more than the energy used to heat and confine the plasma. Of the various possible confinement schemes, the two most popular candidates are Inertial Confinement Fusion (ICF) and Magnetic Confinement Fusion (MCF). Among MCF concepts, the tokamak is the most likely candidate to achieve fusion relevant conditions because of its

physics performance, and the fact that it has achieved the highest triple product to date [2, 18] of around $1.6 \times 10^{21} m^{-3} keVs$ by JT-60, Japan followed closely by JET, EU.

1.1 Tokamak

The general idea of magnetic confinement is that the motion of charged particles is constrained perpendicular to a time invariant uniform magnetic field and unconstrained parallel to it. If however, the magnetic field is slowly¹ varying, the perpendicular energy (relative to the field) of a charged particle changes with a corresponding change in the magnetic field. This leads to the first adiabatic invariant in plasma physics (eqn 1.2), also known as the magnetic moment, averaged over a gyro period [2].

$$\mu = \frac{mv_{\perp}^2(t)}{2B(t)} \quad (1.2)$$

The first MCF based design was the magnetic mirror also known as mirror machine (figure 1.2(a,b)). As charged particles move (in the z-direction, figure 1.2(b)) from the center of the geometry to the end, their perpendicular velocity component increases at the cost of the parallel component to conserve the magnetic moment and the kinetic energy. This happens because the magnetic field strength is higher at the end. If the increase in field at the end compared to the center is sufficiently large, there comes a point when the parallel component of velocity is exactly zero. This leads to confinement parallel to the magnetic fields. This is an effective confinement scheme in principle; however, experiments and theory have shown that coulomb collisions result in particles being scattered out from the ends at a rate that eliminates the possibility of a positive power balance [2].

The tokamak is an alternate design, where the general idea was to close the two ends of a mirror machine onto each other leading to a toroidal shape. Doing this also eliminates the need for confinement parallel to the field. The curvature in the field toroidally and the gradient in the field in a poloidal cross-section then give rise to a charged particle drift which is vertical in the poloidal plane. This problem is resolved by making the fields helical

¹As long as the change in magnetic field is negligible over gyro radius and gyration time scales.

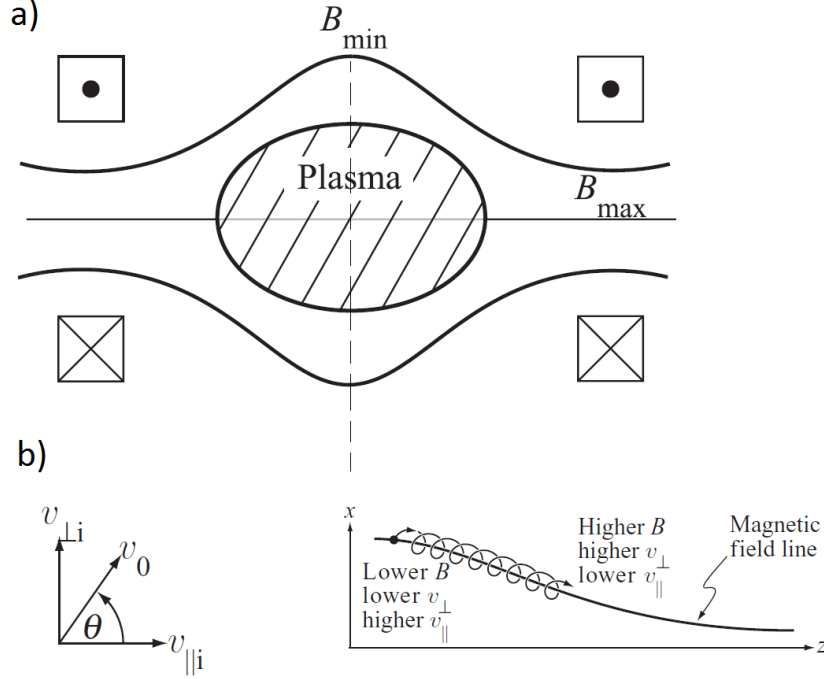


Figure 1.2: a) Mirror Machine b) Particle's trajectory relative to field strength in a mirror machine [2]

in the toroidal direction, such that the vertical drifts cancel out at the top and bottom in the poloidal cross-section.

In a general tokamak geometry (figure 1.3(a)), the magnetic fields exert a pressure proportional to the magnetic field strength squared, given by $B^2/2\mu_0$ Pa. A metric to gauge the plasma confinement efficiency is then defined as β (eqn 1.3); B is the magnetic field and μ_0 is the absolute permeability.

$$\beta = \frac{2\mu_0 n k_b T}{B^2} \quad (1.3)$$

Substituting eqn 1.3 into eqn 1.1 leads to another criterion, eqn 1.4.

$$\frac{\beta B^2 \tau_E}{2\mu_0} > 3 \times 10^2 m^{-3} keVs \quad (1.4)$$

It has been estimated that Q increases sharply as a function of the triple product for values greater than the one ascribed in eqn 1.1 [18]. This then leads to the conclusion that three quantities need to be maximized to cross the threshold of practical fusion energy.

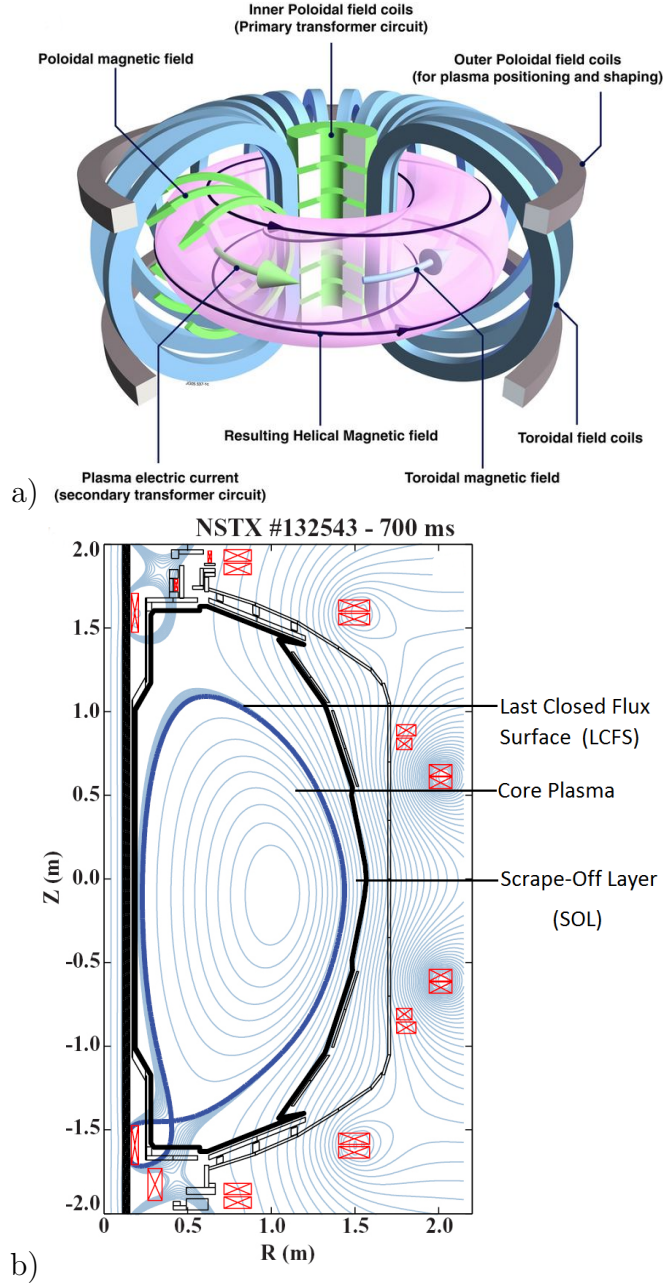


Figure 1.3: a) Generic Tokamak b) Poloidal cross-section of NSTX Shot#132543 with magnetic flux surfaces(blue), SOL, LCFS and core plasma [3]

The obvious candidate is the magnetic field, which provides a squared return on the triple product. Although an area of active and intense research, magnetic field increases are dependent on developments in superconductor technology and are beyond the scope of this work. Additionally, superconductors are prohibitively costly for use on larger devices if designed from superconducting material available today.

Another parameter that can be increased is β . β has an upper limit based on pressure driven MHD (magnetohydrodynamic) instabilities. The highest possible β (≈ 0.4) in tokamaks is achieved by low aspect ratio machines called spherical tokamaks; examples are MAST, UK and NSTX, PPPL which have an aspect ratio of around 1.3 – 1.5. Here aspect ratio A is defined as the ratio of toroidal to poloidal radii. This is convenient because there are practical benefits of low aspect ratio tokamaks, like smaller size and lower associated capital costs. A plasma self-heating mechanism called the bootstrap current, which arises due to the presence of pressure gradients in the poloidal plane and particles trapped in the Scrape-Off Layer (SOL) (figure 1.3(b)), is shown to have a linear dependence on β_p (poloidal beta) [19]. β_p and β_t (toroidal beta) are related to β by eqn 1.5 [19, 20] for a spherical tokamak, where elongation is defined as the ratio of core plasma height to width in the poloidal plane; NSTX, for example, has an elongation, $\kappa \approx 2$ [19, 3]. I_p is the plasma current, a is the poloidal radius and B_t is the toroidal field.

$$\beta_t \beta_p = 25 \frac{1 + \kappa^2}{2} \frac{\beta a B_t}{I_p} \quad (1.5)$$

The final parameter is the energy confinement time. Energy is lost from the plasma by various transport mechanisms. Although significant advances have been made in putting plasma transport in a tokamak on a firm theoretical foundation, a first principles prediction of τ_E has been evasive. This leads to the use of scaling laws to estimate τ_E from one reactor design to another; one of the more recent scaling relations called ITERH-98P(y,2) is given in eqn 1.6 [21, 22].

$$\tau_{E,ITERH-98P(y,2)} = 0.0562 I^{0.93} B^{0.15} \bar{n}_{e,19}^{0.41} P^{-0.69} R^{1.97} \kappa_a^{0.78} \varepsilon^{0.58} M^{0.19} \quad (1.6)$$

Here the parameters from left to right are: plasma current (I), toroidal magnetic field (B), line averaged electron density (poloidally, $\bar{n}_{e,19}$), absorbed power (P), toroidal (major) radius (R), elongation (κ_a), inverse of aspect ratio (ε), and mass of hydrogen isotope used (M).

1.2 Lithium Tokamak eXperiment (LTX)

The choice of first wall material or the material facing the plasma inside a tokamak, also called the Plasma Facing Component (PFC), has engineering and physics implications for the overall design. Empirically, it has been shown that the use of high-Z PFCs lowers confinement in JET [4]. It has also been observed that the use of low-Z coatings, especially lithium, improves plasma performance in various machines; examples include TFTR, NSTX, CDX-U and EAST [13]. One of the primary objectives of the Lithium Tokamak eXperiment (LTX) and its upgrade LTX- β is to investigate the feasibility of lithium PFCs on a high Z substrate to improve plasma performance. The advantages and disadvantages of low and high-Z PFCs are discussed in chapter 2.

LTX is a spherical tokamak (figure 1.4) with a cylindrical vacuum vessel of dimensions 0.9 m height and 1.4 m inner diameter. Inside the vessel are copper shells (figure 1.4) designed to be conformal to a plasma with major radius $R = 0.4m$, minor radius $a = 0.26m$ (aspect ratio $A = 1.6$), and maximum elongation $\kappa \approx 1.5$. LTX operated with a toroidal field ~ 1.7 kG, $I_p < 80kA$ and a shot duration $\tau_{discharge} < 25msec$. LTX- β , an upgrade to LTX has double the field and plasma current and close to double the discharge duration.

The copper shells exist in four segments, made of 3/8 in thick oxygen-free high-conductivity copper. The plasma side of the shells has a 1/16 in SS-304 stainless steel liner explosively bonded to it. The backs of the shells are nickel plated to prevent any contact between the lithium and copper. The shells can be resistively heated to $500^\circ C$. Before plasma discharges, the shells were evaporatively coated by around 100 nm of lithium. The key results from LTX were the observation of flat electron temperature profiles (in the poloidal plane of the plasma) and slightly higher confinement times. To facilitate a

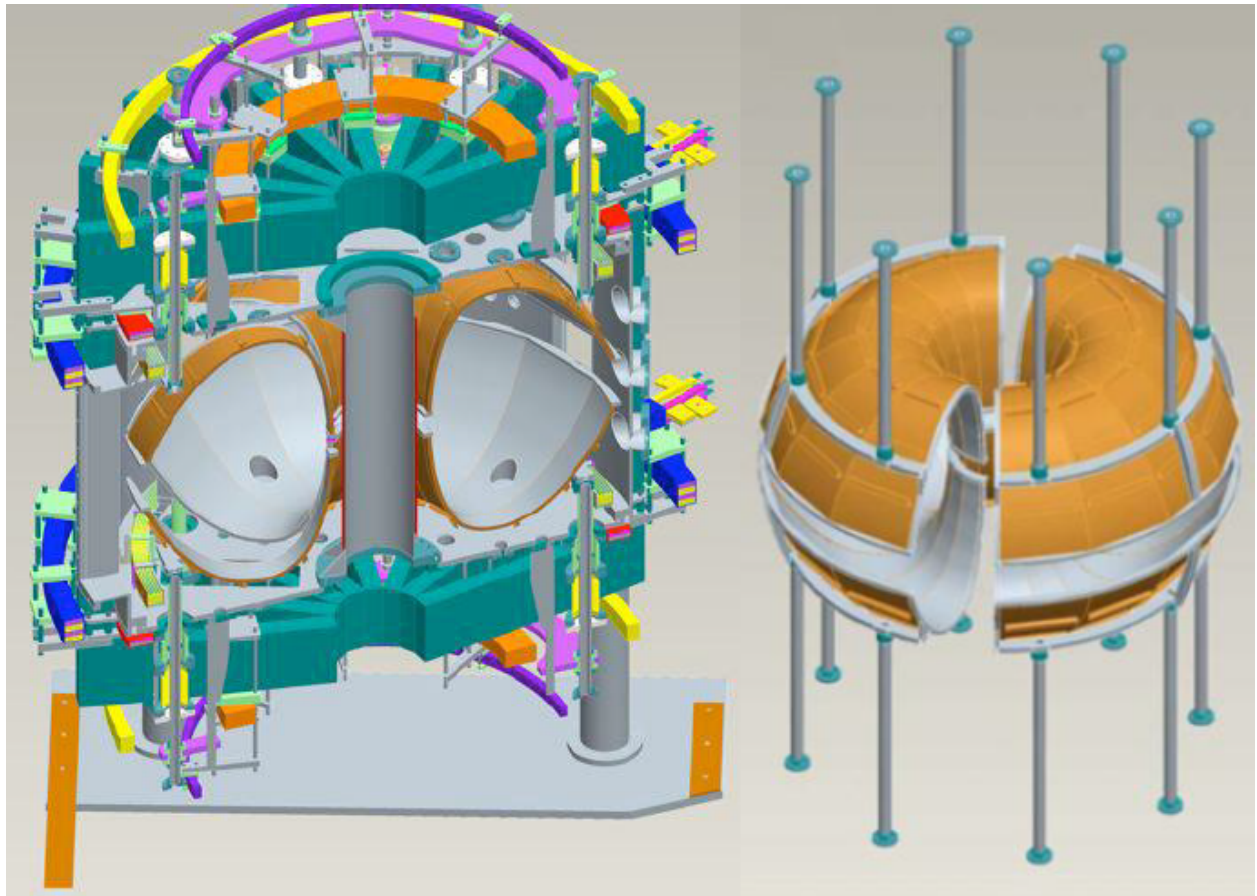


Figure 1.4: LTX Half-Section view (left); Conformal shell(right)

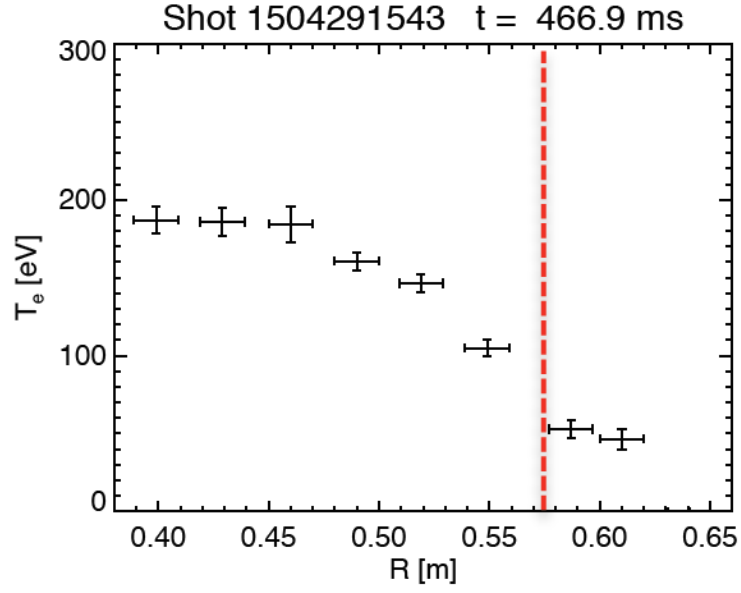
discussion of these results, a brief summary of plasma transport in MCF along with the recycling co-efficient follows.

Neoclassical transport theory provides a widely accepted model in MCF; the theory has been used successfully to make transport predictions for particles, heat and momentum due to coulomb collisions, based on the assumption that the plasma is in a quiescent state [23]. One of the experimentally-verified predictions of neoclassical transport theory is the bootstrap current mentioned earlier. Experimental observations of plasma transport in tokamaks, however, often exceed neoclassical predictions by at least an order of magnitude. The gap between observed transport and neoclassical predictions is euphemistically called anomalous transport [24]. Based on neoclassical predictions, the strongest transport process in the core is the ion thermal conduction or the ion radial heat flow. It is stronger (i.e., faster) than every other process by a factor of $(m_i/m_e)^{0.5}$, where m_i and m_e are ion and electron mass respectively. The ion thermal conduction has an ion temperature gradient dependence [25]. Ion and electron temperature gradient-based instabilities are also suspected to be amongst the drivers of anomalous transport [26]. It would then seem that eliminating temperature gradients (i.e., having flat temperature profiles) can mitigate such transport.

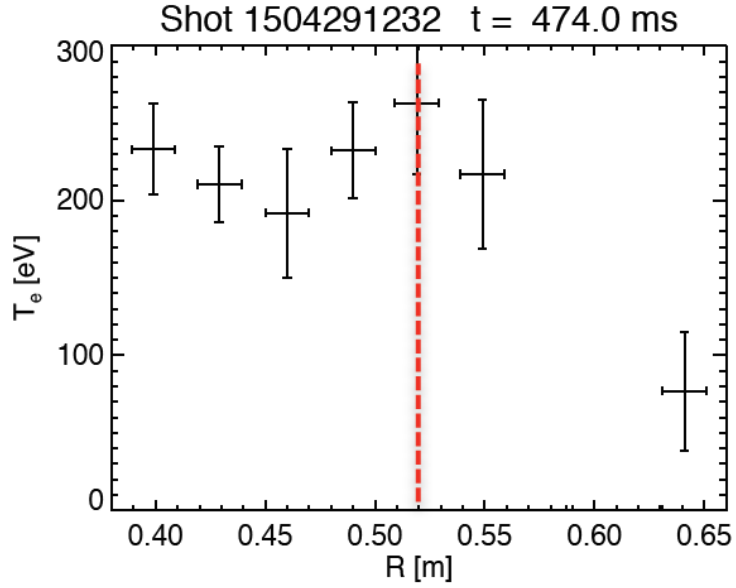
One of the processes that take place in the SOL (between the LCFS and PFC) (figure 1.6(a)) is recycling (R). This is when charged particles hit the PFC and are reflected back as neutrals, as defined in eqn 1.7.

$$R \equiv \frac{\text{flux of hydrogen neutrals from the wall to SOL}}{\text{flux of hydrogen ions from SOL to the wall}} \quad (1.7)$$

Experimentally observed values of recycling lie between $R \sim 0.75 - 1$ [4]. Recycled neutrals that are reflected back usually end up being re-ionized by electrons. The process is effectively an energy sink, where energy has to be supplied by the plasma to continuously re-ionize neutrals at the edge. It should be pointed out that if $R < 1$, all of the hydrogen/deuterium ions were not reflected back; these are said to be retained by the PFC. It has been predicted that low recycling eliminates temperature gradients in a tokamak [27]. Even though reduction in recycling should reduce transport and therefore increase confinement times, widely used scaling laws do not include recycling as a variable (eqn 1.7).



a)



b)

Figure 1.5: Electron temperature profiles measured using the Thomson Scattering system, dashed red line shows the position of the LCFS a) shortly after the termination of gas puffing b) 12 msec after the termination of gas puffing [4]

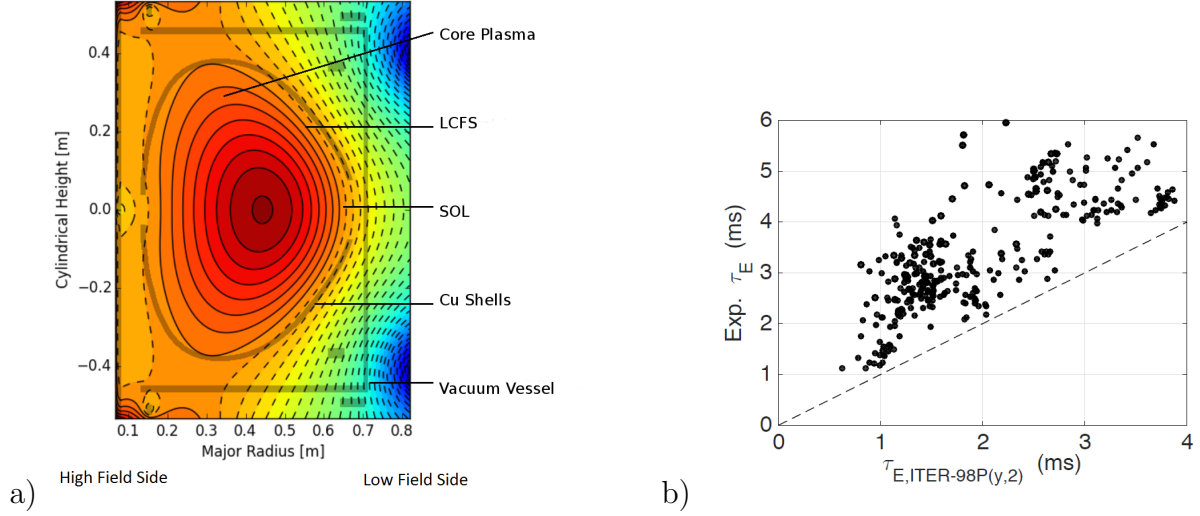


Figure 1.6: a) LTX poloidal cross-section with flux surfaces from a typical shot, showing flux surfaces that close on themselves (solid contours) and, open flux surfaces (dashed contours). The plasma density is superimposed on the flux surfaces and color coded (red-high;blue-low) b) Measured energy confinement times for LTX compared with ITERH-98P(y,2) confinement time

One of the main reasons lithium is so attractive is because its high chemical reactivity means that almost all of the incident hydrogen ions are expected to be retained in the form of LiH. The result is an operating regime of very low recycling, high confinement and reduced anomalous transport.

In LTX, like any tokamak, fields are higher near the central column (centrestack), referred to as the high field side (HFS) in the poloidal plane (figure 1.6(a)). During a discharge, LTX was fueled by gas puffs from the high field side. Once the fueling was terminated, it was observed that the electron temperature profiles flattened. Although the recycling was not measured directly, a comparison of the pressure balance before and after the discharge, based on fast ion gauge data, indicated that about 60% of the puffed hydrogen was retained by the PFC, indicating a low recycling fraction [28]. The electron temperature distributions in the poloidal plane were measured using a Thomson Scattering system (figure 1.5). The LTX results are the first experimental observation of near zero temperature gradient profiles attributed to low recycling PFCs. In addition, experimentally measured confinement times exceeded the ITERH-98P(y,2) prediction by a factor of 2-4 (figure 1.6).

Chapter 2

Background

Since plasma-material interactions (PMI) have a strong impact on the global plasma performance, they need to be well understood to enable a practical choice of first-wall material. To enable a discussion of LTX PFC characterization results, a brief review of various processes at the plasma material interface are discussed next. This is followed by representative results from other tokamaks that have employed lithium. The chapter concludes with the discussion of surface characterization of LTX and certain open questions that this thesis will address.

2.1 Plasma Material Interactions

An analogue of PMI is fluid-material interactions. However, the plasma-material interface is richer in physical processes. One key difference is that a potential develops between the plasma and the wall that repels electrons and accelerates ions, called the sheath potential; another is that since charged particles are involved, various related processes like ionization, recombination and charge-exchange are also relevant (figure 2.1). Coupled with the fact that in a fusion environment, plasma ions can have sufficient energy to sputter material atoms and high energy fusion neutrons are involved, the plasma material-interface is challenging to model.

Most literature loosely classifies solid PFC candidates capable of withstanding heat flux in the fusion relevant range as either a low- Z or high- Z material. High- Z solid materials

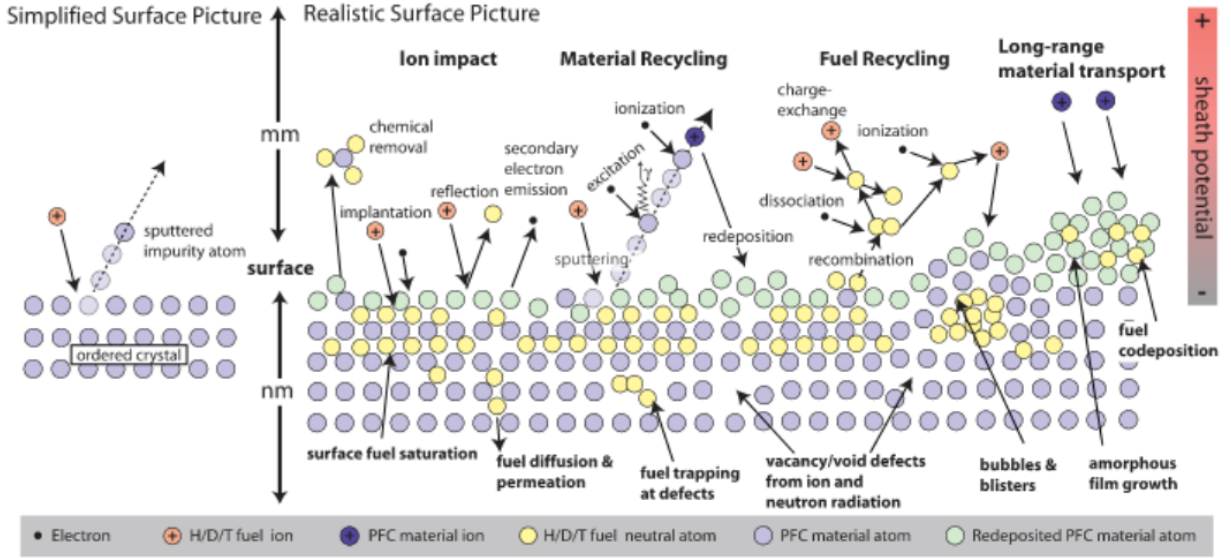


Figure 2.1: Schematic representation of various processes at the plasma-material interface [5]

are preferable because they have high sputter thresholds for incident plasma particles and therefore, have low surface erosion rates (figure 2.2). Other requirements like compatibility with high heat flux, resistance to high energy neutron induced damage and high temperature He embrittlement can be met with a careful choice of materials [29]. Tungsten (W) is popular amongst such high- Z candidates because it can tolerate high heat fluxes without melting; the W melt limit is still below heat fluxes expected during transient events in large reactors like ITER [12]. Since W is a BCC (Body Centered Cubic) material, it is more resistant to neutron induced volumetric swelling [29], which in the long run leads to structural failure. The most likely candidate for fusion is the DT reaction, because it has a higher cross section at lower energies. The reaction results in a high energy neutron (not bound by the confining fields), and a 3.5 MeV alpha particle.

It is mentioned in the previous chapter that energy is lost from the plasma through the transport of heat, particles and momentum. The other energy loss mechanism is radiative loss, when ionized and neutral particles of either fuel (D or T) or impurity species like first wall atoms interact with electrons to produce photons that are not bound by the magnetic fields. For a net positive power gain, power lost radiatively and by transport has to be less than the power produced by alphas. This imposes an upper bound on the maximum

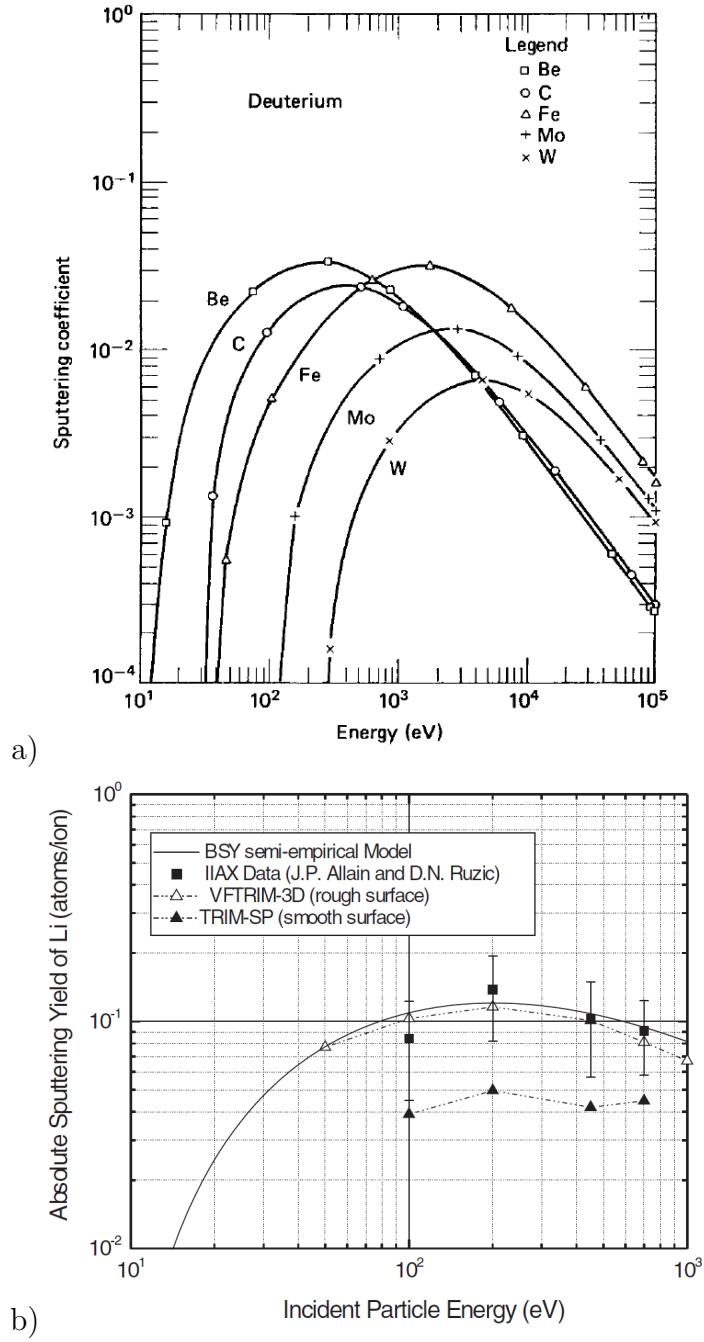


Figure 2.2: Absolute sputter yields of various targets for deuterium ion, note the logarithmic energy scale. a) Sputter yield of W, C, Fe, Mo, Be for deuterium [6]; b) Sputter yield of lithium for deuterium incident at 45° [7]

permissible radiative loss (figure 2.1). Radiative power loss can be further classified (broadly) into recombination losses, where electrons that recombine with partially ionized plasma ions can give out a photon, line radiation losses, the collisional excitation of electrons of a partially ionized ion which then de-excite by emitting a photon, and bremsstrahlung radiation, which is the power loss in electromagnetic fields created by accelerating electrons. The three radiative loss mechanisms, i.e., bremsstrahlung, line and recombination scale as Z^2 , Z^4 and Z^6 respectively (figure 2.3) [6]. Since W is a high- Z material, the plasma has a much lower tolerance for it because of high radiation losses from W impurities in edge plasma.

Another challenge in using tungsten as a PFC is plasma surface interactions in the ITER parameter range, which produce surface morphology and material property changes that are not fully understood. A recent study [30] showed that helium bombardment can cause surface morphology changes such as W "fuzz" and He bubbles, which could lead to enhanced erosion. Such erosion could reduce tungsten lifetime, and increase core plasma contamination, for example, through fuzz overheating and vaporization. Earlier candidates amongst low- Z materials like boron and carbon do not meet the low erosion requirements, as both have high physical and chemical sputter yields [12]; for ITER-like conditions, the erosion rates for Fe (a proxy for stainless steel) and C are on the order of $\sim 1mm/yr^1$; this number can be dramatically larger for hot spots produced under certain conditions [18].

An interesting alternative to solid PFCs under consideration is a macroscopic layer of liquid metal. The argument in favor of such PFCs is that since it is already in a molten state, melting due to high heat flux is not an issue. A low- Z option can be chosen that limits line-radiation losses, neutron and He induced damage, because there are no grain boundaries or crystal structures to damage, and erosion, which can be compensated for by maintaining a flow that continually replenishes the PFC. Lithium seems to be the most popular choice amongst liquid metal PFCs for various reasons. Its high chemical reactivity, for example, makes Li an impurity getter. Another major advantage of using lithium is its secondary electron emission (SEE) coefficient, which is the lowest of any metal [31]. It is well established that SEE can reduce the sheath potential at the wall and cool electrons at the plasma edge, resulting in large power losses. These effects become significant as the SEE

¹per year of continuous operation; $kT_i \sim 200eV$; Flux $\sim 1 \times 10^{19}m^{-2}sec^{-1}$

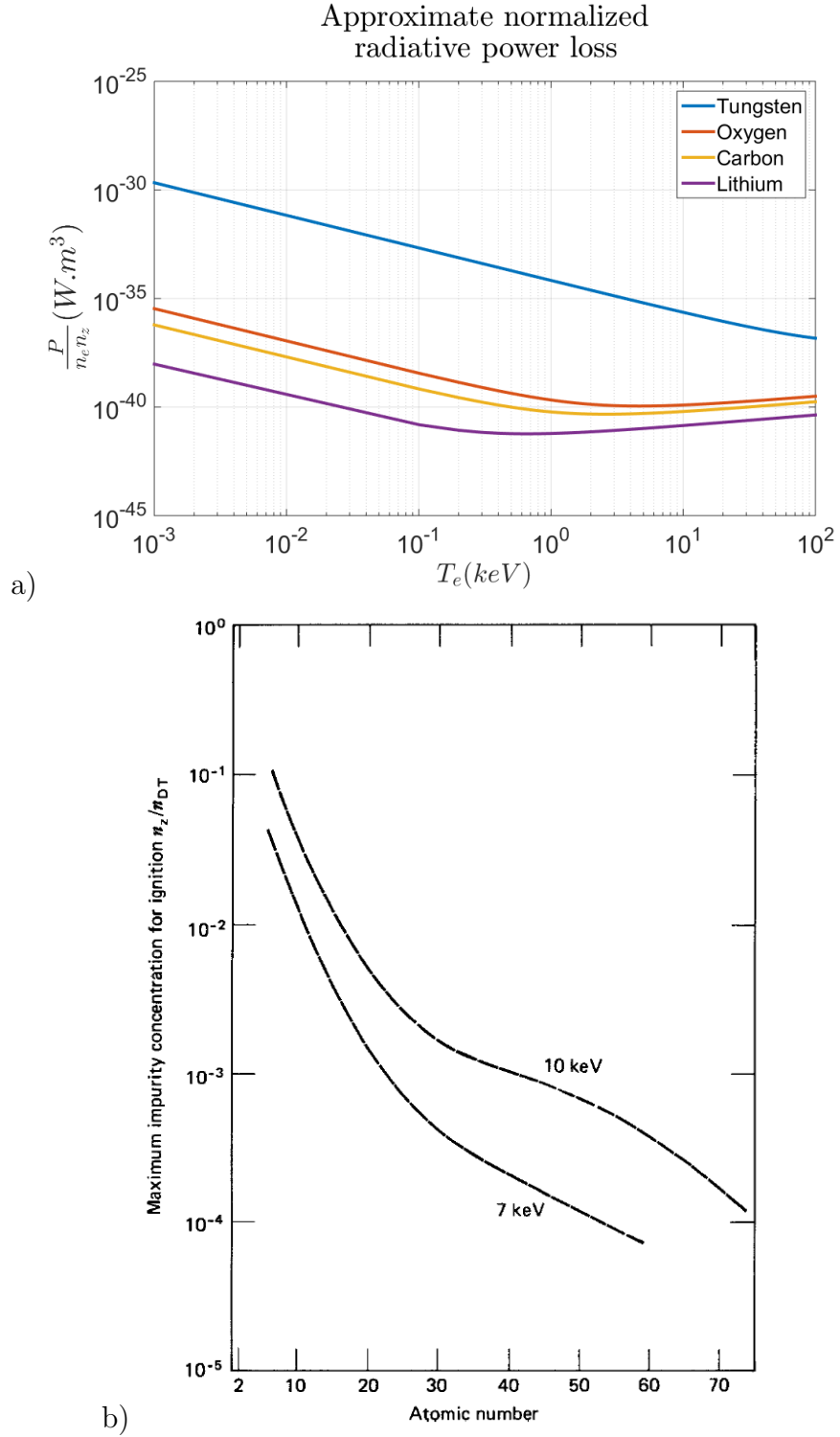


Figure 2.3: Radiative power loss by impurities a) Normalized radiative power loss based on approximate expressions in [6], a more rigorous treatment is provided in [8, 9] (n_e is electron density and n_z is impurity density); b) Maximum allowable impurity concentration normalized to DT concentration as a function of atomic number [6]

coefficient, γ_e , approaches one, making it imperative to maintain a low yield surface. There is, however, a caveat: the SEE yield increases for oxygen contaminated lithium coatings [32] such as the ones observed in LTX.

The factors discussed above make liquid metal PFCs a contender to high-Z PFCs. There are, however, significant engineering challenges associated with such PFCs, like designing a system that could safely handle a flowing liquid lithium loop. Pretreating or PFC conditioning with Li layers is the first step in understanding the various mechanisms that play a role in plasma Li and Li substrate interactions in a tokamak environment, and how they affect each other and global plasma performance.

2.1.1 Brief Overview of Li PFC Experiments

The tokamak plasma geometry is usually classified as diverted or limited (figure 2.4(a)). The first experiment to employ lithium was the Tokamak Fusion Test Reactor (TFTR) at PPPL. TFTR had a limiter geometry, and lithium pellets ($m_{Li} \sim 2.5mg$) were injected into TFTR². The pellets were ablated by the plasma and coated the limiter [33]. Plasma shots after lithium deposition saw an increase in plasma confinement time from $\tau_E = 130ms$ to up to $330ms$ [34]. Under these conditions, TFTR achieved the highest Q of around 0.3 with a DT plasma. There were other noticeable improvements, namely, higher core temperatures, greater neutron production and alpha power, and a reduced gradient in the temperature profile [35]. The spectroscopic data showed suppressed D_α and C_{II} emission and increased Li_{III} emission from the plasma; this led to the conclusion that lithium improved plasma performance by mitigating the influx of recycled DT and wall atoms into the core, and thereby reducing radiative losses [36]. This was followed by theoretical investigation of the impact of recycling that revealed that temperature gradients exist because plasma-neutrals interactions at the edge cool the plasma [27].

Experiments on TFTR were followed by the Current Drive Experiment Upgrade (CDX-U), the predecessor of LTX [37, 38]. CDX-U was also a limiter machine, with a toroidal tray of liquid lithium at the bottom of the vessel; when filled, the tray could hold up to a 5mm (d_{Li}) deep layer of lithium over an area of $A_{Li} = 0.2m^2$. An e-beam was targeted at the

²Several lithium coating techniques were tried on TFTR; pellet injection was among them

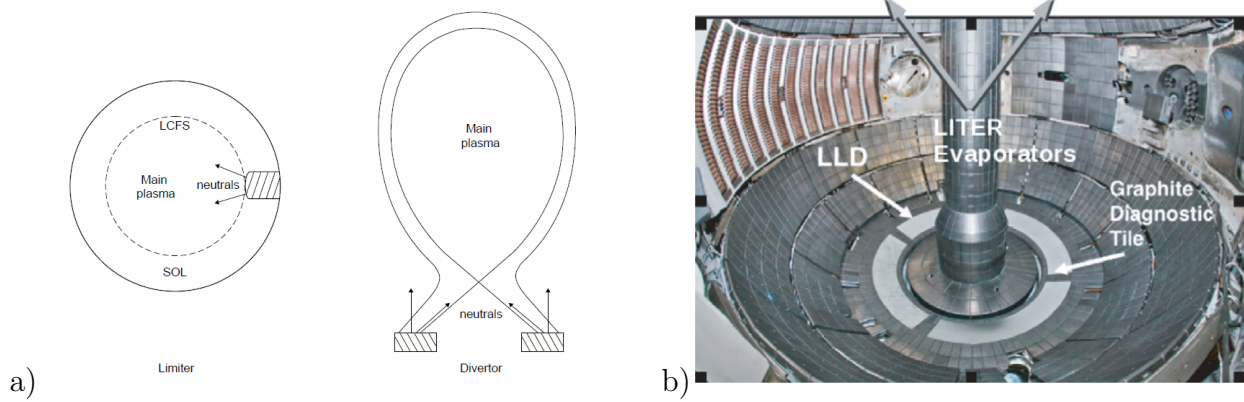


Figure 2.4: a) Tokamak Limiter and Divertor geometries (poloidal cross sections) along with the position of strike points for each; strike points are where the last closed flux surface comes in contact with the limiter/divertor [10]; b) NSTX interior, with the positions of LLD, LITER evaporators [11]

tray, using the vertical fields from the coils, to evaporatively coat the inside of the vacuum vessel with a coating of lithium approximately 10nm in thickness. H_α detectors were placed around the vessel, so that they view the centerstack and the tray simultaneously to measure recycled particle density at these positions [39]. H_α emissions were used with a Monte-Carlo based neutral particle code called DEGAS-2, to arrive at a value of recycling coefficient (R) [40]. CDX-U again saw consistently higher τ_E ; the highest τ_E of $\sim 6\text{ms}$ with a partially filled tray, having $A_{Li} = 0.06\text{m}^2$ and $d_{Li} = 2\text{mm}$, represented an increase over τ_E measured without lithium by a factor of 6 and exceeded ITERH98P(y,1) scaling by a factor of 3. This represented the largest improvement in confinement times in an ohmically heated tokamak [41, 42].

Following the CDX-U campaign, a new divertor was installed in NSTX with four segments at the bottom of the machine, called the Liquid Lithium Divertor (LLD) (figure 2.4(b)); NSTX initially had a diverted geometry with only graphite PFCs. The LLD segments were made of a porous molybdenum coating on top of a stainless steel liner on a copper substrate; they were filled with lithium evaporatively with two lithium evaporators (LITERs) situated directly above them. The segments were designed so that they could be heated. One of the main objectives of the NSTX campaign was to demonstrate that lithium could be employed directly at the divertor, to provide a low recycling surface at the strike point in a high performance tokamak. Improvements in plasma performance were observed; however, plasma

performance decayed as the divertors were heated up. Above a LLD substrate temperature of $T_s > 180^\circ\text{C}$, the performance was indistinguishable from a lithium coated graphite divertor. This decrease in performance was attributed at the time to the rapid accumulation of oxygen contamination on the LLD surface at higher temperatures [11].

2.1.2 Fuel Recycling, Retention and Global Particle Balance

To enable a measurement of the recycling coefficient in a tokamak, a simple point kinetic particle balance in the tokamak volume can be established (eqn 2.1), based on the premise that particles entering and exiting the core flow through the SOL [10].

$$\frac{dN}{dt} = \Gamma_{ext} + \Gamma_{wall-SOL} - \Gamma_{SOL-wall} \quad (2.1)$$

where N is the total hydrogenic (H/D/T) charged particle inventory in the tokamak volume, Γ_{ext} is the flux from an external fueling source such as gas puff or a neutral beam, $\Gamma_{wall-SOL}$ is the flux of recycled neutrals from the wall to the SOL, and $\Gamma_{SOL-wall}$ is the flux of ions lost to the wall from the SOL. Based on the definition of recycling from eqn 1.7, this can be re-written as

$$R_p = \frac{\Gamma_{wall-SOL}}{\Gamma_{wall-SOL} + \Gamma_{ext} - \frac{dN}{dt}} \quad (2.2)$$

Here R_p is the called the plate recycling coefficient, with the assumption that all neutrals exiting the wall are ionized either in the SOL or the core. The fraction of incident ions retained (r_p) in the PFC can be approximated as,

$$r_p = \frac{\int_0^t \Gamma_{SOL-wall} - \Gamma_{wall-SOL}}{\int_0^t \Gamma_{SOL-wall}} \quad (2.3)$$

where, t is the plasma shot duration. Another equation similar to eqn 2.1 can be written for the core plasma particle balance (eqn 2.4)

$$\frac{dN_{core}}{dt} = \eta_{ext}\Gamma_{ext} + \eta_R\Gamma_{wall-SOL} - \Gamma_{core-SOL} \quad (2.4)$$

Here, η_{ext} is the fraction of fuel atoms that make it to the core before getting ionized, η_R is the fraction of hydrogen recycled by the wall that get ionized in the core, and $\Gamma_{core-SOL}$ are the ions that leave the core for SOL due to various transport mechanisms. The product $\eta_R \Gamma_{wall-SOL}$ is then equivalent to the recycled flux into the core Γ_R . Further, defining the global recycling coefficient as eqn 2.5,

$$R = \frac{\Gamma_R}{\Gamma_{core-SOL}} \quad (2.5)$$

eqn 2.5 can be used to yield eqn 2.6

$$R = \frac{\eta_R \Gamma_{wall-SOL}}{\eta_{ext} \Gamma_{ext} + \eta_R \Gamma_{wall-SOL} - \frac{dN_{core}}{dt}} \quad (2.6)$$

Eqn 2.2 and eqn 2.6 have been used in the past in conjunction with spectroscopic measurements and neutral particle modeling to estimate both the plate and global recycling coefficients.

2.2 LTX PFC Characteristics

As pointed out earlier, evaporative lithium coatings on both high Z (stainless steel in CDX-U, LTX) and low Z (graphite in TFTR, NSTX) PFCs have produced improvements in plasma performance. This leads us to a consideration of mechanisms that lower recycling and getter impurities in a Li-conditioned PFC. The original idea behind using Li to condition surfaces was simplistic. Lithium is reactive and will bind hydrogen and its isotopes in an ionic bond (LiH), thereby limiting recycling; it should be noted that this has been shown to be true in the absence of any oxygen in a non-tokamak environment [43, 15]. It has, however, also been shown for lithium on low- Z graphite (e.g., in NSTX PFC studies) that the mechanism is more complicated in tokamak PFCs. NSTX PFC surface analysis was performed after shots with lithium-conditioned PFCs. The PFCs were removed after a run campaign, and X-ray Photoelectron Spectroscopy (XPS) measurements were made, after some chemical treatment to remove surface compounds that developed due to air exposure during the removal of the PFCs from the NSTX vacuum vessel. The data from the XPS scans revealed the

presence of Li-C-O complexes on the surface [13]. This a posteriori information was then used in Density Functional Theory-based Quantum Classical Molecular Dynamics (QCMD) simulations, along with other information gathered with the XPS analysis of laboratory experiments. QCMD as a tool has a history of application in determining the ground state of the electronic structures of molecular and atomic species. The results indicated that D in the surface ends up sharing charges with oxygen that is trapped between graphene layers of graphite PFCs, and forms the Li-C-O complex with intercalated lithium [44]. There were complications in confirming this result experimentally, as the tiles that were analyzed from the NSTX campaigns had to be removed from the vacuum vessel and exposed to air, added complications [13].

2.2.1 Materials Analysis and Particle Probe

The lessons learned from NSTX surface analysis led to the design and construction of the MAPP (Materials Analysis and Particle Probe) (figure 2.5), a collaboration between PPPL and UIUC (University of Illinois at Urbana-Champaign). MAPP was designed to characterize the PFC in-situ, i.e., without any exposure to air; MAPP was used initially on LTX by attaching it to the vacuum vessel at the low field side mid-plane, between the shell gaps (figure 1.6(a)) through a gate valve. The PFC samples on the MAPP probe head would then be inserted through the gate valve and the shell gap to be flush with the plasma facing side of the shells. The samples on the probe head are interchangeable, and included those made of stainless steel³ to match the LTX PFC. The LTX shells and the samples would then be coated with lithium, after which the probe head would be exposed to LTX plasmas. Post exposure, the probe could be retracted into MAPP analysis chamber (figure 2.5(b)) for sample analysis using XPS and Temperature Programmed Desorption (TPD).

XPS is a surface-sensitive material characterization technique based on the photoelectric effect [45, 46] (figure 2.6). Samples to be analyzed are exposed to X-rays of known energy. If X-rays incident on the surface have enough energy, they are able to knock electrons from the surface that are then detected. The electrons are knocked out at an energy characterized

³MAPP had four probe heads which were mounted with SS-316, SS-304 and graphite samples

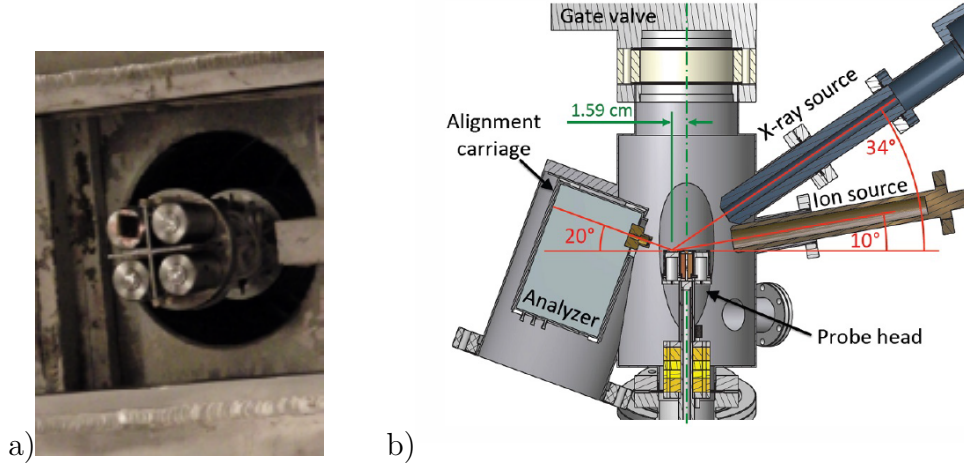


Figure 2.5: Materials Analysis and Particle Probe (MAPP) [12] a) MAPP Probe head inserted in LTX; the Probe Head holds four samples; b) CAD half-section view of MAPP with the probe head retracted to analysis position.

by eqn 2.7.

$$K.E. = \hbar\omega - B.E. - \phi \quad (2.7)$$

where $K.E.$ is the kinetic energy of the detected electron, $\hbar\omega$ is the energy of the incoming photon, $B.E.$ is the binding energy of the electron and ϕ is the surface work function. Electrons bound to different atoms can have binding energies from a few tens of eV to a thousand eV , but they are specific to each element; the $Li(1s)$ peak, for example, has a binding energy of around $55eV$ and the $Au(4f)_{7/2}$ peak of around $84eV$. However, depending on the chemical species on the surface, the binding energies of the electron can shift up by a few eV (compared to elemental binding energies); for example, the binding energy of $Li(1s)$ when the surface is Li_2O is around $56eV$. Therefore, with sufficient energy resolution, both elemental and chemical compositions of the surface can be probed. To first order, the width of an XPS peak is the quadrature sum of three components (eqn 2.8) [47, 48].

$$\sigma_{measured}^2 = \sigma_{intrinsic}^2 + \sigma_{analyzer}^2 + \sigma_{X-ray\ linewidth}^2 \quad (2.8)$$

The X-ray line widths for MgK_α and AlK_α , two popular X-ray sources, are around $0.7eV$ and $0.9eV$, respectively. However, for monochromatic sources it can be lower. The intrinsic and the X-ray contribution are Lorentzian, whereas the detector contribution is

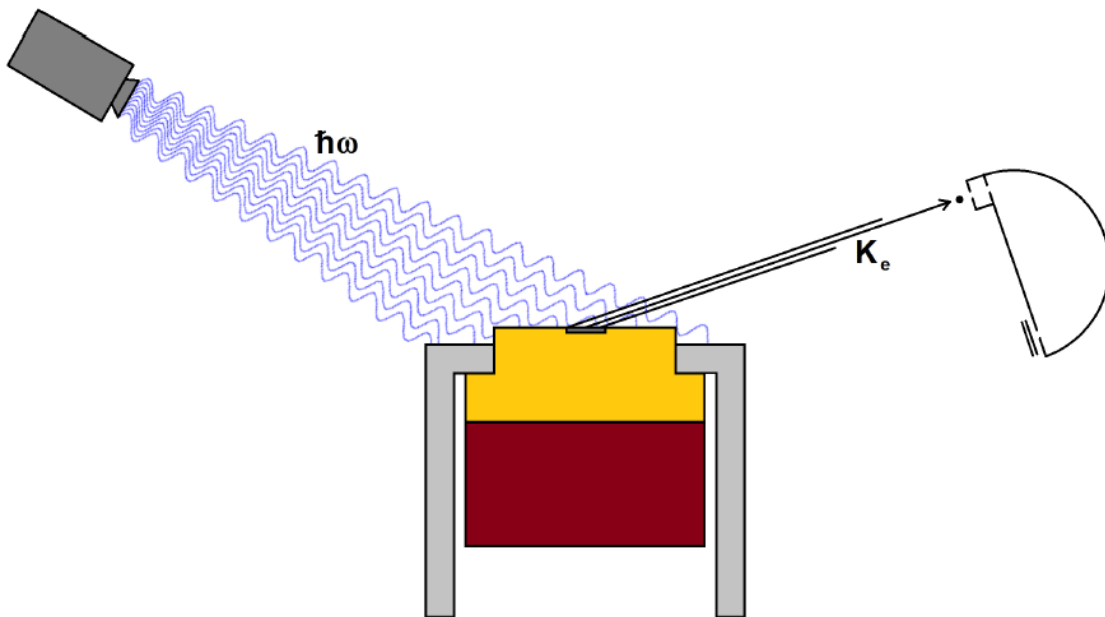


Figure 2.6: X-Ray Photoelectron Spectroscopy schematic representation [12]

Gaussian. The surface sensitivity of XPS comes from the fact that at XPS-relevant energies, the electron inelastic mean free path (IMFP) λ_e is on the order of a few nanometers, and therefore, electrons from only the top few nanometers escape without losing their energy signature [49].

MAPP used the MgK_α ($\hbar\omega = 1253.6\text{eV}$) X-ray source; the energy analyzer was fixed at a pass energy $E_p \sim 50\text{eV}$, which yields a detector energy resolution of around $\sigma_E \approx 2.7\text{eV}$ based on the detector geometry. The detector on MAPP was a Comstock AC-901 spherical sector analyzer; such detectors filter for particles with a specific kinetic energy by letting them pass through two biased sectors of a concentric sphere. With continued use, the MAPP detector resolution reduced to $\sigma_E \approx 3.9\text{eV}$. This reduction in detector resolution was not gradual [12]. It could be attributed to oxidation of lithium coatings that may have been deposited inside the analyzer after the lithium coated probe head was heated to perform TPD. These oxidized lithium coatings might have resulted in an insulating layer, and charge accumulation on the biased sectors that may have affected the photoelectron trajectories in the analyzer. Lower energy resolution made chemical identification of lithium coatings on the probe head samples difficult.

2.2.2 LTX PFC Evolution

LTX was baked for three days before the shell surface was evaporatively coated with lithium. The shells were held at a temperature of 275°C and the vessel at 80°C for the duration of the bake. Post-bake the background pressure (P) was around $1.7 \times 10^{-8}\text{Torr}$, with water vapor at a partial pressure (P_{H_2O}) of $1.4 \times 10^{-8}\text{Torr}$ and hydrogen partial pressure (P_{H_2}) of $1.5 \times 10^{-9}\text{Torr}$. After lithium application, the base pressure was measured to be $6.9 \times 10^{-8}\text{Torr}$; P_{H_2O} and P_{H_2} were measured to be $1.8 \times 10^{-9}\text{Torr}$ and $5.7 \times 10^{-8}\text{Torr}$, respectively. These measurements were made using an ion gauge and a Residual Gas Analyzer (RGA). The surface composition of the SS-316 MAPP sample head was measured using XPS (figure 2.7) after baking, after lithium deposition, and 5 hours after lithium deposition. The elemental composition indicated an increase in the oxygen concentration of the sample head after exposure to LTX residual vacuum conditions; this was attributed to oxidation by water vapor⁴. Since the LTX lithium coating is estimated to be around 100nm , it made sense that the underlying carbon and iron were not seen. The detector is at an angle of 70 degrees from the probe head normal (figure 2.5(b)), and the IMFP for $Li(1s)$ and $O(1s)$ electrons are around 3.07 and 2.07nm , respectively⁵. Using the expression in eqn 2.9,

$$d \sim 3\lambda_e^{Li_2O} \cos(70) \quad (2.9)$$

The XPS probe depth can be estimated to be around 3.1nm and 2.1nm for $Li(1s)$ and $O(1s)$ signals.

The temporal evolution of lithium and oxygen concentrations was also tracked using MAPP (figure 2.8 a)). It was observed that the oxygen ratio increased until it saturated the XPS probe depth, within $\sim 5\text{hrs}$. Beyond that, there are no observable changes in the elemental concentration until about 100hrs , after which the ratio of $Li(1s)$ to $O(1s)$ begins to drop again. The saturation of the ratio of lithium to oxygen at about 2 was attributed to the growth of lithium oxide on freshly-deposited lithium, in the presence of

⁴According to the RGA data the only other species present in the vessel after Li deposition were nitrogen and molecular hydrogen both of which do not carry oxygen.

⁵Calculated using the universal IMFP equation [50], assuming the material is Li_2O .

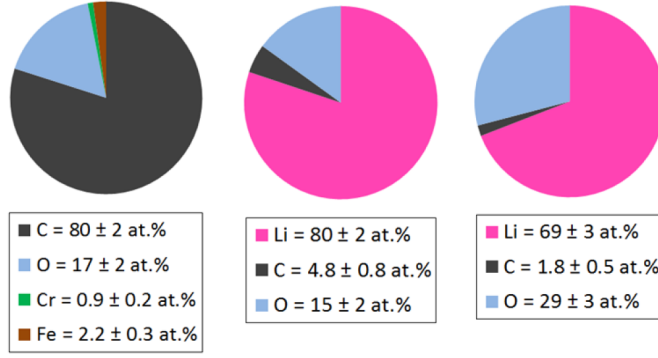


Figure 2.7: MAPP Sample (SS-316) elemental composition before lithium deposition, after lithium deposition and 5 hrs after lithium deposition (left to right) [12]

residual water vapor⁶. This is because Li_2O is the only lithium compound with oxygen that has that stoichiometry, in contrast with the other options $LiOH$, Li_2CO_3 and Li_2O_2 . This is consistent with laboratory experiments that show that on a clean lithium surface under high vacuum with residual water vapor exposure, Li_2O forms preferentially [51, 52]. More specifically, below 100 L_{H_2O} of exposure⁷, Li_2O forms preferentially on a clean surface; above this limit there is a transition to $LiOH$ formation. For LTX-relevant P_{H_2O} , this is equivalent to 14 hours of exposure. It was also observed that the presence of the oxide did not affect plasma performance (figure 2.8); LTX continued to get high plasma currents until ~ 40 days after lithium deposition on the surfaces. High plasma performance in the absence of elemental lithium was a surprising result, because it had been thought that lithium improves plasma performance by reducing recycling, by retaining hydrogen as LiH .

A simplistic explanation of the oxide growth can be provided by the metal oxide growth kinetics model (figure 2.9) [14], which states that in general, the oxide growth kinetics can be modeled by an advection-diffusion equation. At the onset, the oxide growth is driven by advection; a potential develops across the oxide film that drives the metal ions to the gas-oxide interface and oxygen ions to the metal-oxide interface. As the oxide grows in thickness, the potential across the film is shielded by free electrons and eventually, when the oxide grows thick enough, further growth is dominated by Fickian diffusion. Based on the kinetic theory of gases, the flux of H_2O molecules impinging onto the PFC is given by the

⁶The ratio saturates to a value slightly higher than 2 because the IMFP of the $Li(1s)$ electrons is slightly greater than that of $O(1s)$ electrons in lithium and lithium oxide.

⁷Langmuir (L) is a unit of exposure, defined as exposure to $P = 1 \times 10^{-6} Torr$ for 1second.

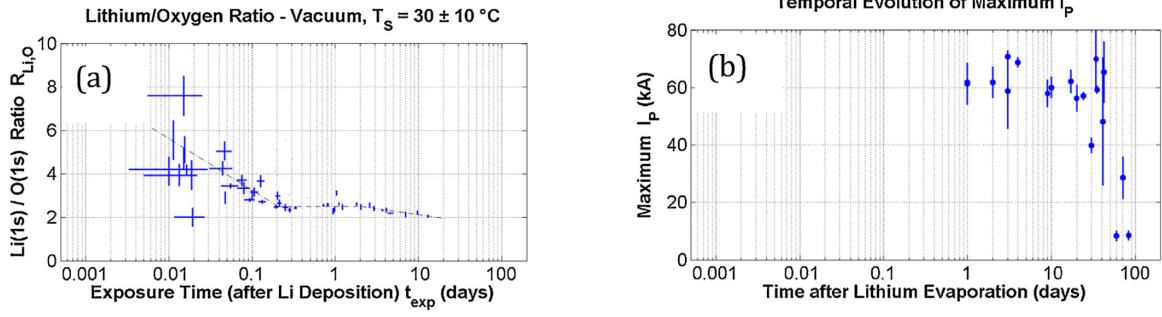


Figure 2.8: a) Ratio of $Li(1s)$ to $O(1s)$ signal as a function of exposure to LTX residual vacuum conditions [13]; b) Maximum plasma current I_p as a function of LTX residual vacuum condition; the x axis in both is time after lithium deposition

Hertz-Knudsen equation as denoted by eqn 2.10.

$$\Gamma_{H_2O} = \frac{P_{H_2O}}{(2\pi m k_b T)^{\frac{1}{2}}} \quad (2.10)$$

For $P_{H_2O} = 1.8 \times 10^{-9} \text{ Torr}$ in LTX after lithium deposition, $\Gamma_{H_2O} = 5.6 \times 10^{15} \text{ m}^{-2} \text{ sec}^{-1}$. Assuming a sticking coefficient $S = 1$ [52], with these fluxes it would take around 13 minutes for a monolayer of oxide to form on the PFC. It was observed that the oxide signature would saturate once the XPS probe depth is reached, i.e., after about 5 hours. Since the XPS probe depth is expected to be around 3 nm for MAPP, it is expected that the oxide layer took 5 hours to grow 3 nm in thickness. The metal oxide growth kinetics model then states that in the thin film limit, the growth rate can be modeled by eqn 2.11

$$\log \frac{dl}{dt} = B_1 + \frac{B_2}{l}; \quad (2.11)$$

where B_1 , and B_2 are material constants that are not dependent on the oxide thickness, and l is the film thickness. Using eqn 2.11, given the monolayer formation time and probe saturation time and solving for B_1 and B_2 , an oxide growth rate of 7.2 Å/hr at the onset and 5.5 Å/hr at the XPS probe depth are obtained. Note that the oxide growth rate would continue to decrease slowly as the film thickness increases. At the oxide growth rate of 5.5 Å/hr , a 100 nm coating would take 180 hours to fully oxidize, which is close to the 100 hour period for which there was no observable change in the lithium and oxygen ratios.

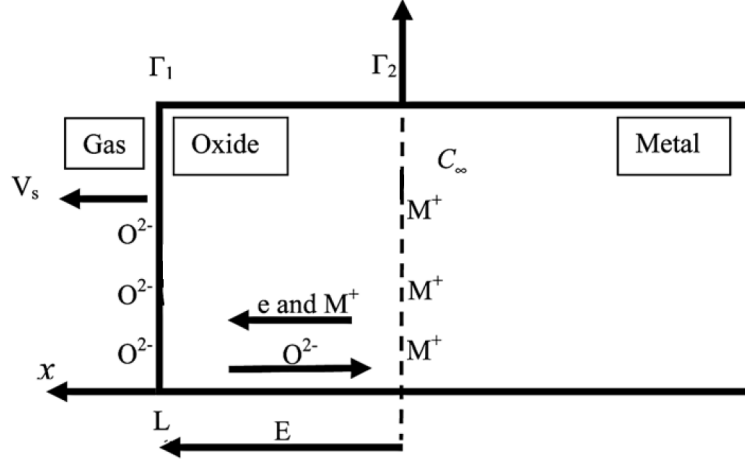
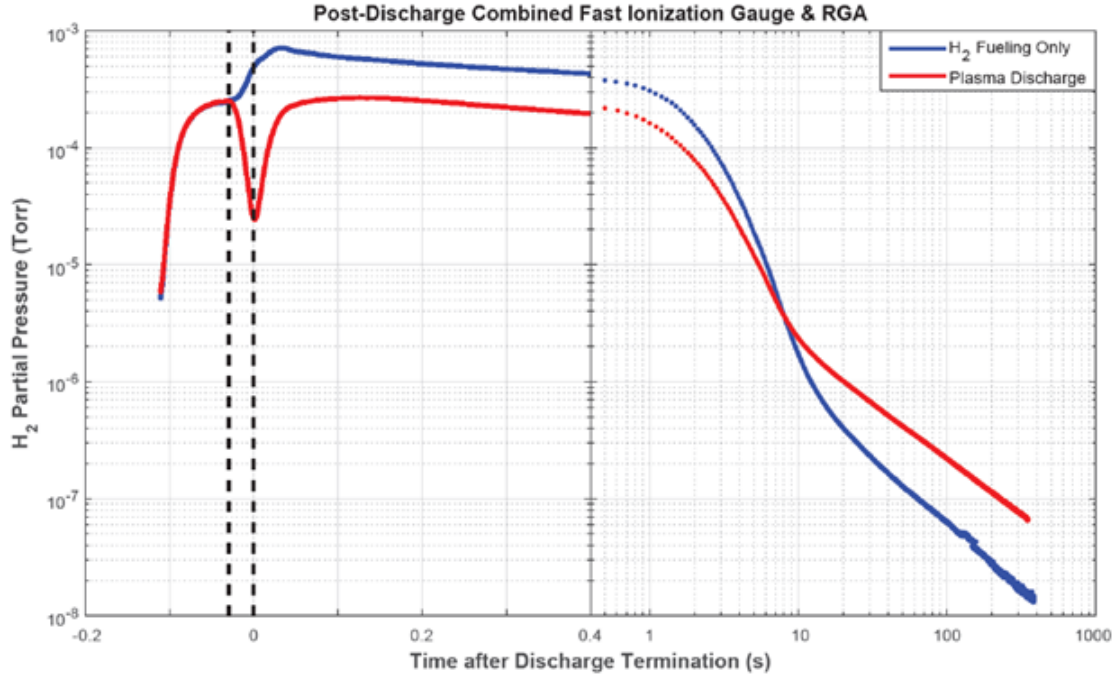


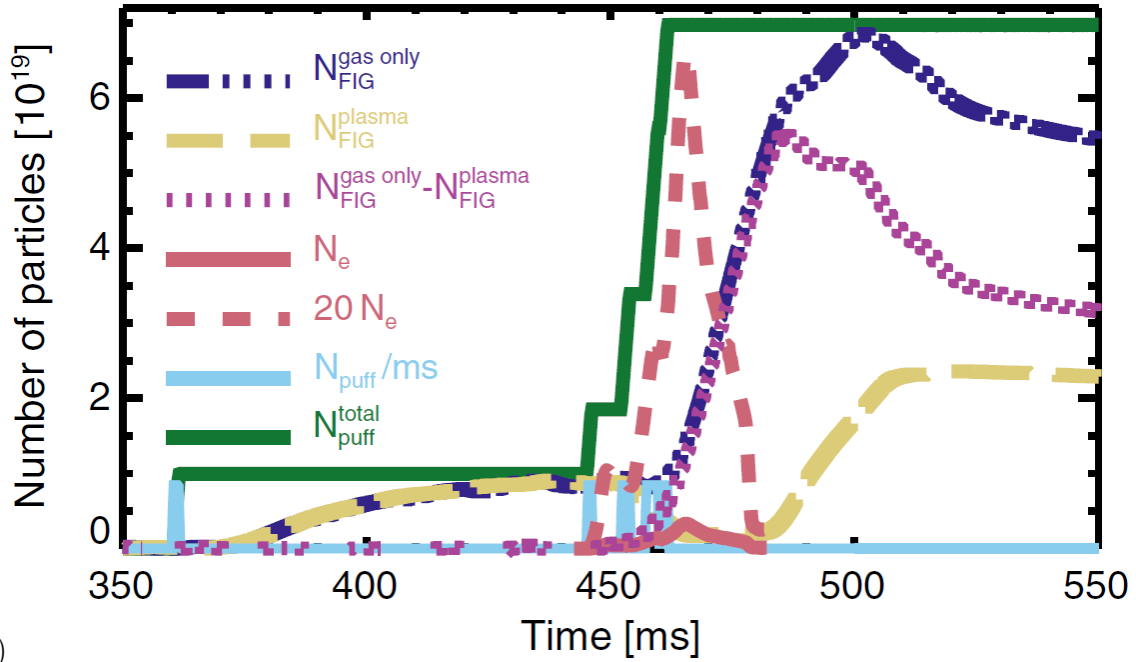
Figure 2.9: Metal oxide growth kinetics schematic; V_s is the oxide growth rate, Γ_1 and Γ_2 are gas-oxide and metal-oxide interfaces, C_∞ is the bulk concentration of the metal ions, E is the electric field across the oxide film. [14]

A look at the RGA and the Fast Ion Gauge (FIG) indicates another interesting observation (figure 2.10). As mentioned in Chapter-1, LTX was fueled by gas puffs at the high field side. The gas puff sequence is pre-programmed before a shot. Several calibration shots were run by initiating the same gas puff sequence and without initiating a plasma; the FIG and RGA data were recorded for these calibration shots. The FIG and RGA data are then recorded for gas puff sequences where a plasma was initiated. A comparison of the two indicates that immediately after the plasma extinguishes, the FIG shows a 60% reduction in H_2 inventory compared to calibration shots where a plasma was not initiated (figure 2.10(b)). Over longer timescales, however, the RGA H_2 reading for shots when a plasma was initiated exceeds the recorded measurement for the calibrated gas puffs (figure 2.10(a)). This leads to the conclusion that while a significant portion of hydrogen is retained during a plasma, the hydrogen outgases over timescales much longer than the plasma duration.

The observation that hydrogen outgases from the PFCs after a shot is supported by another argument. Assume a $100nm$ thick lithium coating on the shells that have an area $A_{shells} = 3.6m^2$. The total number of lithium atoms in the coating would be around $N_{Li} = 1.66 \times 10^{22}$ (assuming standard lithium density $\rho_{Li} = 0.534g/cm^3$). The flux of hydrogen ions hitting the PFC was measured using a Single Langmuir Probe (SLP) and was estimated to be of the order of $\Gamma = 1 \times 10^{23}m^{-2}sec^{-1}$; for a shot duration of $10msec$ over the entire shell



a)



b)

Figure 2.10: Pressure evolution with and without a discharge. a) Longer term evolution of P_{H_2} pressure profile; a comparison between pre-programmed gas puff and pre-programmed gas puff with plasma, the dashed vertical lines indicate the plasma duration; b) P_{H_2} pressure evolution during and after plasma shot, The dashed-dotted blue line is the pre-programmed gas puff ($N_{FIG}^{gas\ only}$) without and dashed yellow line (N_{FIG}^{plasma}) is the pressure profile with a pre-programmed gas puff with plasma.

area, the total number of hydrogen ions that hit the PFC would be around $F = 3.6 \times 10^{21}$. If hydrogen is bound by Li in a one-to-one ratio and not released, that would mean that it would take LTX $N_{Li}/F = 4.6$ shots to saturate the PFCs. If only 60% of the incoming hydrogen ions are retained, the PFCs would saturate in 7.6 shots, figure 2.10(b). However, this was not the case; as shown in figure 2.8(b), plasma performance did not decay after a few of shots, but rather after 40 days and close to a hundred shots.

2.2.3 Open Questions

These observations lead to the open questions listed below. The open questions are answered by the results enumerated in Chapter 5.

- The exact nature of the oxide that grows on freshly deposited lithium is not clear. The argument that lithium oxide grows on top of freshly deposited lithium is solely based on the ratio of Li and O being close to 2. At shorter time scales, these ratios have a high scatter because a large XPS dwell time was required to collect enough statistics with MAPP (figure 2.10(a)). The data at shorter time scales, e.g., within 5 hours of lithium deposition needs to be verified, preferably with higher resolution XPS scans that can determine the exact binding energies of the Li(1s) and the O(1s) peaks. The simplistic view provided by the metal oxide growth kinetics model must also be tested, which can be done by depth profiling of the PFC. Depth profiling is the process of sputtering the surface by a heavy ion for a fixed time (usually Ar^+) to deplete the surface followed by XPS scans and repeating the process.
- It is clear that the PFC is evolving, and as it continues to evolve, it does not affect the plasma performance until a certain exposure time of residual vacuum is reached. What is not clear, however, is whether the reduced performance is due the loss of hydrogen recycling ability of the modified lithium PFC, or because of another reason like the inability of the coating to sequester impurities. This can be tested by measuring the dependence of the recycling coefficient on the temporal evolution of the PFC.

Chapter 3

Offline Experiments

To seek answers to the open questions mentioned in the previous chapter, a series of experiments were proposed. For the purpose of this thesis, they have been classified into offline experiments, performed on a plasma exposure chamber (or plasma chamber), and online experiments, performed on LTX- β .

As discussed previously in chapter 2, section 2.2.2, measurements indicate the retention of hydrogen by lithium-coated PFCs in LTX such that it is free to diffuse out between shots. If this is indeed the case, lithium implanted with a known quantity of deuterium ions should have a significantly lower inventory of implanted deuterium, provided sufficient time passes between exposure and analysis. To investigate this, lithium samples could be exposed to a LTX-like fluence of deuterium ions and then analyzed using Nuclear Reaction Analysis (NRA) to detect deuterium retention, and Rutherford Back-Scattering (RBS) to determine compositional changes. Below we describe the apparatus and equipment used to enable controlled exposures of lithium samples to deuterium ions and benchmark analysis using HR-XPS and RBS.

The analysis could not be completed, unfortunately, because the He^3 beam at the tandem accelerator that was used for RBS analysis became unavailable. However, the results from the baseline XPS and RBS scans of test lithium samples transported between preparation and analysis chamber were able to show how lithium surfaces changed in the process. They indicated what improvements were needed in the sample transfer process to make future RBS analysis of samples exposed to tokamak plasma feasible.

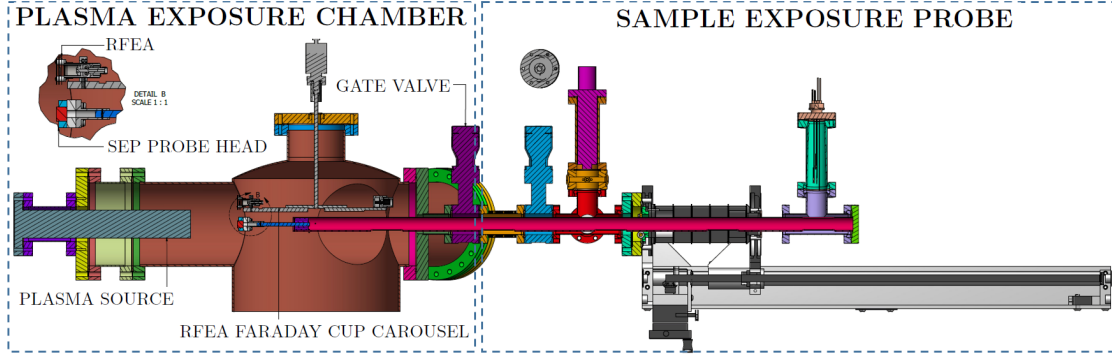


Figure 3.1: CAD Section View of Plasma Exposure Chamber (PEC) and Sample Exposure Probe (SEP) mated together, SEP probe head is shown inserted and the RFEA carousel is shown moved out of the way by raising the carousel on which it was mounted.

3.1 Experimental Apparatus

A multiport ultrahigh vacuum (UHV) chamber, denoted as the Plasma Exposure Chamber (PEC), as shown in figure 3.1, in the Surface Science and Technology Laboratory (SSTL) at PPPL was used to expose Li samples to deuterium ions under controlled conditions. The PEC contained a Tectra Gen-2 ECR plasma source, Stabil 370 Ion Gauge, and a SRS-200 RGA, and was pumped by a 260 l/s turbomolecular pump. The sample carousel in the PEC had a Faraday cup and a Retarding Field Energy Analyzer (RFEA). The sample carousel was mounted on a rotary feedthrough and z-translation stage on top of the vacuum vessel. The manipulator enabled moving the RFEA or the Faraday cup to face the plasma source. They could also be moved out of the way by raising the carousel on which they were mounted, out of the beam path. The plasma source was connected to two precision variable leak valves supplied by deuterium and argon gas lines figure 3.4, and was capable of producing ions in the energy range of 25 to 2000 eV . This source was characterized for argon and deuterium using the chamber-mounted Faraday cup, and for argon using the RFEA. Deuterium ions were used for exposures on Li to differentiate between hydrogen in the sample that originated from residual vacuum and ion exposure.

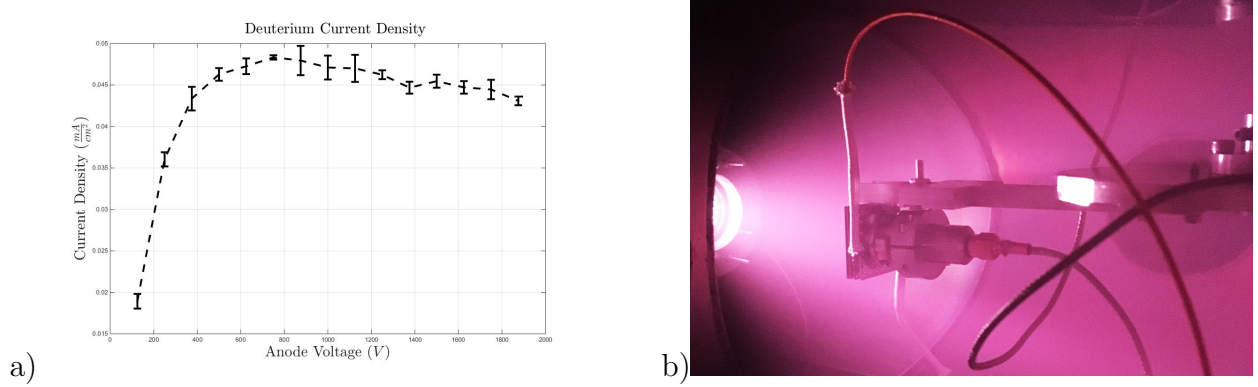


Figure 3.2: a) Deuterium current density as measured by the chamber Faraday Cup; the chamber pressure is held at $2 \times 10^{-3} \text{ Torr}$ b) The RFEA exposed to a deuterium beam.

3.1.1 Plasma Source Characterization

The PEC was fitted with a Gen-2, Tectra Electron Cyclotron Resonance (ECR) microwave source. The source was capable of a peak deuterium flux of $\Gamma = 3 \times 10^{18} m^{-2} s^{-1}$ (figure 3.2). Samples were exposed to a fluence of deuterium ions equivalent to one shot in LTX ($F = 1 \times 10^{21} m^{-2}$), which would be around 6 minutes at peak flux. The samples could then be characterized using Rutherford Back Scattering (RBS) and Nuclear Reaction Analysis (NRA) in facilities at Rutgers University. Additionally, HR-XPS using the Thermo K-Alpha in the PRISM Imaging and Analysis Center (IAC) at Princeton University could be used to probe near-surface elemental and chemical composition of the sample, using depth profiling with HR-XPS scans. RBS can probe the elemental composition of the sample at greater depths ($\leq 11 \mu m$). In RBS, $2 MeV \text{ } ^4He^+$, with a range of $22 \mu m$ in lithium, can be used to probe the sample. NRA using the reaction $D(^3He, p)\alpha$ can determine the deuterium depth and concentration in the sample. The PEC plasma source was further characterized using an RFEA figure 3.3 and was found to form a well behaved beam till, at least, 375 eV beam energy. The RFEA grid voltage was swept using a bipolar operational amplifier (BOP).

Since the PEC for irradiation and the HR-XPS and RBS/NRA analysis chambers are at different locations, care had to be taken to minimize lithium surface contamination during transport. To isolate the effects of sample surface contamination due to sample transfer from the effects of deuterium implantation, control experiments on unirradiated Li samples using HR-XPS and RBS were performed for bulk lithium samples. To facilitate the transport of

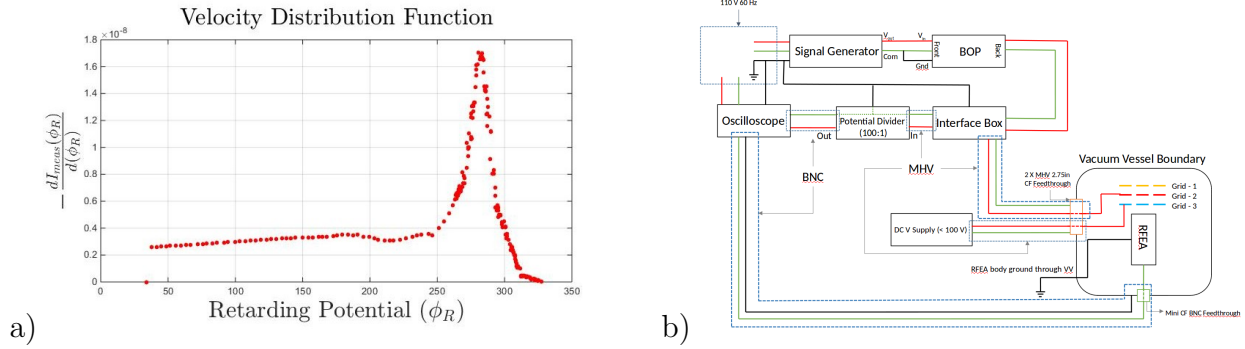


Figure 3.3: a) Ion Velocity distribution extracted from an RFEA trace for 275 Volts on the Anode of the plasma source b) RFEA connection diagram to the sweep circuit and the PEC

these samples between exposure and analysis stations, an Argon Glove Box (AGB) was used to load the samples into transport containers. The glove box has a nitrogen scrubber and humidity control, and is able to maintain a H_2O and O_2 fractions of <5 ppm and <2.5 ppm, respectively, under normal operating conditions. To transport samples between the AGB and PEC, a Sample Exposure Probe (SEP) was designed and constructed (see chapter 4 for more details). The SEP can be wheeled between the AGB and the PEC, and attached via 2.75 inch O.D. conflat flange, as shown in figure 3.1. The SEP is described in more detail in Chapter 4.

Samples were moved from the AGB to the HR-XPS instrument or the RBS beamline using a Vacuum Transfer Unit (VTU) stored inside a heat-sealed mylar bag. The VTU is a Thermo K-Alpha¹ accessory, in which the top cover has a rubber o-ring that can seal with the body once the VTU is pumped through a schroeder valve on its body. Once pumped, the VTU can hold a vacuum ($\geq 1mTorr$) for about 30 min and can be transferred into the Thermo K-Alpha load lock chamber. The top cover can then be opened in vacuum, enabling sample transfer without any exposure to air. The VTU is also used to transfer samples from the AGB to the RBS analysis chamber, where the VTU is opened inside a glove bag installed on the RBS analysis chamber while argon is bled into it to reduce the relative humidity to $\leq 5\%$. The sample is then transferred into the analysis chamber via a gate valve within less than one minute.

¹High resolution XPS system at Princeton University.

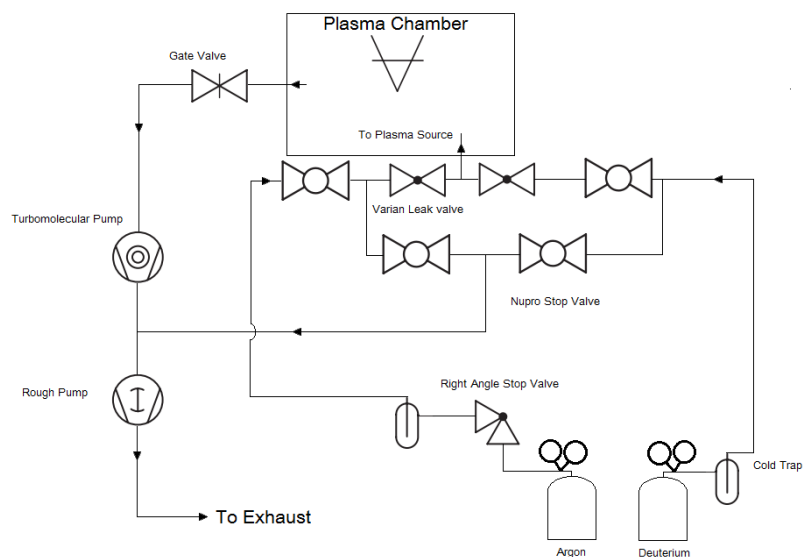


Figure 3.4: Pressurized gas connection to the plasma chamber

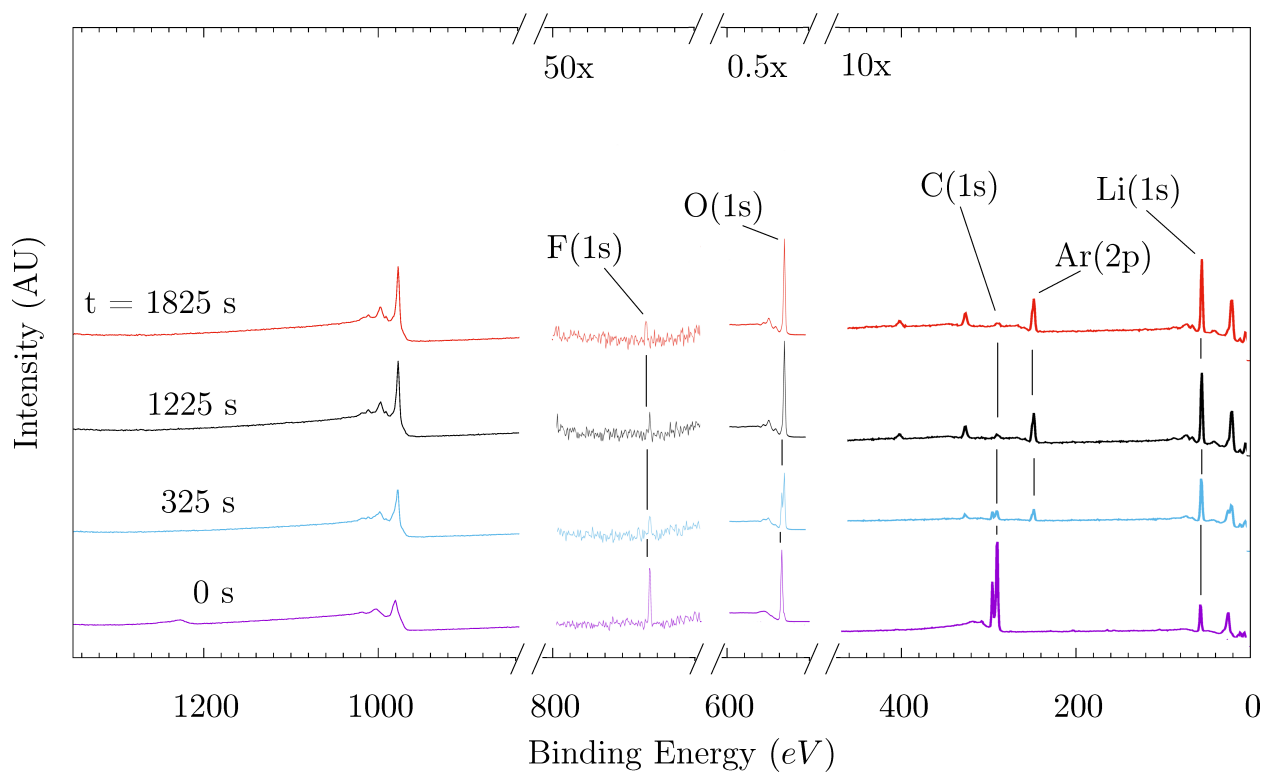


Figure 3.5: HR-XPS Survey spectra for lithium samples performed at 0, 325, 1225, 1825 seconds of sputtering with 500eV Ar^+ ions. Intensities have been scaled as indicated on the top axis

3.2 HR-XPS Analysis of Li Control Sample

Control samples of lithium, which were not irradiated by ions from the plasma source, were prepared by cutting sections of lithium rods (12.7 mm dia.) stored in the AGB. A section of the lithium rod was cut using a cheese cutter and transferred into the VTU, which was then pumped using the glove box antechamber (pumped by a mechanical pump) for 5 min. Once evacuated, the VTU can be moved to either the HR-XPS or RBS/NRA analysis chambers.

For the HR-XPS control sample, after transfer into the Thermo K-Alpha, the post pump down pressure in the analysis chamber was $2.6 \times 10^{-8} \text{ Torr}$. The sample was sputtered with 500 eV Ar⁺ ions for 1825 s in two phases, first for 325 s with survey spectra and then scans of Li(1s), O(1s), C(1s), and F (1s) regions recorded every 25 s. The second phase was for 1500 s, with survey spectra and region scans recorded every 300 s. The survey spectra were recorded at a 200 eV pass energy, and regional scans of Li(1s), O(1s), C(1s), and F (1s) peaks at 50 eV pass energy. The sputter area was set to 2 mm and the X-ray spot size to 400 μm . The take-off angle for the energy analyzer was set to the sample surface normal, and so the probe depth for Li and Li compounds was expected to be about 10 nm. It was observed, as shown in figure 3.5 and 3.6, that with sputtering, the Li(1s) signal increased and saturated at a value corresponding to an atomic composition of 68%, while the C(1s) signal decreased to zero within 200 s of sputtering. The O(1s) signal initially increased and then gradually settled to 31%. The C(1s) region had two peaks, at 288.19 eV assigned to Li_2CO_3 and the other at 284.98 eV due to adventitious carbon, which is ubiquitously present as a surface contaminant and provides a convenient binding energy reference between 284 and 285 eV [54]. All binding energies of other peaks are referenced to adventitious carbon at 284.98, eV as shown in Table 3.1.

Since the C(1s) peak is eliminated within 200 s of sputtering, it is concluded that the top few nanometers off the sample is a mixture of Li_2CO_3 and adventitious carbon. The presence of fluorine is attributed to contamination from a previous version of sample preparation that required the piece of lithium be cut with a knife while holding it on a piece of Teflon. The atomic concentration of element x , C_x , was calculated from the peak intensities, I_x , and the peak sensitivity factors, S_x [49] by the following equation

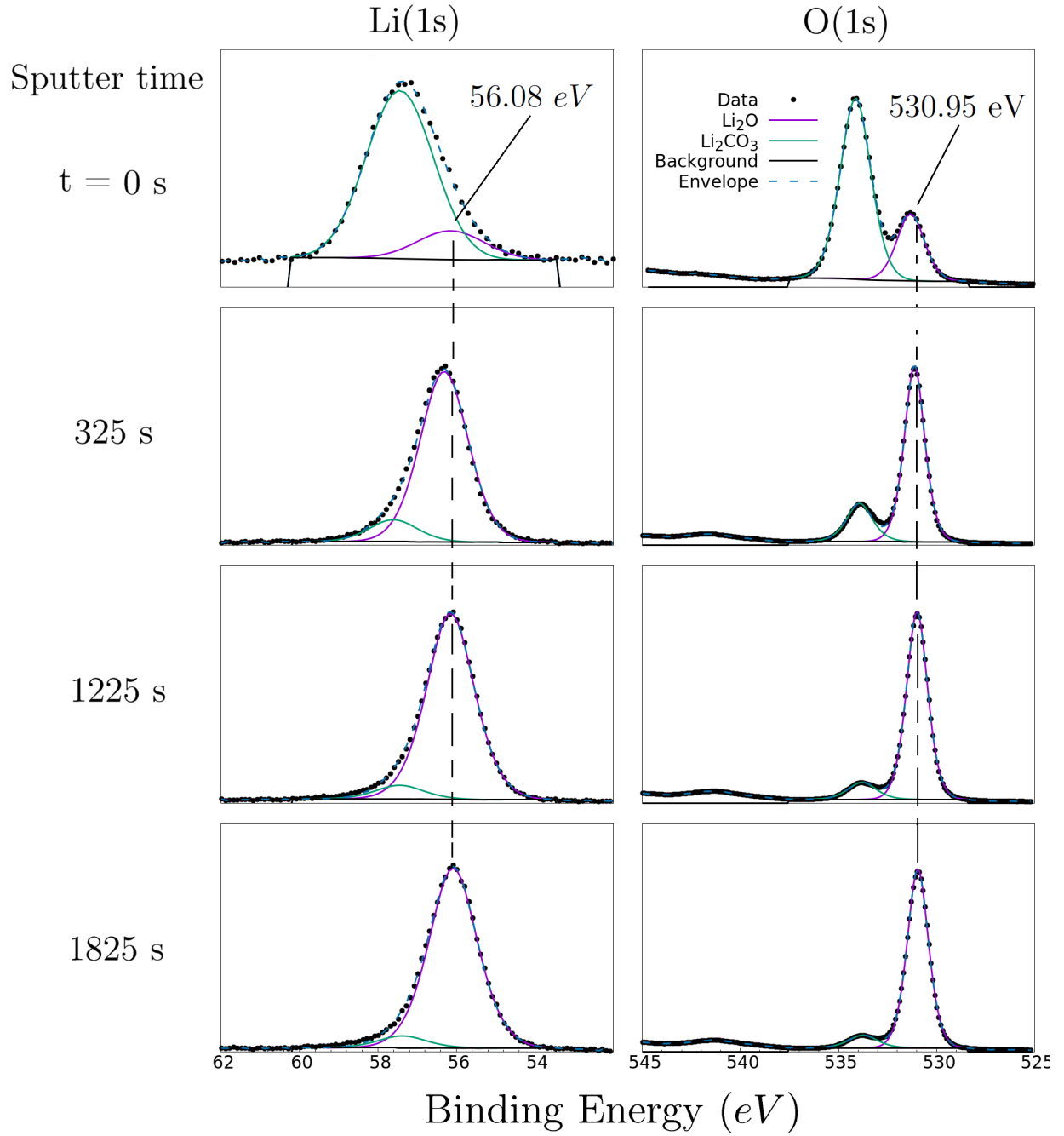


Figure 3.6: Evolution of $Li(1s)$ and $O(1s)$ fitted peaks (50eV pass energy) with sputter time. Left column is $Li(1s)$, top row is before sputtering.

Table 3.1: Probable Composition after 1825 seconds of Sputtering.

Peak	Peak Fit	BE (eV)	Intensity (cps.eV)	Conc. (%)
$C(1s)$	Li_2CO_3	288.19	4735	< 0.5
	Adv. C	284.98	2033	< 0.5
$F(1s)$	C_xF_y	687.75	3591	< 0.5
$Li(1s)$	Li_2O	56.08	36096	57.17
	Li_2CO_3	57.38	2400	11.8
$O(1s)$	Li_2O	530.95	566002	28.35
	Li_2CO_3	533.75	55755	2.01

$$C_x = \frac{n_x}{\sum_i n_i} = \frac{I_x/S_x}{\sum_i I_i/S_i} \quad (3.1)$$

It was observed that the $Li(1s)$ and $O(1s)$ concentrations settled to a ratio of 2:1. In addition, the $Li(1s)$ and $O(1s)$ binding energies ascribed to Li_2O peaks in both signals, are close to binding energies attributed to $Li(1s)$ and $O(1s)$ for Li_2O in the literature (figure 3.6) [48, 55]. This leads to the conclusion that buried beneath the layer of adventitious carbon and Li_2CO_3 , there was a layer of mostly Li_2O that was either thick enough that it could not be sputtered away, or was being formed during sputtering.

The Thermo K-Alpha sputter source was calibrated to have an ion current density $j_p \sim 2.45 \mu A/cm^2$. The absolute sputter yield for carbon in Li_2CO_3 for 500 eV Ar^+ calculated using SDTRIM, is 0.212. Thus, the thickness of the carbonate layer was estimated to be ≤ 1.2 nm. Therefore, the sample was characterized as having a 1 nm layer of Li_2CO_3 and adventitious carbon on top of a layer of unknown thickness of Li_2O , which lies on top of bulk lithium.

3.3 RBS Analysis of Li Control Sample

Another sample prepared with the same procedure as above was transferred into the RBS/NRA analysis chamber using an argon glove bag. The base pressure in the analysis

Table 3.2: Areal Density and concentration of Li, C, and O for Simulated data

	Areal Density ($1 \times 10^{15} atoms/cm^2$)	C	O	Li
Layer-1	25 ± 2	1	0	0
Layer-2	18 ± 1.9	0.161	0.487	0.351
Layer-3	160 ± 15	0	0.321	0.678
Layer-4	$\geq 11\mu m$	0	0	0.99

chamber was $6.5 \times 10^{-7} Torr$. Back-scattered helium ions from a beam of $2 MeV$ $^4He^+$ were detected with a detector placed at an exit angle of 17 degrees from surface normal.

The SIMNRA code [56] was used to fit the measured data to an initial guess of 1 nm of Li_2CO_3 and C, followed by 100 nm of Li_2O and then by bulk lithium. The fit resulted in the simulated profile shown in figure 3.7; the corresponding Li, C, and O areal densities are given in Table 3.2. The data were fit layer by layer, with each layer fit over two regions, 450 – 550 keV and 640 – 800 keV, except for the last layer (layer-4), which was fit over 120 – 800 keV.

Assuming standard mass densities of carbon, Li_2CO_3 , and Li_2O of 2.25, 2.11 and 2.015 g/cm³, respectively, and using areal densities predicted by the SIMNRA fit, we calculate the thickness of each layer as $d_{Layer-1} = 2.2 \pm 0.2 nm$, $d_{Layer-2} = 14 \pm 1.5 nm$ and $d_{Layer-3} = 34 \pm 3 nm$. This leads to a total contamination of $51 \pm 5 nm$ on the lithium surface, formed when transporting it to the RBS beamline using the VTU. TRIM calculations for a 50 nm thick coating of contamination as determined by RBS indicate that a significant proportion of deuterium ions at an energy of 1.5 keV or greater are able to penetrate the coating and interact with the lithium underneath.

In order to address the outstanding problem of the mechanism for hydrogen retention in Li-coated PFCs in LTX/LTX- β , a Plasma Exposure Chamber (PEC) and a Sample Exposure Probe (SEP) were designed and constructed, which could be used for laboratory hydrogen retention investigations and later in-vacuo analysis for LTX- β plasma exposures. Chemical bonding is known as a mechanism for hydrogen retention. Deuterium exposures of lithium samples under controlled laboratory conditions, along with RBS/NRA and HR-XPS, could be used to investigate another mechanism for lowered recycling, presumably observed in LTX.

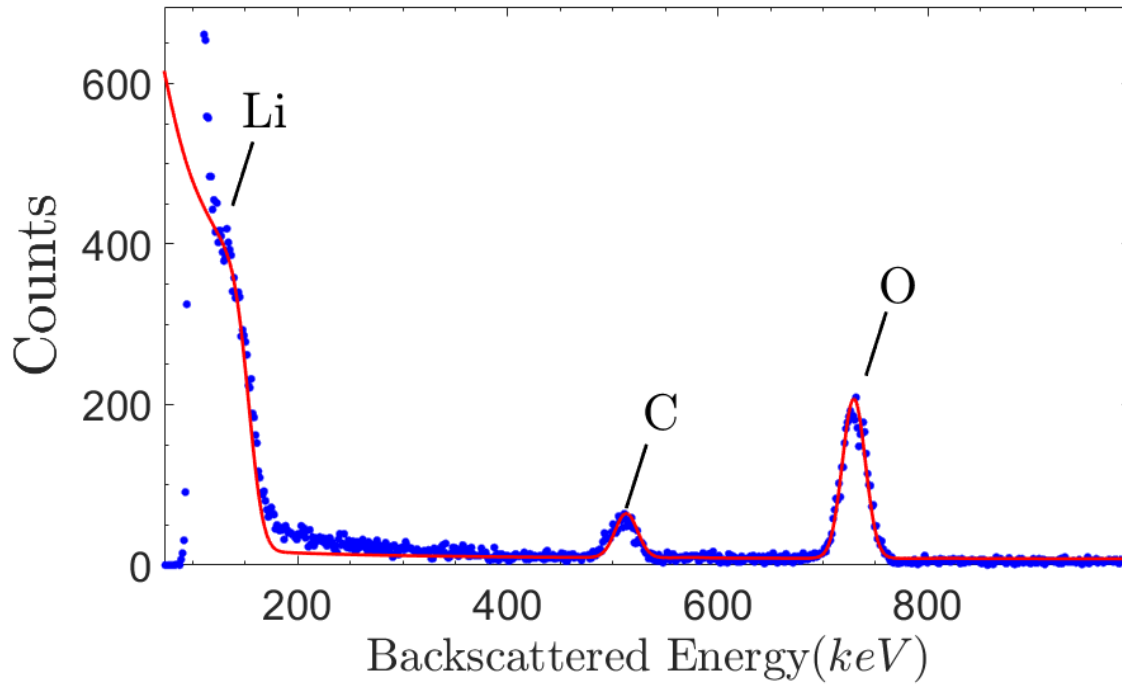


Figure 3.7: Experimental RBS data (blue dots) from the Li control sample and simulated profile (red line) for target data as tabulated in Table 3.2. The detector has a cut-off at 100keV to prevent pulse pile up from ions that reach the detector after multiple scattering events.

They could show that hydrogen retention is possible without long-term chemical bonding, but due to diffusive outgassing at timescales long compared to the shot duration. Analysis of unirradiated lithium control samples, transported using a vacuum transfer unit (VTU) for analysis by HR-XPS and RBS, show contamination on the order of 50 nm. These results provide a baseline characterization for deuterium ion-irradiated lithium samples, where analysis of retained deuterium could improve understanding of the mechanism for hydrogen retention and hydrogen out-gassing between shots in LTX- for Li-coated PFCs.

Chapter 4

Diagnostics Development for Online Experiments

The primary goal of this thesis is to explore the causal links between surface conditions and plasma performance for lithium covered walls on LTX- β . To enable this, a significant effort was spent in designing, building and commissioning diagnostics that would enable key measurements. To analyze the PFC surface, a vacuum suitcase was built that could move samples between LTX and an XPS system nearby. By enabling sample transfers in-vacuo (in-vacuum) the suitcase would permit surface analysis through XPS, depth profiling with an argon ion beam, and Ion Scattering Spectroscopy with a He beam; additionally, the suitcase would provide Temperature Programmed Desorption (TPD) capabilities to enable chemical species identification. In addition to the wide range of core plasma diagnostics on LTX- β , e.g., the plasma current Rogowski coil, microwave interferometer, Thomson Scattering system, etc., a localized edge diagnostic was needed. A single langmuir probe (SLP) was therefore designed and commissioned to get a measure of the ion flux to the surface. Both the SEP and the SLP were installed on the low field side mid-plane ports of the tokamak. Furthermore, they were placed flush with the plasma facing side of the shells to get a measure of the fluence to the PFC surface, and to see how these surfaces change as a function of fluence.

Additionally, LTX- β saw the commissioning of two new lithium evaporators, discussed later in this chapter. A Quartz Crystal Deposition Monitor (QCM) was installed directly

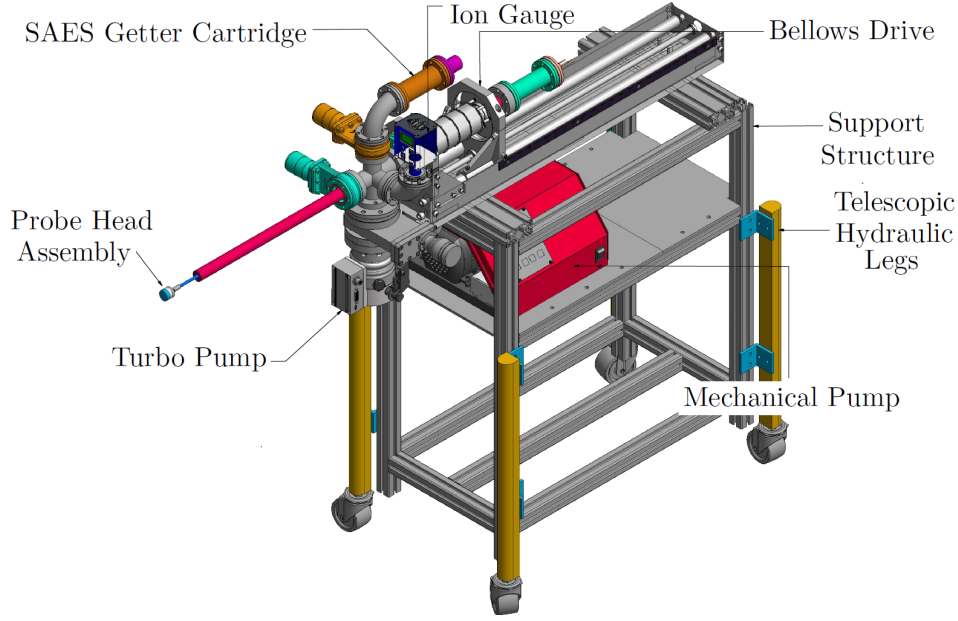


Figure 4.1: Isometric view of the Sample Exposure Probe Assembly

above each evaporator to get a measure of lithium flux from the evaporators and monitor the thickness of lithium deposited on the SEP and the shells. This chapter briefly goes over the design, installation, and commissioning of the SEP, low field side SLP, lithium evaporators and the QCMs.

4.1 The Sample Exposure Probe

The Sample Exposure Probe figure 4.1, also referred to as STS-2 (Sample Transfer System 2) in some design documents or the LTX- β SEP, is effectively a vacuum suitcase. The science goal of the probe is to get XPS and depth profiling measurements for lithium-coated stainless steel samples using PHI. The PHI is a surface analysis station described in Section 4.1.1. LTX base pressures were 5×10^{-8} Torr; water partial pressures are estimated to be an order of magnitude lower. At these pressures, the Li over-layer on the SS PFC is expected to change over a period of hours [12, 13]. Therefore, it is conceivable to get ex-situ, in-vacuo XPS characterization of LTX- β PFCs, provided, LTX- β samples can be transferred to an XPS system that at least match and preferably exceed LTX- β vacuum conditions. Therefore, the science goals of the Sample Exposure Probe can be summarized as follows.

- Enable in-vacuo sample transfer between LTX- β and PHI under LTX-like or better vacuum conditions.
- Get XPS characterization of LTX- β PFC using PHI.

To meet these science goals, a number of design constraints needed to be enforced on the SEP. The following is a non-exhaustive list of the design constraints.

- SEP must be able dock onto LTX- β midplane on a 2.75 in conflat(CF) or a 6 in CF flange.
 1. Once docked, the SEP should be designed such that it can be pumped to near LTX- β like vacuum levels before a gate valve between the SEP and LTX- β can be opened.
 2. Once opened, the SEP must have translation motion, with a stroke long enough such that the probe head can sit flush with the inner face of the LTX- β shells. This is to enable Li deposition and plasma exposure on the probe head that match the conditions on LTX- β .
 3. The probe head and feedthroughs should be designed to enable a ground to the shells.
 4. Once exposed to plasma, the SEP should be designed to separate from LTX- β such that neither LTX- β nor the SEP lose vacuum.
 5. Once separated, the SEP should be able to move as quickly and safely as possible to the PHI.
- SEP must be able to dock to the 6 in CF port¹ on the PHI, without having to vent either system.
 1. Once docked, the SEP must have enough stroke to reach the focal point of the X-Ray source, the ion gun, and the hemispherical energy analyzer on the PHI.

¹The 6 in port ideally suited for this purpose. It is 7.25 in from the focal point of the PHI; this imposes a constraint on the minimum stroke needed for scans

2. The probe head feedthrough should be designed to enable biasing and measuring the ion flux incident on the probe head during sputtering.
- SEP must be able to dock with the mBraun LabStar2000 glove box in L-245.
 1. Once docked, the SEP must have enough stroke to reach inside the glove box, such that the sample can be attached or removed.
 2. The docking should not compromise the argon backfill inside the glovebox.
 - To facilitate the possibility of Temperature Programmed Desorption (TPD), the sample head of the SEP should be heatable to 1200 K at a 4K/sec ramp.
 1. The heating of the sample head should not jeopardize safe operation of SEP, and should not result in any physical deformation of the parts holding the sample/probe head.
 2. It should be possible to monitor the temperature of the probe head.
 - To facilitate XPS and RBS measurements the sample head should be small enough to fit inside the VTU (section 3.1.1) and on the Rutgers beamline sample holder.

4.1.1 Hardware Design

The SEP (figure 4.1) is mounted in a bellows drive that is bolted to a wheeled support structure with telescopic hydraulic legs to facilitate mounting on LTX- β and a surface analysis chamber. The surface analysis chamber is a stainless steel ultrahigh vacuum (UHV) chamber (modified PHI 5300 ESCA System), referred to as the PHI, in the Surface Science and Technology Laboratory (SS&TL) near LTX- β at PPPL. The modification involved moving the X-ray source such that the orientation of the SEP sample head does not have to change from LTX- β to the PHI. The chamber is equipped for XPS, TPD, Ion Scattering Spectroscopy (ISS) and sputter depth profiling. The chamber has a base pressure of 2×10^{-10} Torr; pumping is provided by a 120 L/sec ion pump with 1000 L/sec titanium sublimator (Perkin-Elmer), a 170 L/sec turbomolecular pump (Pfeiffer Balzers, TPU 170 C), and a 33 L/sec turbomolecular pump (Leybold, TurboVac 50) for differentially pumping

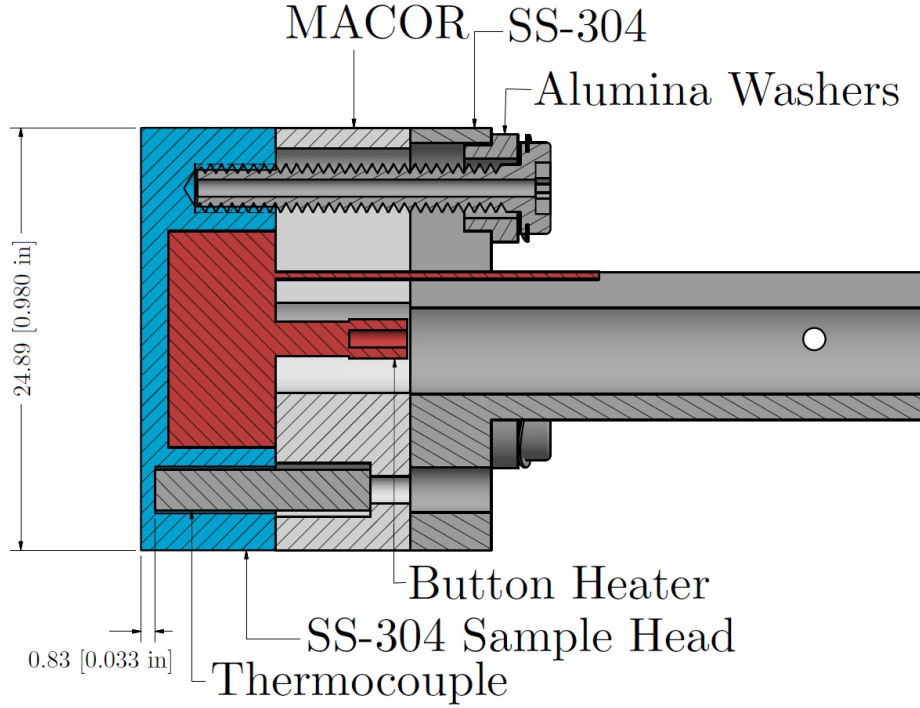


Figure 4.2: Cross-section view of the probe head, showing the thermocouple, button heater and other components.

the ion source. The SEP is equipped with a battery-powered 67 L/sec turbomolecular pump (Pfeiffer Vacuum, Hi Cube) and a 100 L/sec non-evaporable getter pump (SAES Getters, CapaciTorr D-400), and has a base pressure of 1.6×10^{-9} Torr. The base pressure of LTX- β after lithium evaporation is 6×10^{-8} Torr. Therefore, analysis can be performed for LTX- β PFCs by moving samples in-vacuo, under better vacuum conditions than on LTX- β , to a high resolution system that is nearby. In doing so, design constraints that are imposed on the analysis station, for example by the space in the test cell of the tokamak, are eliminated, enabling analysis with systems that possess higher resolution and better signal-to-noise ratios. Vacuum conditions during transfer and analysis that are better than on LTX- β reduce the rate of sample contamination, and therefore, provide adequate time required for physical transfer of the probe, its surface analysis and return to the tokamak. XPS is conducted with a dual-anode X-ray source (PHI model 04-548) and a spherical capacitor analyzer (SCA; PHI model 10-360). All XPS spectra are taken with Mg K α X-rays generated at 15 kV and 300 W. ISS and ion sputtering are conducted with a differentially-pumped ion source (PHI model 04-303).

The probe head, figure 4.2, is made of SS-304, to match the plasma facing side of the shells in LTX- β . An Ultra High Vacuum (UHV) button heater is placed on the back of the probe head. The insulator is electrically and thermally insulated from the support structure with a MACOR washer. The support structure is connected to a SS-304 rod that mates with another MACOR bushing, secured inside a 1 inch ID tube with retaining rings. The MACOR bushing provides an additional thermal barrier between the bellows and the probe head. The SS-304 1 in tube slides through the bellows and is supported by three zirconia roller bearings (separated by 120 degrees from one another) mounted on a collar on the outlet of the bellows. The back of the 1 in tube is threaded into a double faced flange tapped with a 32 thread per inch (TPI) tap to match the 32 TPI threading on the tube.

4.1.2 Instrumentation and Commissioning

The instrumentation on the SEP consists of a PID controller that takes the thermocouple as an input, and can be programmed to give a step or a ramp input to a DC power supply to a temperature setpoint. The probe head is floating with respect to the probe body, and therefore, can be biased to measure ion current when being bombarded by an ion beam. The probe ion gauge is digitized using a "Raspberry Pi" [57] module that communicates with an RS-485 cable. The turbopump and backing pump controller have their own power supply. Everything is powered by a 650 VA UPS that should provide 40 minutes of backup at full load. The physical distance between LTX- β and the PHI is roughly 180 feet, and travel time between them with the SEP, is about 3-5 minutes. At each location, while mounting the SEP either to the PHI or to LTX- β , a transfer volume between the machines has to be pumped down; after trial and error, it was decided to use a standard 2.75 in conflat tee for the pumpcart connection figure 4.3.

Optimum results were obtained (figure 4.4) when the tee is kept well baked and pumped down when not in use and following steps are followed. The procedure follows the movement of the SEP from LTX to the surface analysis chamber, but the same procedure can be applied to move the probe back to LTX.

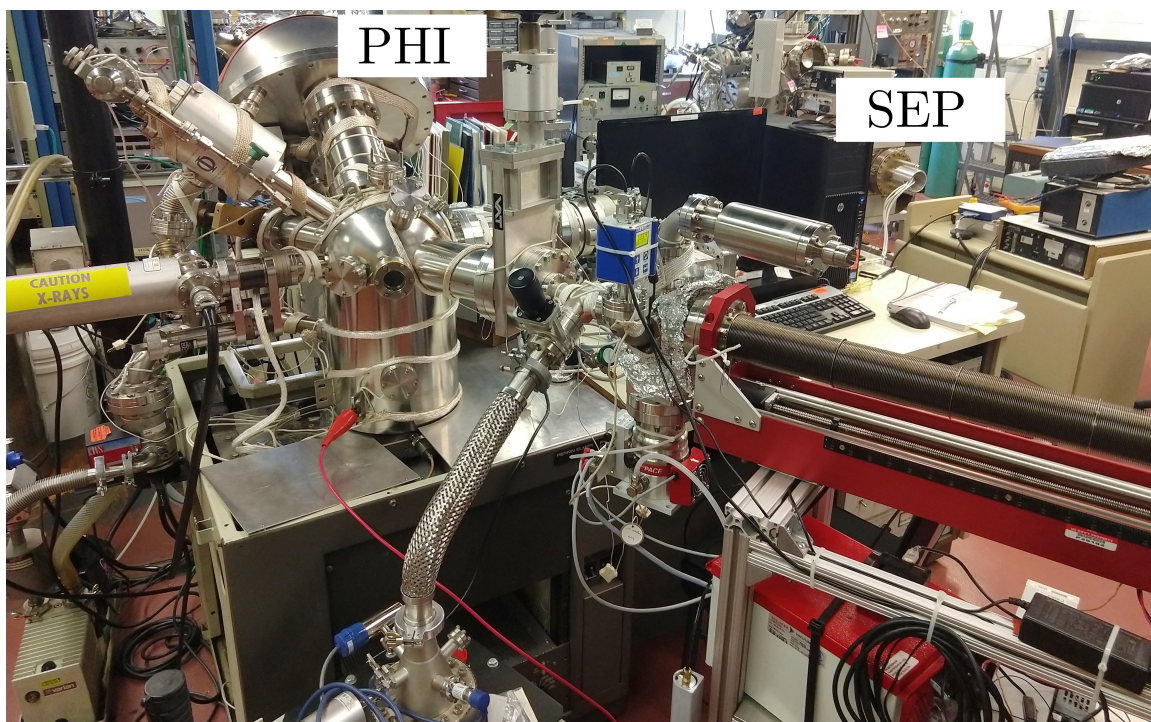


Figure 4.3: SEP shown mated to the Surface Analysis Chamber (PHI) through a standard tee, which is pumped by a turbopump backed by a oil-free scroll pump through a gate valve.

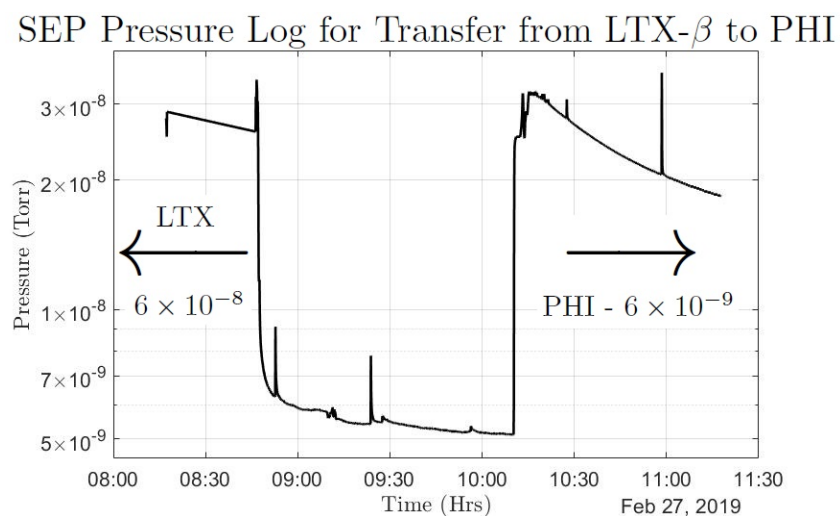


Figure 4.4: Plot of the pressure as measured by the ion gauge on-board the SEP for the first successful transfer of the SEP from LTX- β .

- Vent the tee between LTX and the SEP with liquid nitrogen while the tee is warm with a light bake.
- Open the conflat connection between the SEP gate valve and the tee and cover it with foil immediately.
- Wheel the probe to the PHI.
- Close the gate valve to the tee to the surface analysis station and shut the turbo down.
- Vent the tee to dry nitrogen from liquid nitrogen boil off, while warm.
- Make the connection between the SEP and tee, switch the bake off on the tee, and begin pump-down by restarting the pump cart and opening the gate valve to the pump cart
- Give the tee about 40 minutes to pumpdown, or till the pump cart ion gauge reads $\leq 5 \times 10^{-7} Torr$.
- Open the 6 in gate valve between the tee and the surface analysis chamber; this usually brings the pressure in the analysis chamber from $\sim 5 \times 10^{-10} Torr$ to $\geq 1 \times 10^{-8} Torr$.
- Flash the titanium sublimation pump (TSP); this brings the pressure down to about $\sim 6 \times 10^{-9} Torr$.
- Open the SEP to the analysis chamber, insert, and scan.

4.1.3 Performance and Comparison

Better resolution and signal to noise ratio (SNR) on XPS scans help understand how surfaces change in a tokamak and consequently in understanding how they impact plasma performance. Initial XPS scans using the SEP on the PHI show both improved resolution and better signal to noise ratio compared to MAPP. An example of this improvement is shown in figure 4.5, the two scans belong to the adventitious carbon $C(1s)$ peak on the stainless steel probe head of MAPP and SEP analyzed on the PHI respectively. The scans show a reduction in full width at half maximum (FWHM) by a factor of 2.2. The SNR was

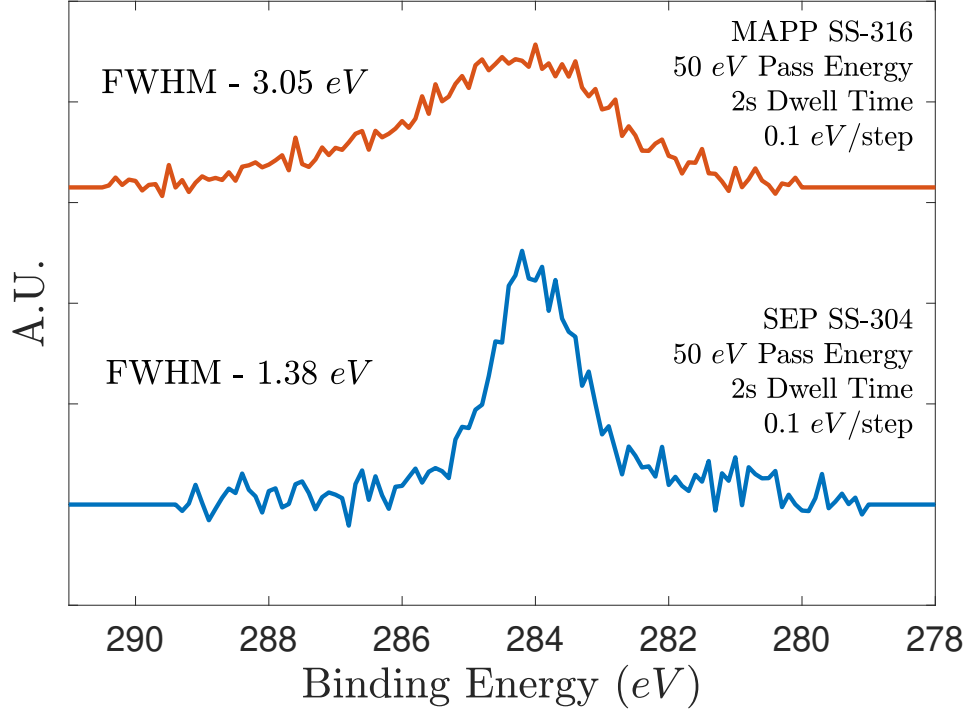


Figure 4.5: Adventitious Carbon C(1s) peak on MAPP and SEP using PHI

measured for both peaks using a commonly used expression for XPS [58] and determined to be 13.5 for the MAPP peak and 23 for the SEP using PHI. This is because of the higher intensity of the X-ray source on the PHI, and a smaller distance to the probe head. The C(1s) peak shown in figure 4.5, blue (bottom) trace, at 50eV pass energy shows a FWHM of 1.8eV and an SNR of 64.

An example of how improved resolution on XPS scans is helpful in identifying species on the surface is shown in figure 4.6. It was hypothesized that LiOH grows on the surface of Li deposited on SS shells of LTX over longer time scales (i.e., hours and beyond), but MAPP did not have the requisite energy resolution to confirm this. Figure 4.6 shows a regional O(1s) scan of the SEP probe head obtained using the PHI. The scan was taken 4 days after lithium was deposited on the LTX- β shells. The SEP was docked on LTX- β , and the probe head was made flush with the shells during the Li deposition, and subsequent plasma and residual vacuum exposure. The O(1s) scans show two distinct peaks; the difference in binding energy of the two peaks is consistent with previously reported difference between Li₂O and LiOH [59].

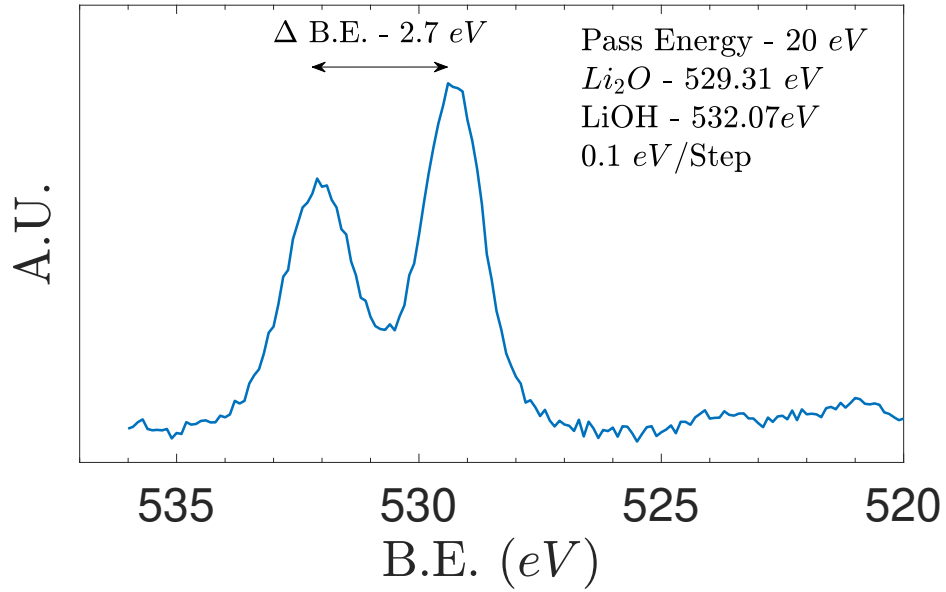


Figure 4.6: O(1s) narrow scan of the SEP using the PHI.

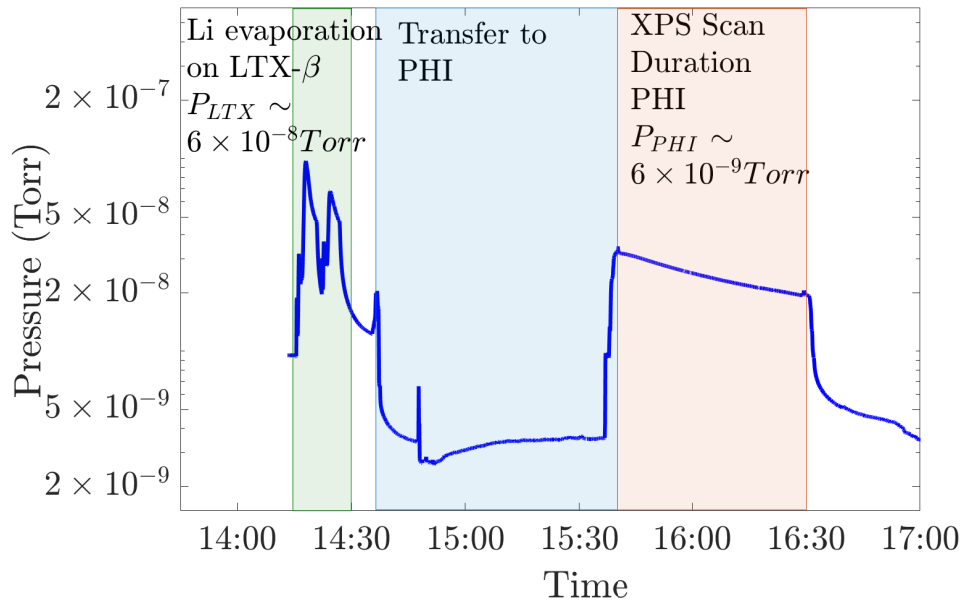


Figure 4.7: Pressure log from the SEP Ion gauge for transfer from LTX- β to PHI; green region shows pressure during lithium evaporation on the vessel walls and SEP, blue region shows SEP pressure during transfer, and red region shows pressure for the duration of XPS scans.

Because of the vacuum conditions in LTX- β , during transfer and in the PHI, it is also possible to probe the surface using XPS at time scales comparable to MAPP. Large error bars at shorter time scales exist in MAPP data because of the time to collect counting statistics to quantify elemental composition. A typical MAPP scan took 45 minutes to take a survey over a broad energy range and a few regional scans over a narrow energy range of the elements of choice under vacuum conditions comparable to LTX. The SEP, including transfer to PHI, takes 2 hours. However, during transfer and XPS scans, the pressure is maintained between $2 - 7 \times 10^{-9}$ Torr, as shown in figure 4.7. This is an order of magnitude lower than the LTX- β base pressure. Furthermore, the partial pressures of oxygen-carrying impurities (P_{H_2O} , P_{CO_2} , assuming all of P_{28} is CO, to get an upper bound of oxygen carrying impurities) is measured to be between $0.6 - 1.5 \times 10^{-9}$ Torr in SEP. The partial pressure P_{H_2O} in the PHI during scans is measured to be 8×10^{-10} Torr. Since partial pressures of oxygen carrying impurities are lower in both PHI and SEP compared to LTX- β by factor of 2-4, we expect the monolayer formation time to increase by the same factor. Therefore, we expect the surface changes during the MAPP and SEP measurements to be comparable. This is illustrated by the fact that MAPP measured the elemental composition of freshly deposited Li in LTX to be in the range of 70-80%. The SEP with PHI measures the same quantity as being 77.4 ± 1.2 %.

It should be pointed out, however, that systems like MAPP can enable analysis at shorter time scales, if compact equipment with improved resolution can be designed and installed where large changes in magnetic fields are expected. Since MAPP is remote controllable, which is an advantage where test cell access is limited during plasma operations, these two solutions are presently complimentary to each other. On the other hand the SEP is the first sample transfer system implemented at an experimental fusion facility that maintains active pumping during transfer to enable material characterization.

4.2 Low Field Side Swept Single Langmuir Probe

The low field side single langmuir probe (LFS SLP) is a tungsten wire, encased in alumina casing and mounted inside a bellows to enable sweeping the scrape-off layer of LTX- β . The

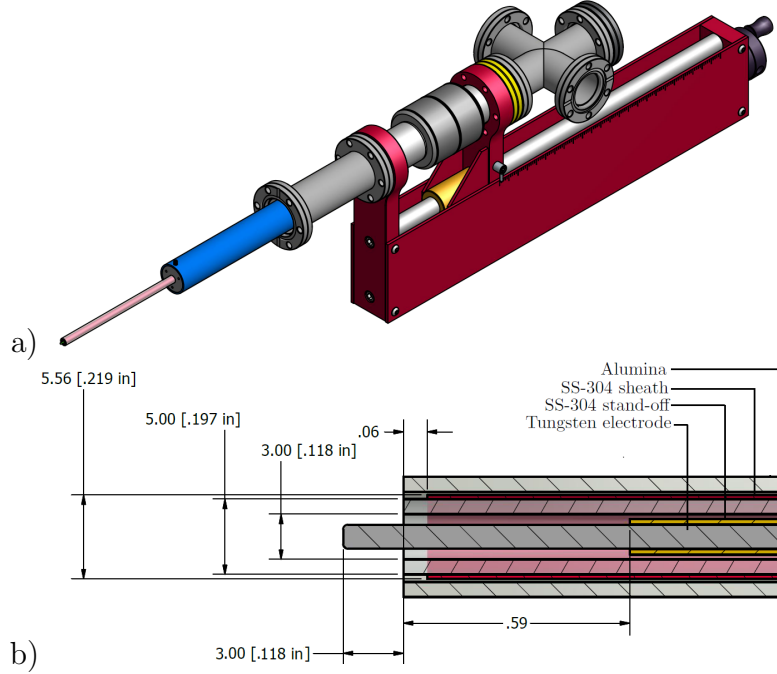


Figure 4.8: a) Bellows assembly for the low field side single langmuir probe b) Sub-assembly showing dimensions of the probe-tip and protective sheath.

choice of a single langmuir probe was made in light of the high edge temperature in the earlier flat temperature profiles measured on LTX. In addition to the low field side single langmuir probe, a series of 4 single tipped langmuir probes have been mounted on the center stack. All probes are ground through the shells, which are grounded in turn to the vessel.

4.2.1 Hardware design

The LFS SLP is mounted in a bellows drive with 12 in stroke, figure 4.8; the bellows drive is physically mounted at the midplane, between LM toroidal field coils. The probe tip is a tungsten wire whose ends have been rounded off with a grinder. The tip is 1 mm in diameter and is 3 mm in length. The tip is inserted into a stainless steel tube to provide a standoff between the tip and the alumina tubing that goes over it, providing a 0.5 mm annular gap between the two. This is done to ensure that the spacing between the probe tip and sheath is large enough, so that it cannot be bridged by lithium during operations. The probe tip is connected to a double sided Sub Miniature A (SMA) feedthrough, which is connected to the tungsten electrode through a kapton coated co-axial cable. The sheath

of the probe is connected to the vacuum vessel, and consequently to the return of the SMA feedthrough via a stainless steel collar that mates the probe tip subassembly to the tube that goes through the bellows. Like the SEP, the tube that goes through the bellows is threaded into a double-faced flange on the other side of the bellows drive.

4.2.2 Instrumentation and Commissioning

The low field side and high field side probes, due to design choices made regarding the probe tip's size, can draw ion saturation currents close to tenth of an ampere and an ampere, respectively, under certain LTX-like operating conditions. Larger probe currents favored using current transformers to detect and digitize probe currents (figure 4.9). The probe was swept using a Kepco Bi-Polar Operational Amplifier (BOP); the BOP is a programmable power supply that was fed using an arbitrary signal generator. The output of the BOP, either a sine or a triangular wave at 1000 kHz was put across the probe and triggered about 10 seconds before the initiation of a shot by LTX- β digitizer. The voltage signal was digitized through an isolation amplifier, and the current signal was obtained using a current transformer. The current signal was passed through a pre-amplifier before being digitized, the pre-amp was set for a pass-band of 300 Hz to 100 kHz, to reduce aliasing noise in the digitized signal, since, the digitization frequency was 500 kHz.

Figure 4.10 depicts the first set of data collected using the probes using the circuit illustrated in figure 4.9. The primary goal of the LFS SLP for this thesis was to measure the ion flux to the surface for a shot. This can be done by measuring the ion saturation current.

$$\Gamma_i = \frac{n_e}{Z_i} \sqrt{\frac{T_e}{m_i}} \quad (4.1)$$

where Γ_i is the ion flux to the surface, n_e is the plasma density, Z_i is the charge state of the ions, T_e is the electron temperature and m_i is the mass of ion. Ion saturation current is further related to electron density by the following relationship.

$$n_e = \frac{I_+}{eA_P \sqrt{\frac{T_e}{m_i}}} \quad (4.2)$$

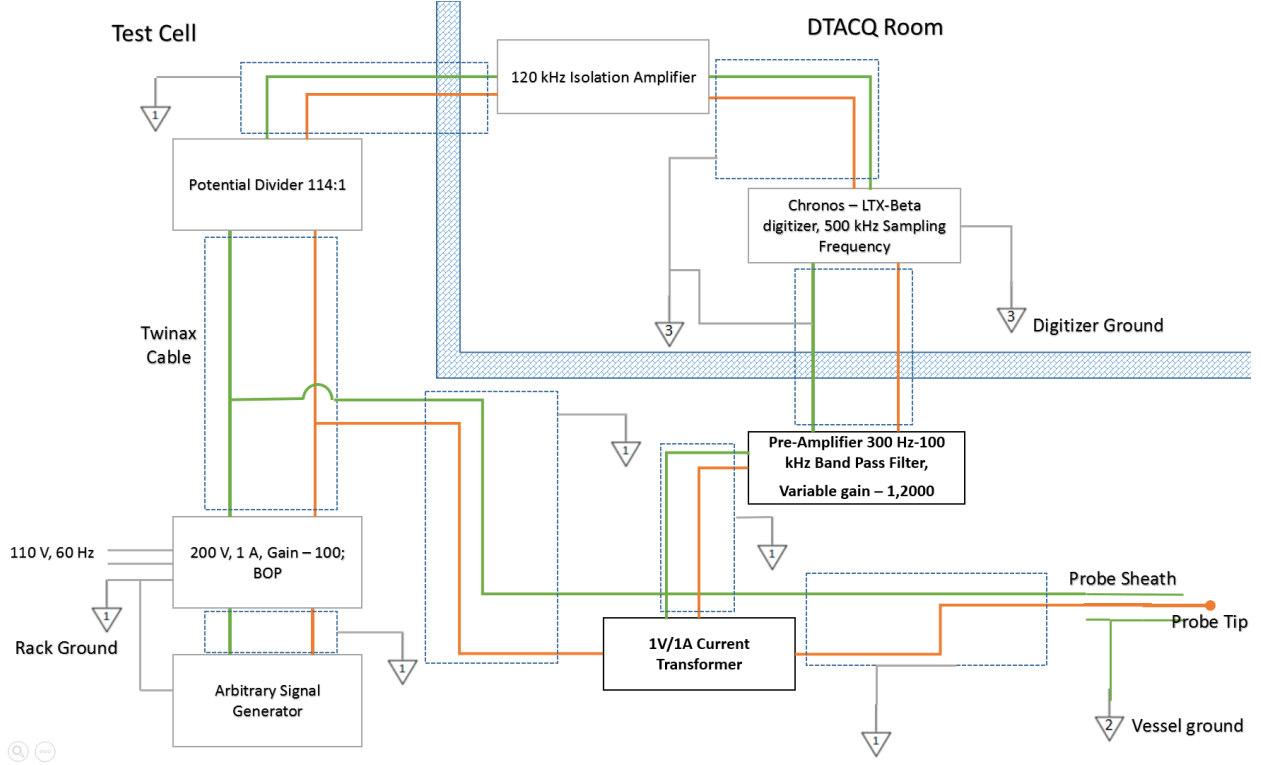


Figure 4.9: Langmuir Probe circuit used for sweeping and digitizing

where, I_+ is the ion saturation current measured by the probe, figure 4.10. Substituting eqn 4.2 into 4.1 yields a simple expression for ion flux, for figure 4.10 (a) the ion flux using the above expression can be estimated to be $2.5 \times 10^{22} m^{-2} s^{-1}$ which yields a $2.5 \times 10^{20} m^{-2}$ for a 10 msec shot like 101265. The probe traces in figure 4.10 depict two identical shots' traces near the beginning and the end of the discharge. The equilibrium reconstructions show the plasma limiting on the low field side in the beginning and then moving and collapsing on the high field side mid-plane limiters.

4.3 Lithium Evaporators and Quartz Crystal Microbalances

LTX- β features two lithium evaporators located toroidally opposite to each other. Each of the LTX- β lithium evaporators consists of a basket made of stainless steel mesh, suspended through two yttria rods for support. Evaporator temperatures are measured with a Type-K

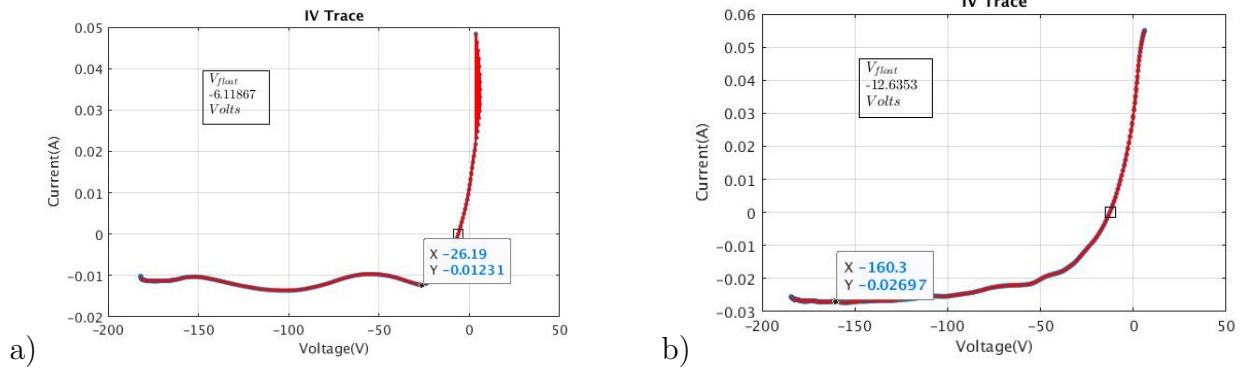


Figure 4.10: a) IV trace from low field side single langmuir probe, shot 101265, 12 msec after breakdown b) IV trace from high field side single langmuir probe, shot 101272, 18 msec after breakdown

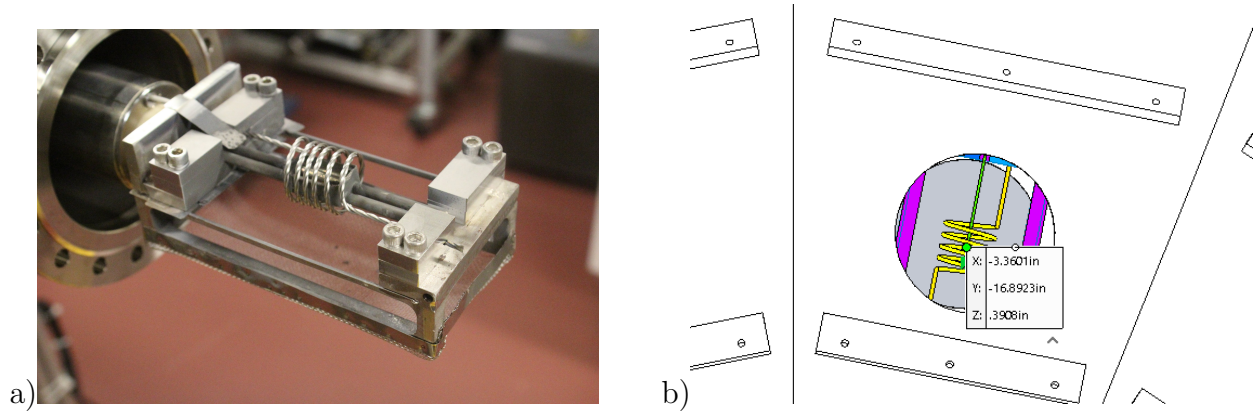


Figure 4.11: a) Lithium evaporator sub-assembly, the picture shows the tungsten heating element around a stainless steel screen basket that carries lithium. b) View of the evaporator subassembly from the top shell penetration, where the QCM is located.

thermocouple inserted into one of the yttria rods. The basket is surrounded by a tungsten coil heater that can be quickly ramped up to 60 amps (~ 500 W) to radiatively heat the lithium pieces loaded in the basket, figure 4.11 (a). The lithium pieces are pre-cut and loaded into a stainless steel container in an argon glove box for transfer under argon. Lithium evaporators are back-filled with dry argon and lithium coupons carefully transferred into the evaporator from the container. A slight outflow of argon from the evaporator assembly is maintained, thereby minimizing the exposure of lithium to atmosphere. LTX- β has two evaporators installed in diametrically opposite toroidal locations to provide near full coverage of PFCs by lithium coatings. Once lithium is loaded, the evaporators are pumped out and inserted into LTX- β , such that they are at the center of their respective poloidal planes. Each evaporator is situated under a shell penetration that provides line of sight to a Quartz Crystal Microbalance (QCM) figure 4.11 [60] (b). The QCMs are used to keep track of lithium deposited per evaporation.

The QCMs are oscillating quartz crystals, whose frequency changes as their mass changes when lithium is deposited on them. The frequency change can be directly related to the thickness of the lithium deposited if certain assumptions about film density and porosity are made.

4.3.1 Predicting Lithium Coverage on the Shells

Assuming the evaporator to be a point source, the mass deposited per unit area at the QCM can be approximated using the following relation [61].

$$\frac{dM_{QCM}}{dA_{QCM}} = \frac{M_e \cos \theta_{QCM}}{4\pi r_{QCM}^2} \quad (4.3)$$

where $\frac{dM_{QCM}}{dA_{QCM}}$ is mass per unit area at the QCM M_e is the total mass of lithium evaporated from the source, θ_{QCM} is the angle between the vector from source to the QCM normal ($\theta_{QCM} = 0$ in this case since the QCM is directly overhead the evaporator) and r_{QCM} is the distance between the point source and the substrate. Similarly, if we discretize the shell surface into sufficiently small triangular element, the lithium deposited per unit area per element can be approximated using the following expression.

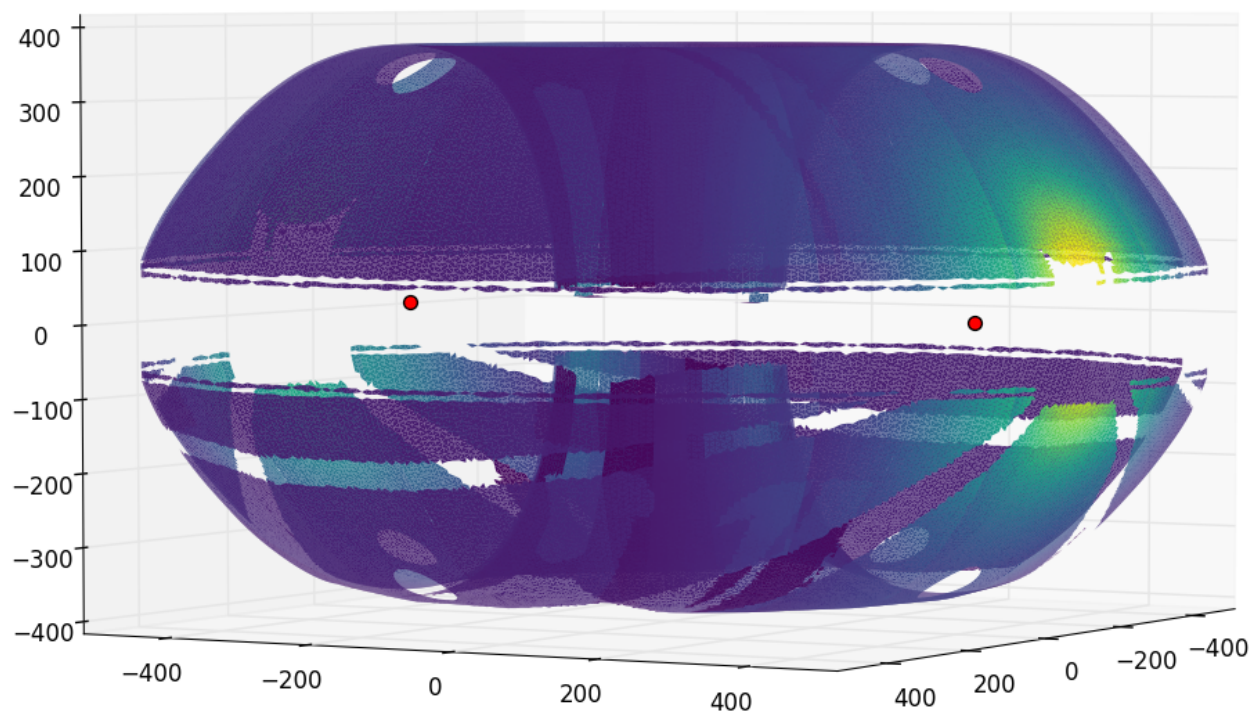


Figure 4.12: Lithium Shell coverage as predicted by the ray tracing model, from both evaporators. Evaporators are assumed to be a point source, whose position is depicted by the red dots, brighter color means more thickness.

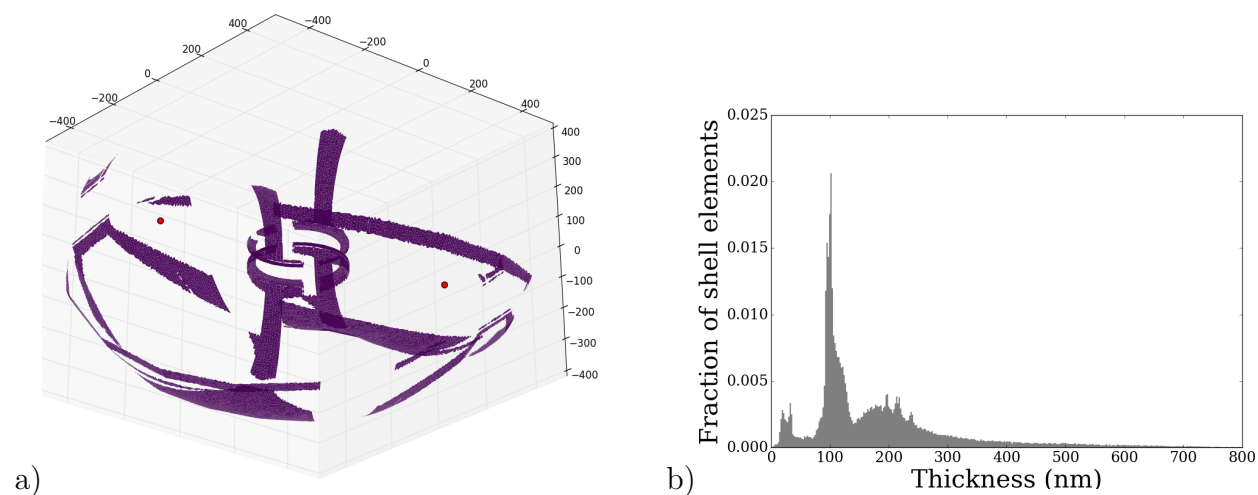


Figure 4.13: a) A view of shell elements that get no lithium from either evaporators b) Distribution of lithium thickness on shell elements that have line of sight to at least one evaporator.

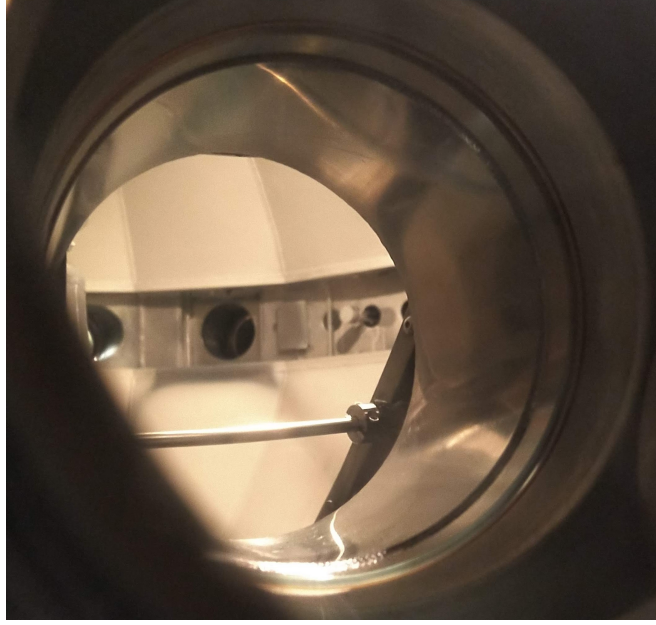


Figure 4.14: Low field side view of the port that hold one of the evaporators. Shadows are cast by lithium evaporations

$$\frac{dM_{elem}}{dA_{elem}} = \frac{M_e \cos \theta_{elem}}{4\pi r_{elem}^2} \quad (4.4)$$

rewriting eqn 4.3 for M_e and assuming lithium is deposited with a constant frequency

$$M_e = \frac{V_{QCM} \rho_{Li}}{A_{QCM}} 4\pi r_{QCM}^2 \quad (4.5)$$

Which can be further simplified as

$$M_e = t_{QCM} \rho_{Li} 4\pi r_{QCM}^2 \quad (4.6)$$

A similar equation can be written for an arbitrary shell element

$$M_e = \frac{t_{elem} \rho_{Li} 4\pi r_{elem}^2}{\cos \theta_{elem}} \quad (4.7)$$

equating 4.4 and 4.5 and solving for t_{elem}

$$t_{elem} = t_{QCM} \cos \theta_{elem} \frac{r_{QCM}^2}{r_{elem}^2} \quad (4.8)$$

Therefore, provided there is line of sight from the evaporator to an arbitrary element and the thickness of lithium deposited on the QCM is monitored, a lithium deposition profile can be estimated for the shells. A FORTRAN code was written using ray-tracing [62] and eqn 4.8 to estimate lithium coverage of the shells. Figure 4.12 depicts the solution of the code, the ray-tracing algorithm accounts for obstructions from shell elements, evaporator elements and the center-stack. Figure 4.13 (a) depicts the elements from the shell that saw no lithium coverage from either evaporators and figure 4.13 (b) is the lithium thickness distribution on shell elements for 100 nm of lithium deposited on both QCMs. The analysis concludes that around 86% of the shell surface area is coated with lithium. However, this is likely a conservative estimate. The photograph in figure 4.14 shows the low field side port of one of the evaporators on the inside was taken immediately after a lithium evaporation, back-illumination is provided by the vessel electron filament, that shadow cast on the low field side bottom shell by the evaporator carriage is more diffuse compared to the prediction in figure 4.12. There is no shadow seen on the low field side top shell in figure 4.14 in contrast to the prediction in figure 4.12.

Chapter 5

Surface Analysis and Correlation With Plasma Performance

The previous chapter highlights the hardware developed and used for characterizing the surfaces. This chapter goes into some details of LTX- β upgrade, surface science measurements and local recycling estimates.

The chapter begins by covering the upgrade and first high resolution measurements of evolution of evaporative lithium coatings in a tokamak, followed by a discussion on how lithium coatings affect plasma performance.

5.1 Upgrade to LTX- β

The upgrade to LTX- β included the ability to operate at higher fields and with more efficient Li evaporators (Fig. 5.1). The machine has been operated with 600 kW of neutral beam injection and a few hundred nanometers of lithium coatings [63]. Figure 5.3 illustrates the main plasma parameters of a wide variety of discharges through the upgrade campaign. It was observed that the discharges grew longer and had higher plasma current after lithium evaporation. In Fig. 5.3, lithium PFC discharges are divided into two groups. Discharges after the first lithium evaporation (represented by black bubbles in Fig. 5.3) had higher electron density, but were shorter in duration with lower plasma current. Discharges after subsequent lithium evaporations (represented by red bubbles in Fig. 5.3) could achieve

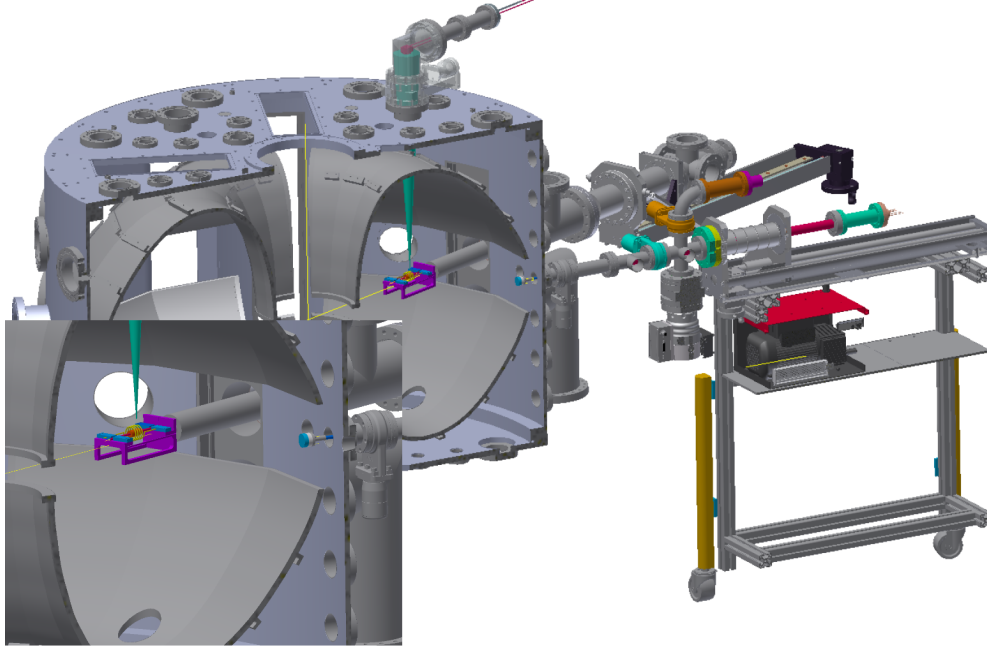


Figure 5.1: CAD section view of the evaporator inserted to the central poloidal location, the SEP, and the QCM above the LTX- β vacuum vessel. Also visible are the stainless-steel-clad copper shells inside the vacuum vessel. Inset shows zoomed in view of the evaporator sub-assembly and trajectory of lithium vapor toward the QCM.

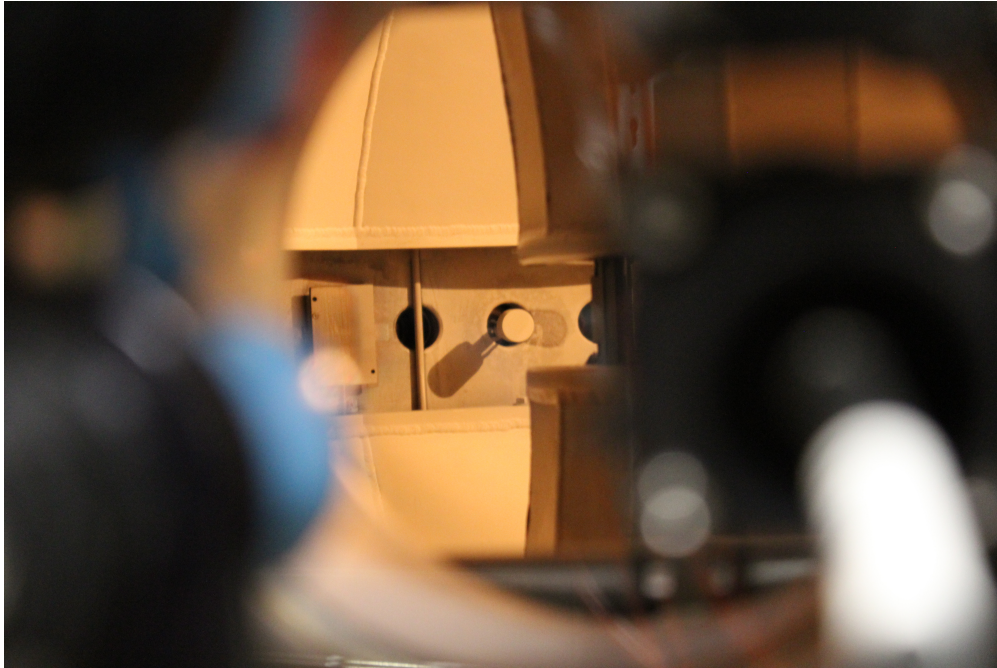


Figure 5.2: The SEP sample head immediately after a lithium evaporation. The sample head face is flush with the inner face of the LTX- β shells. Two shadows from the SEP sample head are visible, the shadow to the lower-left of the probe is cast by an in-vessel filament that is illuminating the vessel interior, the shadow to the right is cast by the lithium evaporator.

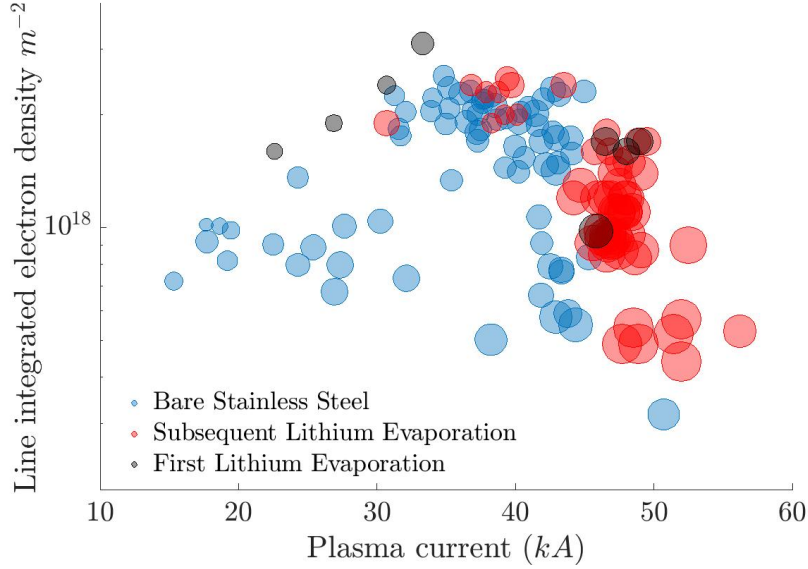


Figure 5.3: Line integrated electron density as a function of plasma current for LTX- β discharges; bubble size is proportional to plasma current flat-top duration of 4-40 msec.

longer durations and higher currents. Spectroscopic data indicated a reduction in carbon and oxygen impurities and an increase in lithium line emission when discharges were initiated after a fresh coat of lithium [63].

Simultaneously, the Sample Exposure Probe (SEP) is inserted to be flush with the plasma facing side of the shells, as shown in Fig. 5.2. The SEP is left in this position for lithium evaporations and subsequent plasma discharges. This paper analyses five such lithium evaporation events (Table-5.1). The lithium deposited per evaporation is recorded by the QCM; these recorded values can be used to estimate the thickness of lithium deposited on the SEP using the expressions for evaporative flux[61]. Assuming the evaporator sub-assembly to be a point source, the lithium thickness on the SEP can be estimated by Equation 5.1, where t_{SEP} is the thickness of lithium on the SEP, t_{QCM} is the lithium thickness measured by the QCM, θ is the angle from the point source to the SEP surface normal, r_{QCM} is the distance from the QCM to the evaporator source and r_{SEP} is the distance of the evaporator source to the SEP.

$$t_{\text{SEP}} = t_{\text{QCM}} \cos(\theta) \frac{r_{\text{QCM}}^2}{r_{\text{SEP}}^2} \quad (5.1)$$

Table 5.1: Chronology of lithium evaporation events on LTX- β

Days*	Li thickness QCM (nm)	Estimated Li on SEP (nm)
30.6	22	89.5
31.7	7	28.5
37.5	108	439.5
41.8	50.8	206.7
44.5	40	162.8

*Days from the first XPS measurement as referenced in Fig 5.4.

Once a desired exposure of residual vacuum or plasma discharges is achieved, the SEP is removed from LTX- β and moved to the Surface Science and Technology Laboratory (SSTL) at PPPL where it is docked to an Ultra High Vacuum (UHV) system that has a high resolution X-Ray Photoelectron Spectroscopy (XPS) spectrometer [64]. The transfer is made within limited time (< 1.5 hr), such that fluence of impurities on the surface is similar to a MAPP scan [64].

5.2 Enhanced Surface Analysis Capabilities

Prior to the introduction of lithium, surface conditioning at LTX- β involved Ne glow discharge conditioning (GDC) and simultaneous high temperature shell bakes at 250 °C. To ensure that the SEP sample head accurately represented the LTX plasma facing shells, the SEP was inserted flush with the shells during GDC and baked, and was maintained at the same temperature as the shells. Surface elemental composition was measured using XPS before and after the GDC (Fig. 5.4). It was observed that the elemental concentration of C declined while the concentrations of Fe and O went up; this is attributed to the sputtering of the adventitious carbon by Ne, which would result in the underlying iron oxides to appear brighter on the XPS scan. The sampling depth is expected to be around 6 nm [64]. For these measurements the SEP is left exposed inside LTX- β except for the brief intervals during which it is taken off for taking XPS data. Following the first lithium evaporation and subsequent LTX- β discharges, surface concentrations were measured again; the measurements show that the stainless steel substrate of the SEP was completely covered

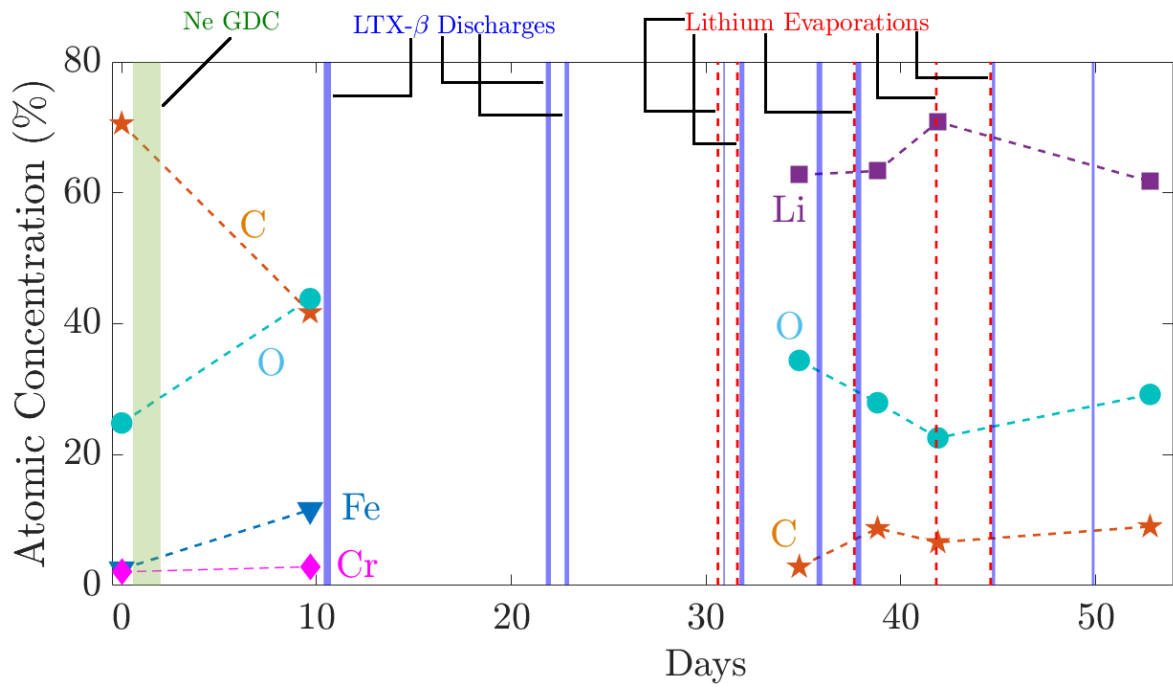


Figure 5.4: Elemental concentrations measured using the SEP. Vertical green bar annotates the neon glow discharge duration, vertical blue bars represent the time duration over which LTX- β discharges were initiated, dashed red lines represent lithium evaporations on the shells and SEP.

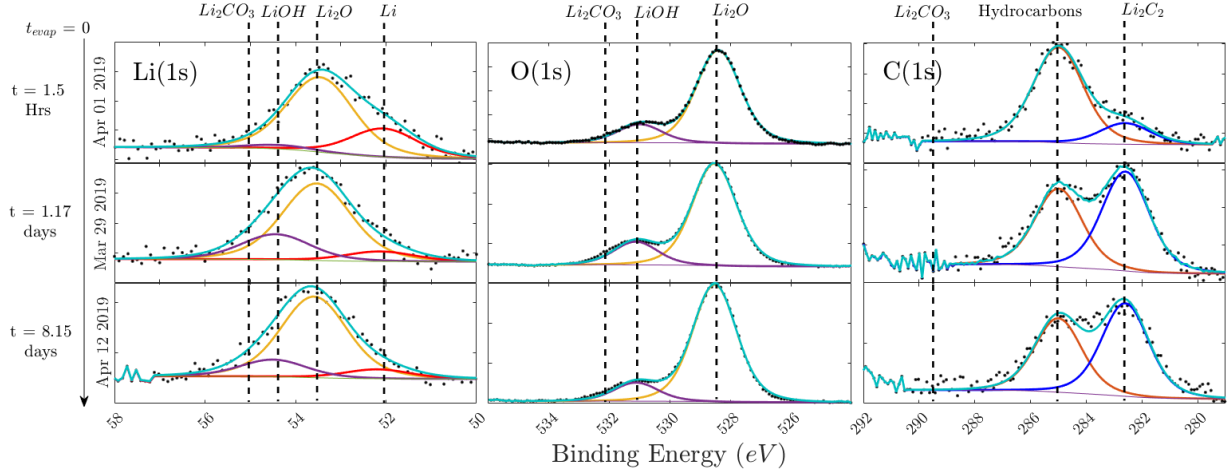


Figure 5.5: Narrow band regional XPS scans for Li(1s), O(1s) and C(1s) along with probable fits are shown in left, middle and right columns respectively. The scans are arranged row-wise in increasing order of time from a lithium evaporation.

by lithium. XPS measurements made for relatively fresh lithium coatings show higher Li and lower O concentrations; as the surface accumulates LTX- β residual vacuum exposure time, the O concentration seems to climb up and Li concentration is seen to decrease relative to O.

5.2.1 Surface Chemical Species Identification Using the SEP

Coupled with the XPS system at SSTL, the SEP enabled chemical identification of species present on the surface. Fig. 5.5 and 5.6 represent the regional narrow band scans collected for the samples whose elemental compositions are shown in Fig. 5.4. Similar studies have been performed for boronized NSTX-U PFCs [65], and have enabled identification of oxygen retention mechanisms that resulted in improved plasma performance.

The O(1s) peak, shown in the middle column of Fig. 5.5 exhibited two features which were identified to be Li_2O and LiOH at the binding energies of 528.5 and 531.1 eV respectively. The absolute values of these binding energies and the difference between them is consistent with results cited elsewhere[66, 67]. The O(1s) Li_2CO_3 peak was identified to be at 532.1 eV [66, 67, 68], for measurements that were taken after the first application of lithium on steel PFCs of LTX- β Fig. 5.6. All peaks are referenced to a hydrocarbon peak in the C(1s) region at 285 eV. An additional feature in the C(1s) region at 282.6 eV is attributed to lithium

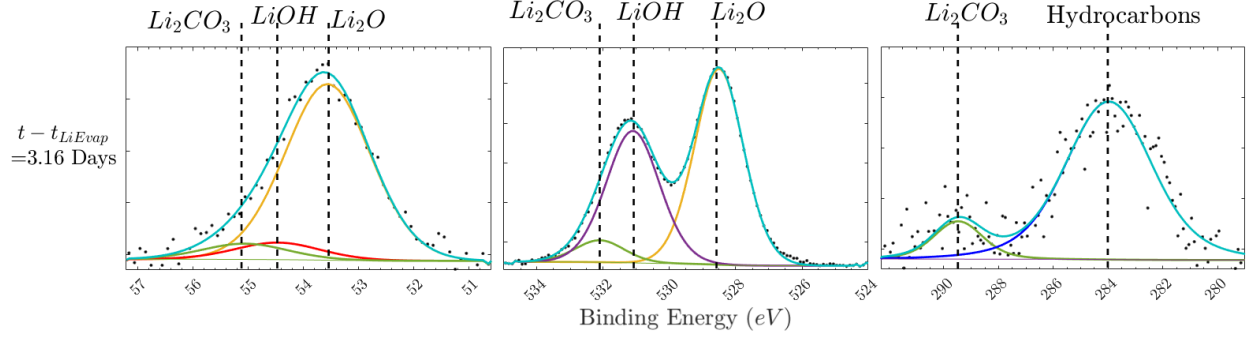


Figure 5.6: Narrow-band regional XPS scans along with probable fits for Li(1s), O(1s) and C(1s) are shown in left, middle and right columns respectively. The scan was taken 3.16 days after lithium was deposited on bare stainless steel walls and sample head of the SEP.

carbide with reference to the hydrocarbon peak at 285 eV; this assignment is consistent with values in the literature [69]. The higher energy feature in the C(1s) region visible in Fig. 5.6 at 289.4 eV is attributed to Li_2CO_3 . The Li(1s) region in both Fig. 5.5 & 5.6 was fit with peaks at 52.03, 53.4, 54.3 and 55 eV for Li, Li_2O , LiOH and Li_2CO_3 , respectively. The difference in binding energies of these fits were forced to be consistent with values reported in literature [66, 68, 52].

The narrow region scans elaborate on the richness of surface chemistry of evaporative lithium coatings on PFCs. The surface chemistry is both a function of tokamak residual vacuum and plasma exposures, and is expected to be similar across machines that employ lithium coatings. However, the rate of growth of these species will be dependent on each machine's residual vacuum and plasma exposure conditions. The O(1s) region indicate that the primary lithium species on the PFC is Li_2O followed by LiOH. First application of lithium as shown in Fig. 5.6, however, appears to result in the formation of Li_2CO_3 and LiOH in addition to Li_2O ; this was observed along with plasma performance that was moderate in comparison to performance after a few more evaporations, as witnessed by an increase in plasma current and density, as seen in Fig. 5.3. This is likely a result of vacuum and PFC surface conditions being different from samples represented by Fig. 5.5, for which lithium was evaporated on already lithiated PFCs. The carbonate production is likely a result of adventitious carbon on the stainless steel surface, which although reduced in magnitude after glow discharge conditioning, was still amongst the two largest elemental constituents of the steel PFC.

Two novel observations can be made about lithium PFCs that consist of evaporative lithium coatings. First is the formation and growth of lithium carbide, as can be seen in the C(1s) regional scan in Fig.5.5. The second is the presence of a relatively large elemental lithium peak in row 1 of Fig.5.5 column 1. The presence of elemental lithium indicates that the oxide grows on top of lithium deposited during evaporation events.

The chemical evolution of lithium coated evaporatively on stainless steel PFCs was tracked through surface conditioning, lithium deposition and plasma discharge events. This was made possible due to the SEP. The results support the hypothesis that for evaporative coatings of lithium under low-water residual vacuum, Li_2O grows before transitioning to LiOH . It can be further hypothesized that the first few lithium evaporations of a few hundred nanometers in total on LTX- β shells were able to limit carbon uptake in subsequent lithium coatings from underlying stainless steel. The presence of elemental lithium seen in freshly deposited lithium coatings indicate limited oxygen co-deposition with lithium and hint at an ordered growth of lithium oxide on top of elemental lithium. Since, low recycling in LTX was achieved with similar coatings, it is likely that hydrogen uptake by both lithium oxide and lithium must have been responsible for achieving lowered recycling. Indeed, it has been demonstrated in offline experiments that hydrogen uptake capability of lithium and lithium oxide are comparable[70].

5.2.2 Estimating Oxide Overlayer Thickness

The Li(1s) region scan for freshly deposited lithium (Fig. 5.5, row 1, column 1) can be used to estimate the overlayer thickness of Li_2O on Li, provided we assume that the oxygen was not co-deposited with the lithium. The assumption seems reasonable because of low partial pressures of oxygen carrying species during an evaporation, as measured by the RGA (by about a factor of hundred). For the regional scan mentioned above, the signal intensities for Li and Li_2O , I_{Li} and $I_{\text{Li}_2\text{O}}$ were measured to have a ratio of ~ 2.6 .

For an arbitrary material, if the XPS signal from the first (topmost) monolayer is I_0 , then the signal I_n from an arbitrary monolayer n can be represented by the following equation.

$$I_n = I_0 e^{-x/\lambda} \quad (5.2)$$

Here, x is distance of the monolayer n from the top and λ is the electron inelastic mean free path (IMFP). The total signal I can therefore be approximated by the following integral,

$$I = \int_0^\infty I_0 e^{-x/\lambda} dx \quad (5.3)$$

If the electrons need to travel thickness a before they can exit the material, eqn. 5.3 can be modified as,

$$I = \int_0^a I_0 e^{-x/\lambda} dx = I_0 \lambda (1 - e^{-a/\lambda}) \quad (5.4)$$

If $\frac{d}{\cos\theta} = a$, where the sample surface normal is at θ degrees from the electron analyzer axis, the signal from Fig. 5.5, row 1, column 1 can be approximated as d nm thick Li_2O on Li , therefore the signal intensity from Li_2O can be approximated using eqn. 5.4 as

$$I_{\text{Li}_2\text{O}} = I_{0,\text{Li}_2\text{O}} \lambda_{\text{Li}(1s) \rightarrow \text{Li}_2\text{O}} \cos\theta (1 - e^{-d/(\lambda_{\text{Li}(1s) \rightarrow \text{Li}_2\text{O}} \cos\theta)}) \quad (5.5)$$

The signal I_{Li} from a pure metallic lithium system can be approximated using eqn 5.3; however, since the lithium is buried under the oxide of a known thickness, the lithium thickness will be attenuated by the appropriate exponent of the form given in eqn 5.2, where, $I_{0,\text{Li}_2\text{O}}$ is the signal from the top monolayer of Li_2O , $\lambda_{\text{Li}(1s) \rightarrow \text{Li}_2\text{O}}$ is the $\text{Li}(1s)$ electron IMFP in Li_2O and z is in the same direction as d , the attenuated signal can be expressed in the following form,

$$I_{\text{Li}} = \left[\int_0^\infty I_{0,\text{Li}} e^{-z/(\lambda_{\text{Li}(1s) \rightarrow \text{Li}} \cos\theta)} \right] e^{-d/(\lambda_{\text{Li}(1s) \rightarrow \text{Li}_2\text{O}} \cos\theta)} \quad (5.6)$$

Simplifying the notation by assigning $\lambda_{\text{Li}(1s) \rightarrow \text{Li}} = \lambda_{\text{Li}}$ and $\lambda_{\text{Li}(1s) \rightarrow \text{Li}_2\text{O}} = \lambda_{\text{O}}$; further assuming $I_{0,\text{Li}_2\text{O}} = 4I_{0,\text{Li}}$, since the density of Li_2O is roughly 4 times that of elemental lithium, eqn 5.6 and eqn 5.5 can be rewritten as,

$$I_{\text{Li}_2\text{O}} = 4I_{0,\text{Li}} \lambda_{\text{O}} \cos\theta (1 - e^{-d/(\lambda_{\text{O}} \cos\theta)}) \quad (5.7)$$

$$I_{Li} = \left[\int_0^\infty I_{0,Li} e^{-z/(\lambda_{Li} \cos \theta)} \right] e^{-d/(\lambda_O \cos \theta)} = I_{0,Li} \lambda_{Li} \cos \theta e^{-d/(\lambda_O \cos \theta)} \quad (5.8)$$

Taking the ratio of eqn 5.7 to eqn 5.8 and rearranging leads to a simple expression for oxide overlayer thickness,

$$d = \lambda_O \cos \theta \log \left[\frac{I_{Li_2O} \lambda_{Li}}{4 I_{Li} \lambda_O} + 1 \right] \quad (5.9)$$

Eqn 5.9 leads to a thickness of 1.2 nm for the signal from Fig. 5.5, row 1, column 1, using IMFP values provided in [50] and $\theta = 54^\circ$ as mentioned in chapter 4. This means that an oxide layer 1.2 nm thick or roughly 5 monolayers of oxide grows on Li during transport and analysis after a fresh evaporation in LTX- β , since Li_2O is expected to have a monolayer thickness of 0.23 nm. This analysis can be repeated a few times while varying residual vacuum exposure times and monitoring oxide film thickness. The data can then be fit to the oxide growth model mentioned in chapter 2.

5.3 Co-relating Surface Conditions to Local Recycling for Primarily Li_2O Surface

Using the SEP with the PHI, various compounds that grow on evaporative thin lithium films have been successfully detected; in section 5.2.1 it was briefly discussed how these coatings quickly grow Li_2O on them before the coating transitions to LiOH . We further observe that the presence of a few nm of Li_2O on top of elemental Li does not seem to degrade plasma performance. This has been pointed out for historical LTX results in section 2.2.2; although a direct estimate of recycling is not available for all of the shots analyzed in section 2.2.2, it is observed that the plasma current is comparable even after weeks have passed after a lithium evaporation. These observations lead to the hypothesis that Li_2O itself might be responsible for hydrogen retention that results in improved plasma performance. To test the hypothesis, the sample exposure probe and the single langmuir probe were used. Additionally, the spectroscopic emission of Li, O and H were tracked using LTX filterscopes. The LTX filterscopes are treated in more detail in earlier work on LTX[71].

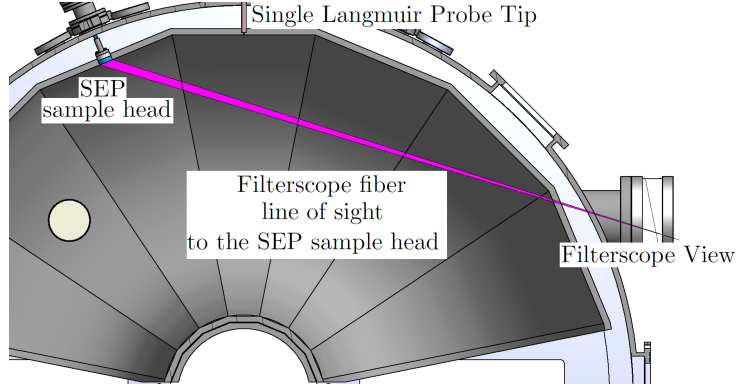


Figure 5.7: A top half-section CAD view of LTX- β showing the positions of the SEP, SLP flush with the shells and the line of sight of a fiber connected to Li_{II} , O_{II} and D_{β} filterscopes, focused on the SEP, the fiber was focused such that the view through the fiber was smaller than the surface area of the SEP sample head.

5.3.1 Experimental Setup and Sequence of Events

The sample exposure probe sample head, previously coated with lithium for the data collected in section 5.2.1, had been passivated by a partial vent such that the surface was mostly Li_2CO_3 . The SEP sample head was subsequently heated in a controlled manner to about 200°C, which seemed to get rid of most of the carbonate, leaving behind a Li_2O surface that slowly oxidized to $LiOH$. Simultaneously, the LTX- β vessel was back-filled with argon to calibrate the Thomson Scattering laser prior to these experiments. The back-fill resulted in the lithium coatings inside the vessel turning brown for the most part; this was thought to be a combination of lithium nitride and lithium carbonate. The vessel was baked at 200°C just before plasma operations. Both the LTX- β vacuum vessel and the SEP were subjected to conditions that contaminated their surfaces. They were then baked to the same T, and this provided matching surfaces for the pre-lithium baseline conditions. The SEP was mounted on the the LTX- β vessel and made flush with the low field side of the shells, as shown in fig 5.7. Simultaneously, the single langmuir probe was mounted on a low field side midplane port and inserted into the same position as the SEP (fig 5.7).

A filterscope fiber bundle was installed behind an 8-inch conflat viewport. One of the fibers of the fiber bundle was made to focus on the SEP sample head such that the view through the fiber was smaller than the probe area (fig 5.7). This was done to sample emissions primarily from the surface of the probe. The fiber was split into three channels, looking at

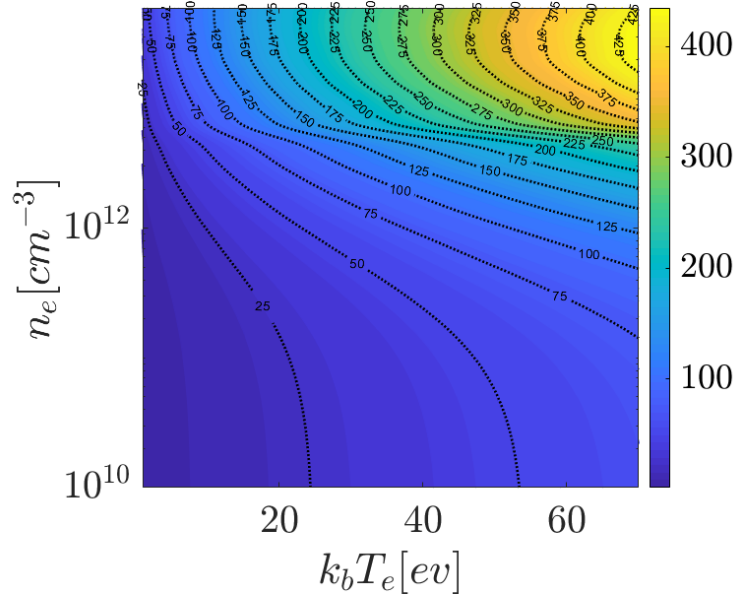


Figure 5.8: S/XB coefficients for H_β as a function of $k_b T_e$ and n_e . Data interpolated from [16]

$D_\beta = 486nm$, $Li_{II} = 548.6nm$ and $O_{II} = 441.6nm$. Li and O emission lines were chosen, since they are the prime surface constituents, and D_β was chosen instead of D_α because it had a better signal-to-noise ratio. The line integrated-emission intensity is proportional to the measured signal using the following equation.

$$I_\lambda \left[\frac{\text{photons}}{m^2 - s - sr} \right] = CV_{sig} \quad (5.10)$$

where I is the intensity at a particular wavelength, V_{sig} is the digitized signal and C is a proportionality constant. Furthermore, the intensity I is related to the flux from the surface (assuming small ionization lengths) by the following expression.

$$\Gamma_i^{wall} = 4\pi(S/XB)I_\lambda \quad (5.11)$$

$$R_{plate} = \frac{\Gamma_i^{wall}}{\Gamma_i^{surface}} \quad (5.12)$$

S/XB coefficients are tabulated in the ADAS database [16]. The coefficient is the ionization rate normalized by the product of excitation rate and radiative decay probability, or branching ratios. Γ_i^{wall} , provided by eqn 5.11 and normalized by $\Gamma_i^{surface}$ (obtained from

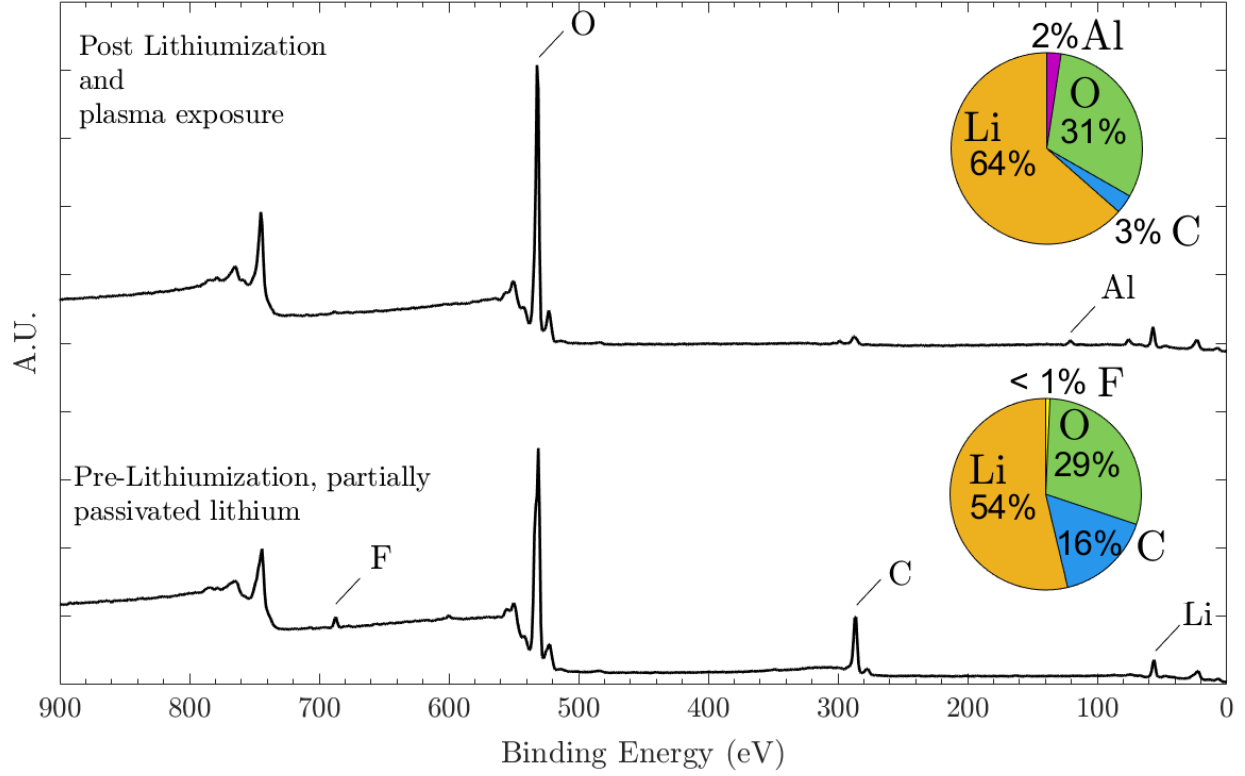


Figure 5.9: Pre (bottom) and post (top) exposure broad energy range XPS survey scans. The pre-lithiumization SEP sample head showed larger amounts of carbon and some fluorine, this was followed by 2 weeks of residual vacuum exposure, where lithium was evaporated after a week of plasma exposure and plasma shots were taken a few days before evaporation and 8 days after evaporation; post exposure scans reveal little carbon and some quantity of aluminum, likely from a damaged langmuir probe alumina sheath.

the single langmuir probe), is used as an estimate for local recycling. Since $I_{\lambda}S/XB$ actually gives the ionization rate and not a quantity that is equal to the flux of neutrals from the wall, eqn 5.12 is an approximation. Estimates of the neutral ionization length for LTX- β -like plasmas indicate the value to be in centimeters,[71] and therefore, eqn 5.12 is actually a poor estimate. However, more rigorous estimates require Monte Carlo neutral particle modeling with a plasma profile from LTX- β , which are out of scope for this work.

5.3.2 XPS Scans Before and After Plasma Exposure

After docking the SEP onto LTX- β , the probe saw a week of residual vacuum exposure at typical vacuum vessel pressures. Lithium was then evaporated and shots 101355 to 101395 were taken eight days later. Based on data presented in earlier sections, this should have been

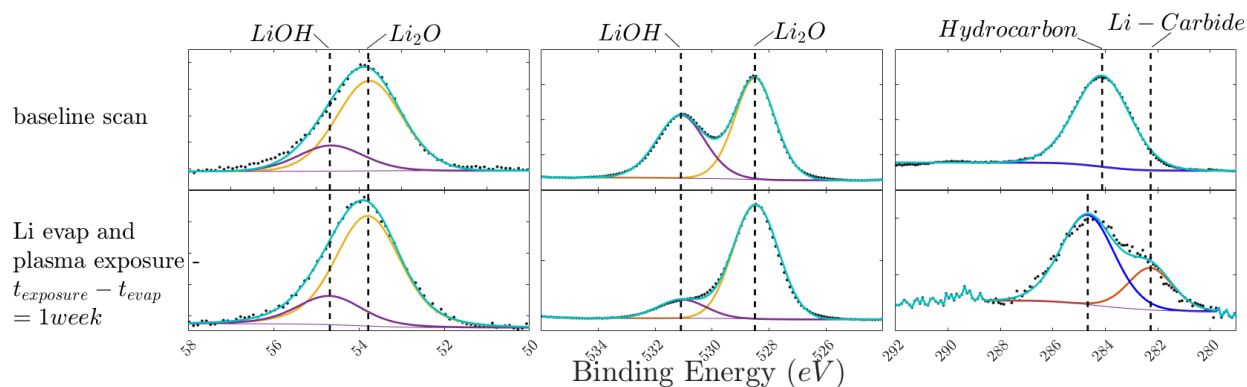


Figure 5.10: Narrow band regional XPS scans for Li(1s), O(1s) and C(1s) along with probable fits are shown in left, middle and right columns respectively. Peaks identified were close in binding energy and FWHM to the features observed in section 5.2.1 Fig. 5.5. It was observed that the large hydroxide peak goes away after lithium and plasma exposure, carbide feature is similarly visible in the post exposure carbon scan.

enough time to oxidize most of the top 6nm of the evaporated lithium. The QCM recorded 140 nm for the evaporator close to the SEP; this translates to a lithium thickness of close to 500 nm on the SEP based on eqn 5.1. An XPS scan was taken right before the probe was installed in LTX- β , and the probe was transferred back to the PHI 12 hours after the last shot (101395) to take scans again. A comparison of the survey spectra is shown in fig 5.9. Pre-exposure survey spectra show a larger carbon feature compared to post-exposure; this is likely a result of the fact that the probe saw multiple power outages, one of which was after the probe was baked to 200 C. Post-exposure scans show little carbon and aluminum; the low carbon content is consistent with previous results and the presence of aluminum can be explained by the damaged alumina sheath from the single langmuir probe next to it (more details in section 5.3.4). The presence of fluorine prior to plasma exposure is puzzling. This could be from a high temperature bake that the PHI and the SEP were subject to, since the gate valves on both systems are viton sealed, and fluorine is a constituent of viton.

Narrow regional scans for Li(1s), O(1s) and C(1s) are shown in fig 5.10; the binding energies and peak widths are consistent with the previous dataset as described in section 5.2.1. Although pre-exposure scans contained larger amounts of carbon, the region of the narrow scan that should correspond to Li_2CO_3 did not see a large feature. It is possible that a carbonate feature can be fit to the Li(1s) and O(1s) scans of the sample. This would only improve the fit marginally, and it was avoided to maintain a fitting philosophy of minimum

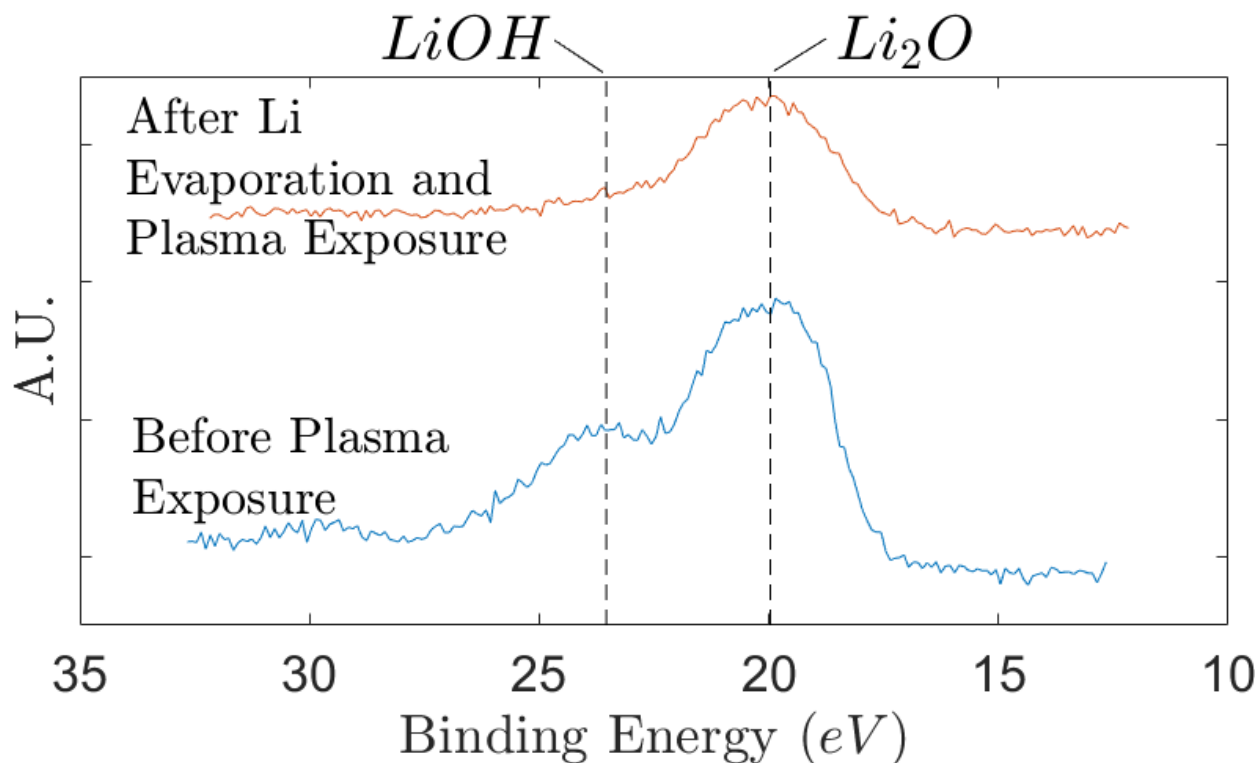


Figure 5.11: Narrow band regional O(2s) scans before and after exposure, the peaks are identified to be Li_2O at 19.96 eV and LiOH at 23.54 eV, the ratio of $\text{Li}_2\text{O}/\text{LiOH}$ peak intensities in O(2s) is lower compared to O(1s), indicating that LiOH is on top of Li_2O .

number of peaks for explaining most of the data. The prime constituent post-exposure, as seen earlier, is Li_2O . However, the pre-exposure Li_2O and LiOH both constitute a significant fraction of the surface.

Additionally, for both pre and post-exposure scans, the O(2s) narrow region peak was recorded. This was done to look at the relative weight of the hydroxide vs oxide feature in O(1s) and O(2s) for a direct comparison, fig 5.11. Since the O(2s) peak is detected at low binding energies, which consequently means electrons have higher kinetic energy when they escape the surface, the O(2s) signal samples deeper into the surface. The ratio of Li_2O and LiOH peak intensities for the O(1s) signal, as seen in fig 5.10 (top row), is measured to be 1.35, whereas the same ratio for the O(2s) signal is measured to be 1.67. This indicates a larger Li_2O signal for O(2s) compared to O(1s).), indicating that LiOH is likely a surface species for the baseline scans.

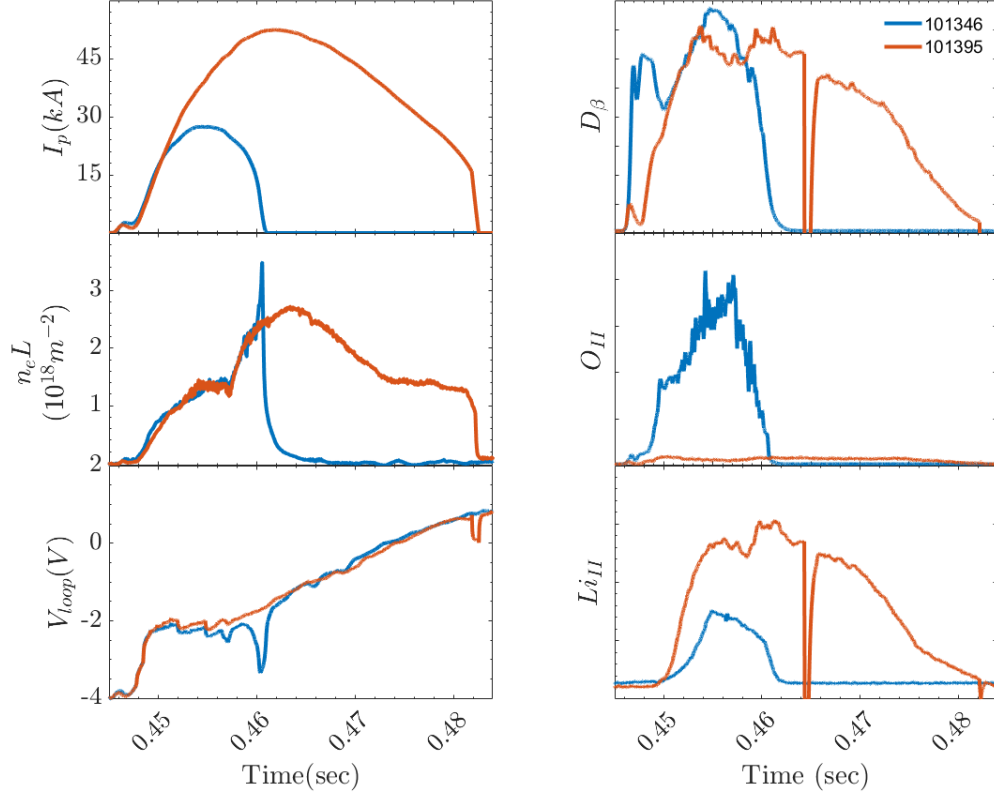


Figure 5.12: Two shots 101346 (before lithium evaporation) and 101395 (8 days after lithium evaporation) are compared with similar coil programming and gas puff programming such that the line integrated electron density(column 1 middle row) are similar to each other

5.3.3 Plasma Performance Before and a Week After Lithium Evaporation

Plasma performance was compared using all available discharge parameters. A plasma current Rogowski coil [72] measures the plasma current. The LTX- β 1 mm interferometer measures line-integrated plasma densities along the poloidal midplane. The loop voltage is measured using the toroidal flux loop [72]. The integrated emission intensities ($D_\beta = 486nm$, $Li_{II} = 548.6nm$ and $O_{II} = 441.6nm$) are measured by the filterscope fiber looking at the Sample Exposure Probe. All signals are filtered using a $0.7 \mu sec$ filter to remove noise introduced by the ohmic solenoid power supply.

Figure 5.12 shows key plasma performance indicators for two shots, 101346 and 101395. Shots 101346 and 101395 are typical of their run day. 101346 was a day before lithium evaporation and 101395 was 8 days after lithium evaporation. These shots were chosen in

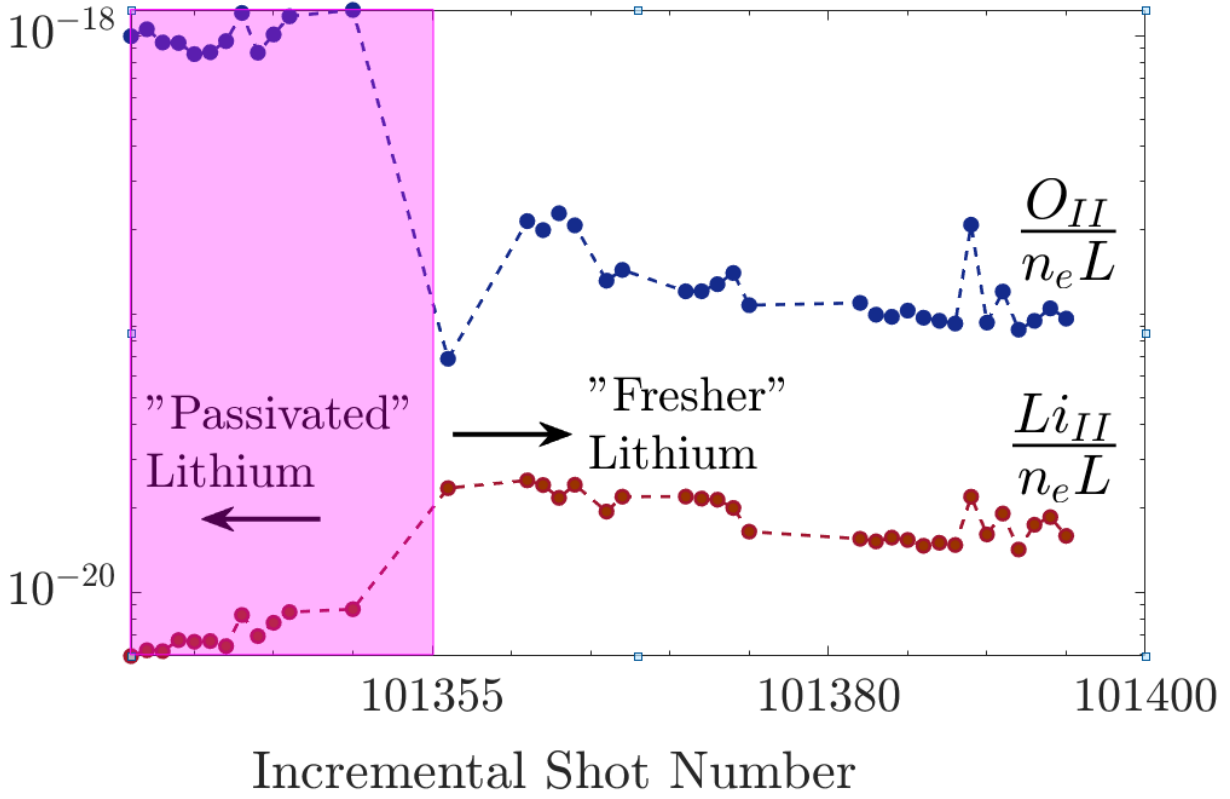


Figure 5.13: O_{II} and Li_{II} as measured by the fiber whose view is shown in Fig. 5.7, the signals are averaged over the first 10 msec of the shots where densities are similar. O_{II} normalized by the line integrated electron density sees a drop by an order of magnitude and $\frac{Li_{II}}{n_e L}$ sees an increase by an order of magnitude. The plot highlights that oxidized lithium coatings are capable of sequestering oxygen and thereby improving plasma performance.

particular since they had closely matching line integrated electron densities. The shots have identical coil programming; however, significantly more gas had to be pumped in to initiate a breakdown for 101395. Since LTX- β has no feedback control on the plasma current, its magnitude and duration are a qualitative measure of plasma performance. Even 8 days after evaporation and substantial oxidation of the PFC, the improved plasma performance is observed. The O_{II} is seen to reduced and Li_{II} emission is seen to increase. The loop voltage is similar; however, there is an improvement in both shot duration and maximum plasma current.

Additionally, OII and LiII line integrated emission intensities were tracked for all the shots for the two run days corresponding to before lithium and 8-day-old lithium. Fig 5.13 represents the trends for the fiber focused on the SEP. The raw signals for emission intensities

are normalized by line-integrated electron densities to normalize the effect of emission from the plasma volume. A strong drop in the O_{II} was seen in shots after lithium evaporation, and an increase by an order of magnitude was observed in Li_{II} intensities. This indicates a propensity of Li surfaces to sequester oxygen by forming Li_2O and/or a propensity of the surface to let go oxygen more easily, either by chemical or physical sputtering, once $LiOH$ is formed. The D_β signal over the same period for the two classes of shots normalized by the line integrated electron density was relatively flat. Strong O_{II} emission is also evident in fig 5.1.2, (column two, middle frame) before lithium evaporation.

Plasma equilibrium reconstructions using PSI-TRI [73] show little difference in the way the plasma evolves. Both 101346 and 101395 start with a large plasma volume and limiting on the low field side, and eventually moving towards the high field side and collapsing on the high field side midplane limiter.

5.3.4 A Note on Local Recycling

The following section elucidates an attempt to quantify local recycling, and observations regarding hydrogen pumping, for the two classes of shots discussed in section 5.3.3. The key difference between the two run days was that 2.5 to 3 times more gas had to be pumped in after lithium evaporation to match the same line integrated electron density. In fact, gas puff programming identical to shot 101346 was unsuccessful in initiating a break-down post lithium evaporation. Fig 5.14 compares gas puffs for two run days with gas calibration shots, or shots that had the same gas puff programming as a plasma shot but a breakdown was not initiated.

Gas calibration shots for 101346 and 101395 were not available; two corresponding shots were chosen for the same run. Gas puff programming for pre lithium shot 101328 and its gas calibration shot 101330 are shown in fig 5.14 on the left. The plasma on 101328 quenched at 0.465 seconds. At the instant the fast ion gauge read a difference of less than a percent between 101328 and 101330. The plots for the hydrogen pressures thus nearly overlay, and the small difference between the two is reflected in the purple trace (with legend entry - Retained) in fig 5.14. However, for post lithium (8 days old) lithium shot 101382 and its

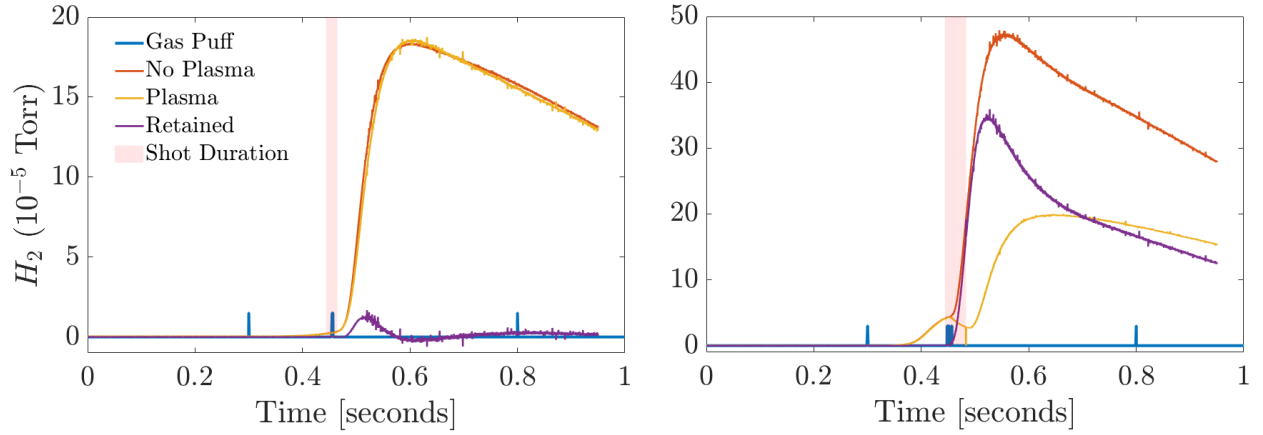


Figure 5.14: Gas puff behaviour before and after the lithium evaporation, on the left are shots 101330 (gas puff only), 101328 (plasma shot) and their difference, the timing and duration of the gas puffs are also indicated, the duration of the plasma shot (yellow trace) is highlighted by the width of the vertical red band. On the right shots 101381 (gas puff only) and 101382 (plasma shot) are shown along with their difference, the plots show that tokamak PFCs are retaining a substantial portion of the hydrogen pumped in during a discharge even with partially oxidized days old evaporative lithium coatings.

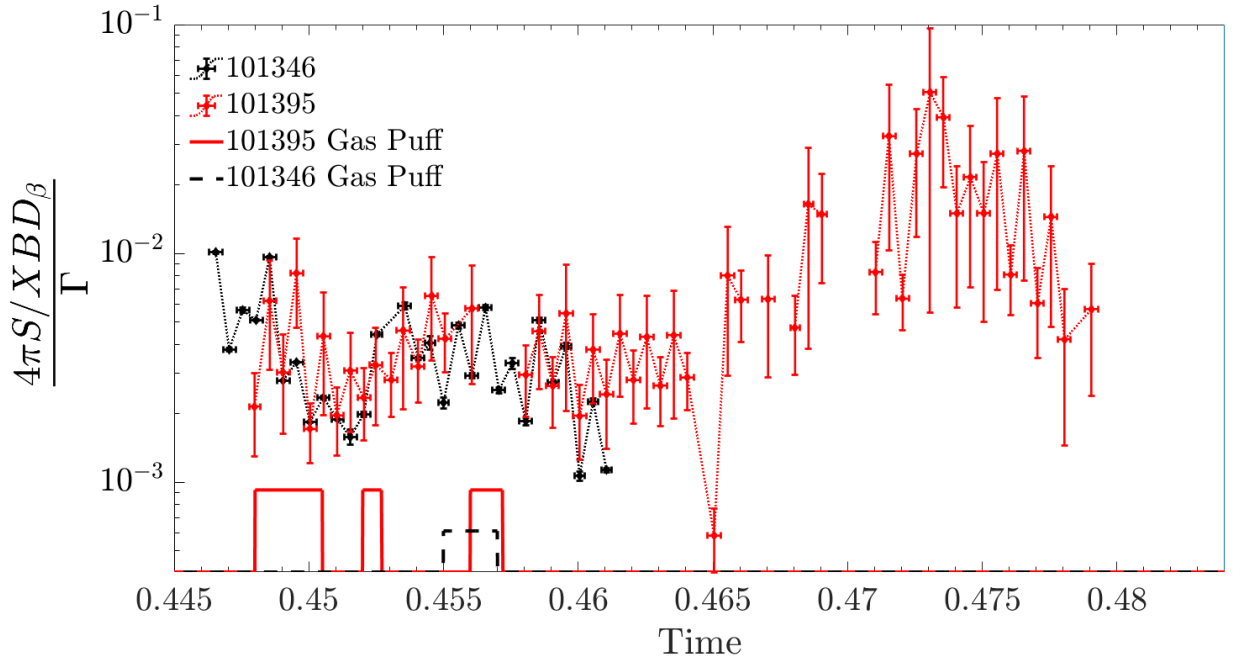


Figure 5.15: Shots 101346 (before lithiumization) and 101395 (8 days after lithiumization) are compared, the ordinate axis indicates a proxy for local recycling coefficient, based on eqn 5.11 and 5.12, on the SEP sample head. It is assumed that the plasma is toroidally symmetric. Relative sizes of the gas puffs for the two shots are shown, total pressure in the vessel and pressure profile is expected to be similar to fig 5.14

corresponding gas calibration shot 101381, the difference at the end of the shot at 0.483 seconds is 85%. This higher retention of hydrogen is shown on the right side of fig 5.14.

Earlier surface science experiments have shown that Li_2O can retain hydrogen at rates comparable to pure lithium films in vacuum [70]. The retention data presented in fig 5.14 is consistent with that picture. LTX- β is eventually expected to have shot-averaged global recycling measurements, based on neutral particle modeling and $Ly - \alpha$ emissions, since $Ly - \alpha$ is less prone to reflections from PFC surfaces compared to visible light lines such as D_β . Based on this information, it is hypothesized that global particle recycling will not change substantially after initial lithium evaporation as Li_2O grows on the lithium surface. Rather, a sharper drop in recycling is expected when LiOH accumulates on the surface.

Local recycling as estimated by eqn eqn 5.11 and 5.12 were also tracked for shots 101346 and 101395 fig 5.15. No large difference between the shots emerge. However, it should be noted that post-lithium shot had similar $\frac{(S/XB)D_\beta}{\Gamma_i}$ to pre-lithium shots, in spite of the fact that almost three times as much hydrogen had been puffed into LTX- β . This is consistent with the difference in the hydrogen retention by the LTX- β PFCs after lithium evaporation discussed earlier.

There seems to be a modest increase in $\frac{(S/XB)D_\beta}{\Gamma_i}$ for shot 101395 towards the latter half of the discharge, which seems puzzling. However, more detailed analysis of the langmuir probe data, shown in fig 5.16, which indicates that Γ_i drops by an order of magnitude towards the latter half of the shot. This is reflected in the n_e estimates, which show a 1 to 2 order of magnitude drop. The electron temperature sees an uptick for the latter half of the shot as well. Lower density and higher temperatures at the edge are both consistent with lowered plate recycling; This provides independent confirmation of earlier results when flat electron temperature profiles were achieved after edge fueling ended. However, the ratio $\frac{(S/XB)D_\beta}{\Gamma_i}$ is seen to go in opposite direction. A possible explanation for this behaviour can be the fact that $(S/XB)D_\beta$ is related to the ion flux and not neutral hydrogen flux. The neutral ionization length is directly proportional to neutral hydrogen speed, which scales with incoming ion speed, and inversely proportional to electron density. It can then be hypothesized that for the latter half of the discharge, the ionization length from the surrounding surfaces increases sufficiently to be measurable along the fiber line of sight to the SEP.

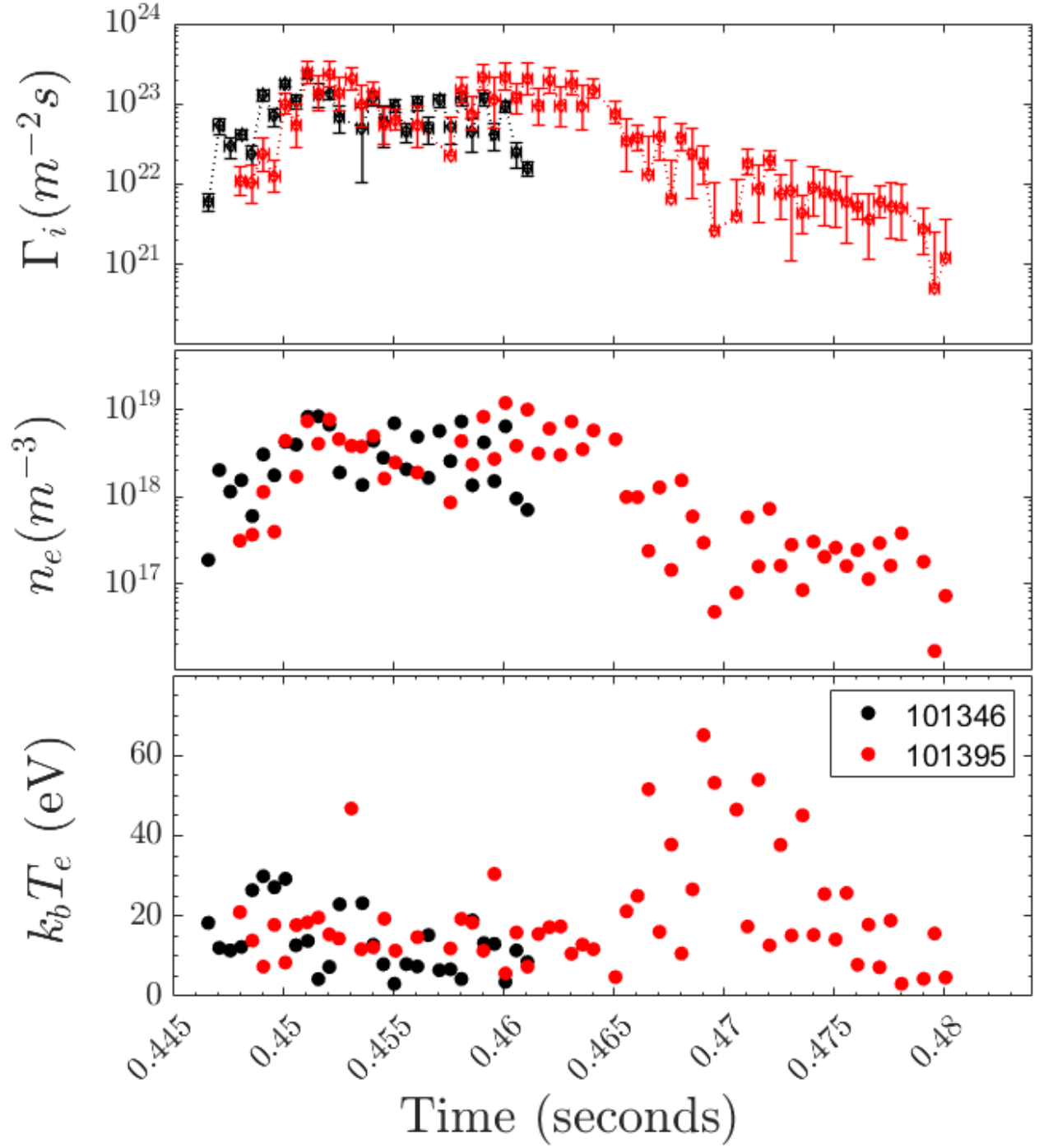


Figure 5.16: Shots 101346 (before lithiumization) and 101395 (1 week after lithiumization) are compared, the ordinate axis indicates a proxy for local recycling coefficient since D_β is acquired from a fiber which has a narrow solid angle looking directly at the SEP sample head, $\Gamma(a)$, $kT_e(a)$ and $n_e(a)$ are ion flux, electron temperature and electron density as measured by the the single langmuir probe, it is assumed that the plasma is toroidally symmetric.

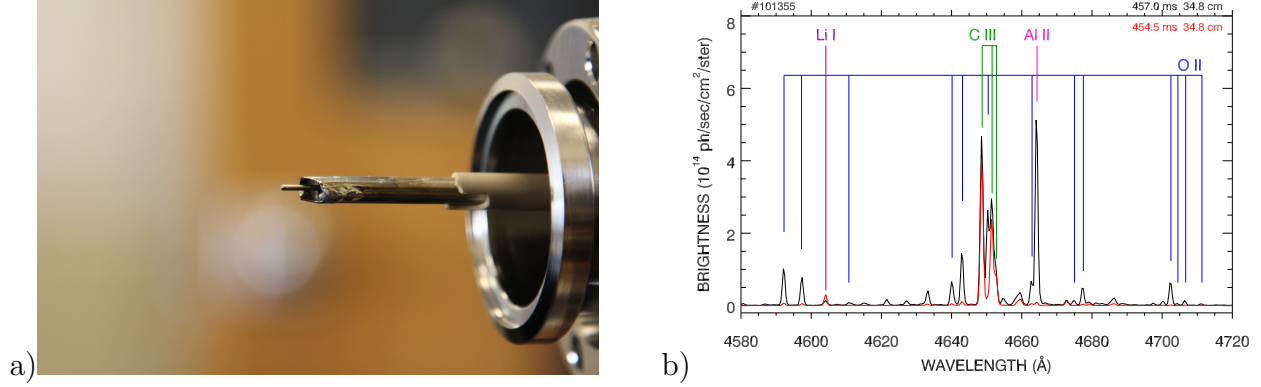


Figure 5.17: a) An image of the damaged single langmuir probe, the outer alumina sheath had broken away and the inner stainless steel sheath (return) had melted in the co-electron direction b) HAL spectra for shot 101355 overlayed for 454.5 and 457 msec, showing a bright Al line at 457 msec - courtesey: R. Bell

For the first shot of post lithium run day - 101355, the high-resolution visible (HAL) spectrometer identified a bright aluminum line (fig 5.17). This was the first instance such a line had been detected. The langmuir probe was removed a few days later and a visual inspection showed that the outer alumina sheath had broken away, possibly due to thermal shock from energetic (runaway) electrons, and the stainless steel sheath underneath it had melted in the electron drift direction. The tungsten probe tip itself was intact, however, so the probe still collected data. Examination of the exposed probe tip showed that the probe area increased by a factor of 1.65 in the electron drift direction and a factor of 1.1 in the opposite directions. These increases in the probe tip areas were taken into account while putting error bars on the $\frac{(S/XB)D_{\beta}}{\Gamma_i}$ in figures 5.15 and 5.16. The error bars are larger compared to those for the pre lithium evaporation measurements, but the general trend is still observable.

Chapter 6

Conclusion and Future Work

The thesis began with a literature review of historical LTX results, and certain open questions were posed in section 2.2.3. The first of these questions related to identification of the species that grow on lithium films on LTX, how these films interact with the plasma and affect plasma performance. The remaining two were about how the plasma interacts with these films and the possible explanations for hydrogen outgassing from surfaces after shots for lithiumized PFCs (fig 2.10).

This chapter concludes the thesis by highlighting the degree to which the questions were answered. Recommendations for future work to further address them are also included.

6.1 Conclusions

The conclusions are listed in the order in which they were presented in the thesis.

Offline characterization of lithium PFCs is difficult unless multiple characterization techniques are locally available, and sample transfers from the plasma exposure location to the analysis facility can be made in a clean, quantified and calibrated way. The offline experiments in chapter 3 established the efficacy of surface analysis techniques under controlled laboratory conditions. The feasibility of sample transfer to RBS facility was demonstrated. The work also demonstrated the necessity for sample transfer approaches under high vacuum.

To this end, a large part of the thesis involved the design and use of the Sample Exposure Probe or SEP (section 4.1 and Appendix-A). At the conclusion of the thesis, most of design goals were demonstrated. The only exception was Temperature Programmed Desorption (TPD). Although the heater for the TPD was installed on the SEP, time did not permit surface studies with this capability.

The SEP demonstrated that vacuum suitcases can afford a solution that avoids building material characterization test stands around a tokamak, where space and access can limit the type and energy resolution of the instruments they include. As long as care is taken so that residual vacuum exposure during transport is less than tokamak residual vacuum exposure, the SEP enables samples to be brought to facilities where multiple and more powerful characterization techniques compared to those attached to tokamaks can be utilized.

The thesis provides the first identification, using XPS with sufficient energy resolution, of chemical species that nucleate on evaporative lithium coatings in a tokamak. This relates to the first open question posed in section 2.2.3. Based on the peaks identified using XPS, it can be said that lithium evaporators on LTX- β mostly deposit elemental lithium that quickly begins to transform into lithium oxide (section 5.2.1); a growth rate can then be extrapolated based on XPS data. These results further substantiate the hypothesis that lithium oxide grows on elemental lithium before the surface transitions to lithium hydroxide for LTX- β like vacuum conditions. The presence of lithium carbide is new information, since in the presence of lithium, carbon and oxygen, lithium carbonate should form. Binding energies are reported in table 6.1.

It was observed that the presence of lithium hydroxide is consistent with poor plasma performance; such plasma saw higher O_{II} emission compared to mostly Li_2O surfaces. The thesis hypothesizes that the oxygen in LiOH is loosely bound compared to Li_2O and is readily released to the plasma during a shot, thereby cooling the plasma radiatively. This perhaps answers a longstanding question about LTX and LTX- β plasmas that saw good performance (high plasma current) weeks after lithium evaporations, before the surface transitions from Li_2O to LiOH . This was one of the possibilities assumed for LTX, but not confirmed until the direct measurements of Li_2O and LiOH were made in the present work for LTX- β PFCS. Additionally, comparison of the time evolution of gas puffs with and

without plasmas indicated that even lithium coatings which were days old, and are mostly Li_2O for at least the first 6 nm, pumped hydrogen better than LiOH coatings (fig 5.14).

The single langmuir probe analysis shows that for post-lithium shots (101395, 8 days old), the density drops and the temperature rises after fueling is terminated (fig 5.16). This provides independent support for the measurement of flat electron temperature profiles and high edge temperatures with the Thomson scattering diagnostic under similar conditions on LTX. It should be noted that the single Langmuir probe, on a bellows drive for varying its position relative to the LTX- β plasma, was constructed for this work. As a practical matter, the langmuir probe circuit used a current transformer instead of a resistive circuit (section 4.2.2). This provides a simpler solution to measuring and isolating plasma current from a single langmuir probe, provided that the sweep frequency is within the transformers bandwidth.

Moreover, more hydrogen gas to the tune of 2-4 times compared to pre-lithium discharges, is required to initiate a discharge post lithium evaporation. The temperature rise and density drop after fueling terminations are exactly the conditions under which LTX observed lowered recycling. Lithium coatings thus keep plasmas from collapsing radiatively by sequestering impurities, and at the same time, pump hydrogen. The present work has shown, for the first time, what compounds actually are on the lithium-coated PFC surfaces when impurity sequestering and hydrogen pumping are present and absent.

6.2 Recommendation for Future Work

More questions can be answered with the addition of the SEP as a tool for PFC characterization. To that end, a few simple experiments might be able to inform on them.

- A central question that remains unanswered is how does recycling change as lithium coatings oxidize to lithium oxide first and then lithium hydroxide; i.e., is there a knee point in R at the transition from Li_2O to LiOH ? Based on the data provided in Chapter-5, it is hypothesized that R will not change dramatically as Li converts to Li_2O . Sharper changes (drops), on the other hand, are expected as the surface begins to accumulate LiOH . Additional Lyman- α detector arrays need to be installed to avoid the problems

with reflections that limit the utility of measurements in the visible range for global recycling.

- The growth rate of oxide coatings can be pegged down by taking more data points following the application of evaporative coatings as a function of time. These data can then be used with the thin film growth rate model to arrive at a growth rate of oxide at a given pressure. This information can provide vital clues regarding the dependence of plasma performance on the relative concentration of Li_2O and LiOH .
- The absolute quantity of hydrogen retained can be estimated by TPD measurements (which the SEP is capable of); relating this to recycling studies will provide key insight into retention mechanism and its relationship to plasma performance for Li_2O and LiOH coatings on lithium.
- Density Functional Theory-based Quantum Classical Molecular Dynamics studies of how lithium oxide and hydroxide films react with one another, pure lithium and incoming hydrogen ions can provide insights regarding the detailed chemistry of retention and impurity sequestration.
- The temperature dependence and the impact on plasma performance for these films remains unexplored and can be probed with the SEP. The properties of liquid lithium films are of interest to LTX- β , and the conducting shells can be heated from room temperature to several hundred degrees above the melting point of lithium.
- The SEP probe head can be used as an implantation sample to get an idea of ion implantation depth. A silicon wafer can be mounted on the sample head and later removed for Secondary Ion Mass Spectroscopy (SIMS) to estimate implantation depth and profile. This will enable comparison with SDTrim studies that can reveal the incoming ion energy distribution. This will clarify what part of the evaporative coating (surface or bulk) interacts more with hydrogen.
- A more rigorous estimate of recycling needs to be explored to truly capture how oxidized lithium interacts with the plasma. The method used in chapter-5 to arrive

Table 6.1: Detected binding energies of various compounds on lithium surfaces using SEP with PHI; absence of any uncertainty indicates single dataset

Peak	Species	BE $\pm 2\sigma$ (eV)
<i>Li</i> (1s)	<i>Li</i>	52.12 ± 0.13
	<i>Li₂O</i>	53.6 ± 0.26
	<i>LiOH</i>	54.5 ± 0.26
	<i>Li₂CO₃</i>	55
<i>O</i> (1s)	<i>Li₂O</i>	528.49 ± 0.01
	<i>LiOH</i>	521.09 ± 0.01
	<i>Li₂CO₃</i>	522.1
<i>C</i> (1s)	Li-Carbide	282.52 ± 0.32
	Hydrocarbon	284.6 ± 0.98
	<i>Li₂CO₃</i>	289.4
<i>O</i> (2s)	<i>Li₂O</i>	19.96
	<i>LiOH</i>	23.54

at a local recycling coefficient can be used for a steady state plasma source that can be well diagnosed, using a gridded energy analyzer or a langmuir probe. A practical setup could be developed using the SEP and the ECR plasma source mentioned in Chapter-3. In such a setup, the filterscope fiber can be made to look parallel to the SEP surface as it is swept backward to track the ionization flux, which can be related to neutral particle density using plasma parameters measured separately.

- Another exciting possibility is Raman spectroscopy. Small form factor Raman probes are already commercially available. One of these probes can be mounted on the SEP vacuum chamber to look at the sample between shots. The advantage Raman spectroscopy is its ability to detect and identify LiH, which is harder to do with other analytical methods.
- When the oxide layer is growing, it is unclear whether the plasma ions incident on the PFC are mostly interacting with oxidized lithium or bulk lithium below it. It is also unclear how contaminated the fresh lithium coatings are on LTX, because the data at shorter time scales has considerable uncertainty (figure 2.8(a)). The cause

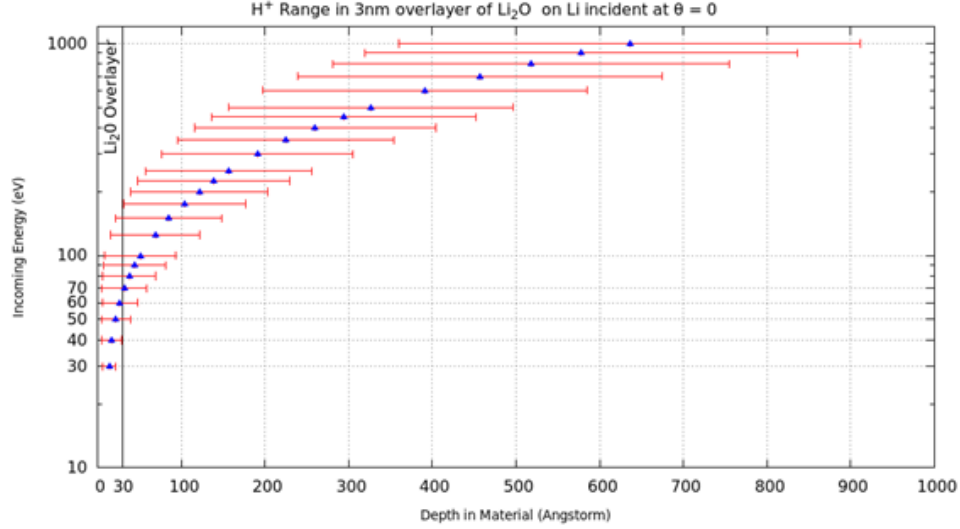


Figure 6.1: TRIM runs for hydrogen ion implantation range for incoming energies between 30eV and 1keV; the target is modeled to be a 3nm layer on top 100nm pure lithium (the red error bars are Range Straggle).

of this uncertainty includes the fact that the impact energy and angle distribution of ions in the SOL that end up being accelerated by the sheath and hitting the PFC, are unknown for LTX. If these parameters can be determined and the LTX PFC is well characterized, TRIM [53] runs can be made to model the implantation profile of hydrogen ions (figure 6.1), and may enable a quantitative comparison of the retention capabilities of oxidized lithium and freshly-deposited lithium.

- It could be hypothesized that incident hydrogen is bound by the lithium-oxygen mixture in some metastable state, such that it is free to diffuse out at the end of the shot. This provides a motivation to determine diffusion coefficients of all hydrogenic species in lithium compounds like Li_2O , $LiOH$, and Li_2CO_3 . First principles Molecular Dynamics (MD) based simulations have been used in the past to compute diffusion coefficients of deuterium in lithium (figure 6.2) [15]. The results indicated that the diffusion coefficients depend on the ratio of lithium to deuterium. Computing diffusion coefficients at lower temperatures, however, is computationally intensive because diffusion scales strongly with temperature. If such calculations are possible, however, they might be able to shine some light on the time dependence of the hydrogen retention seen in the RGA data.

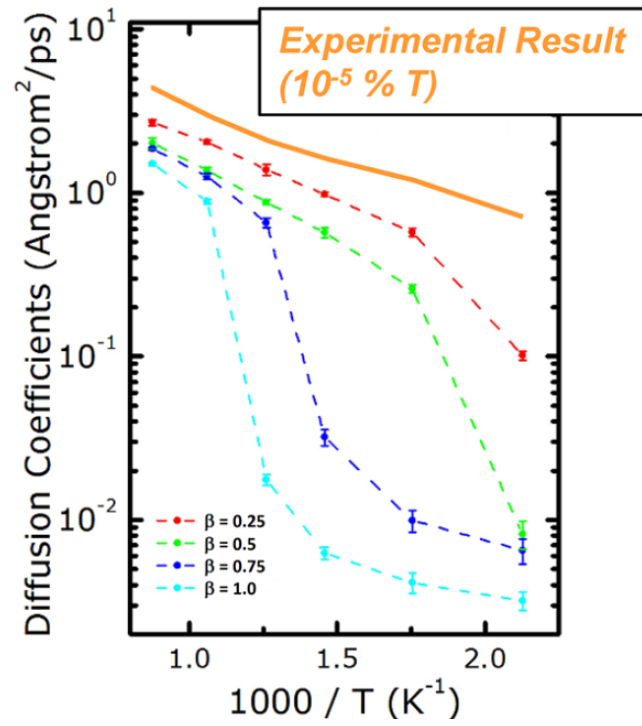


Figure 6.2: Deuterium diffusivity in lithium based on first principles MD simulations (β is the ratio Deuterium-to-Lithium concentrations). [15]

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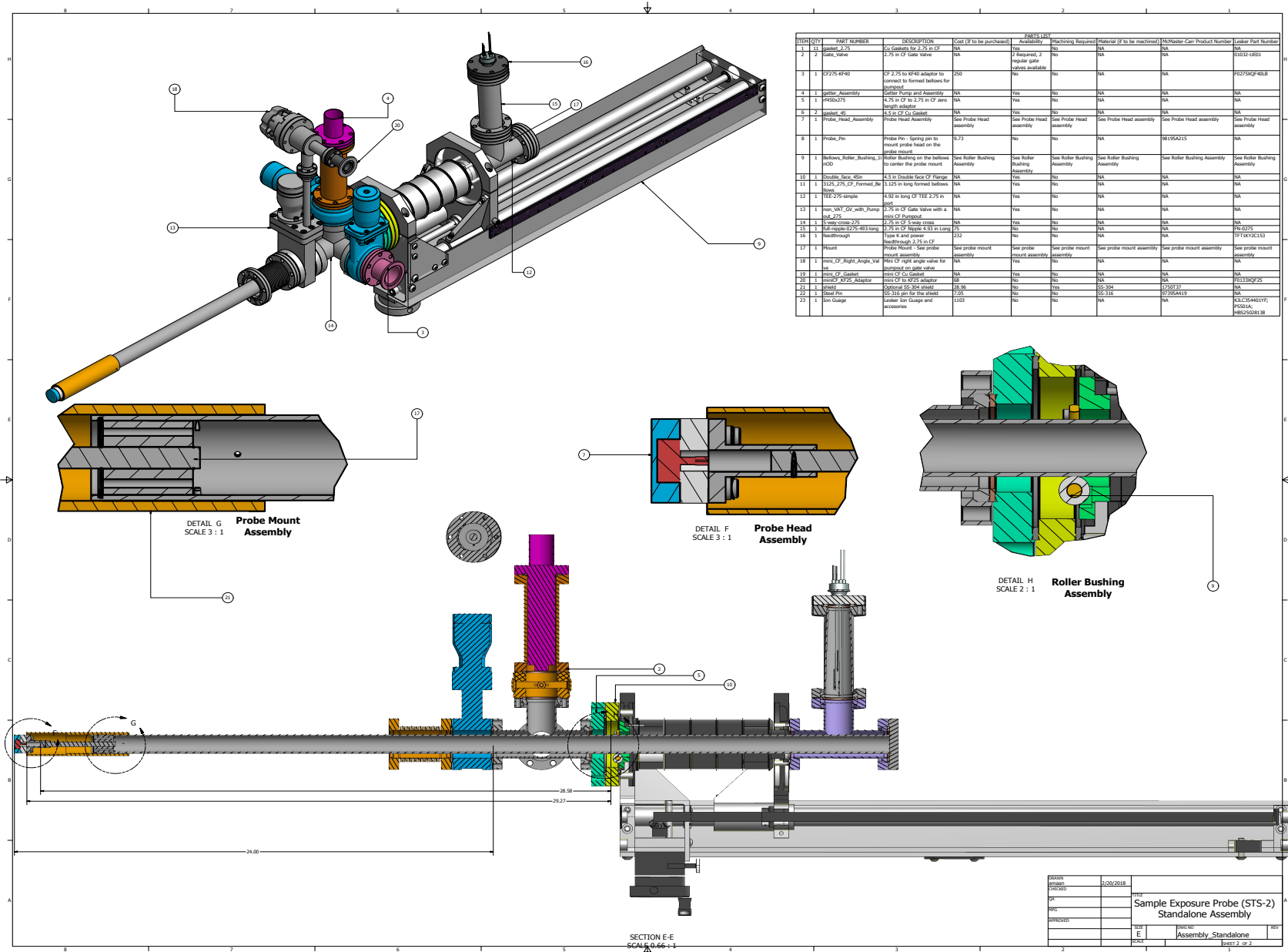
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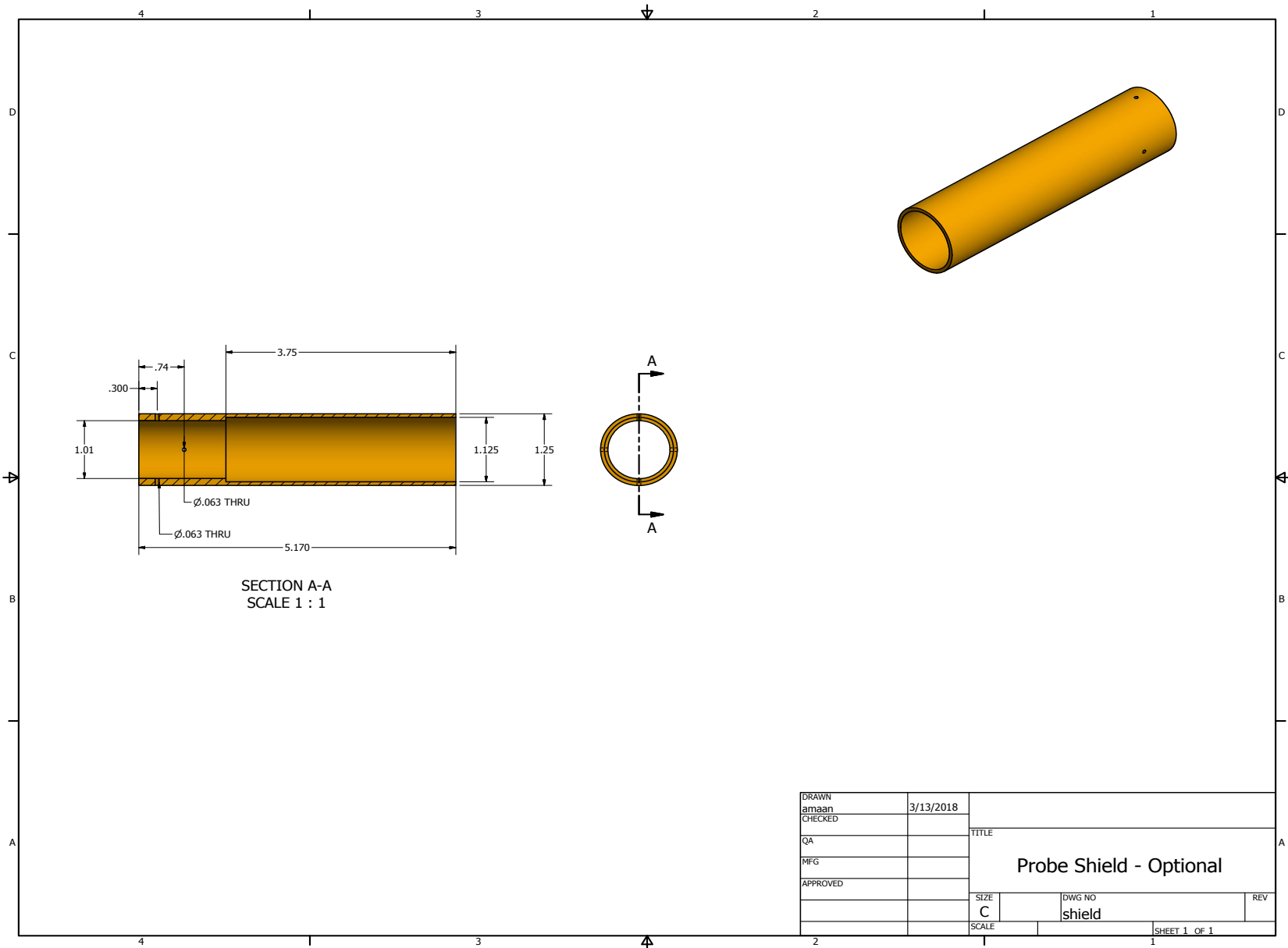
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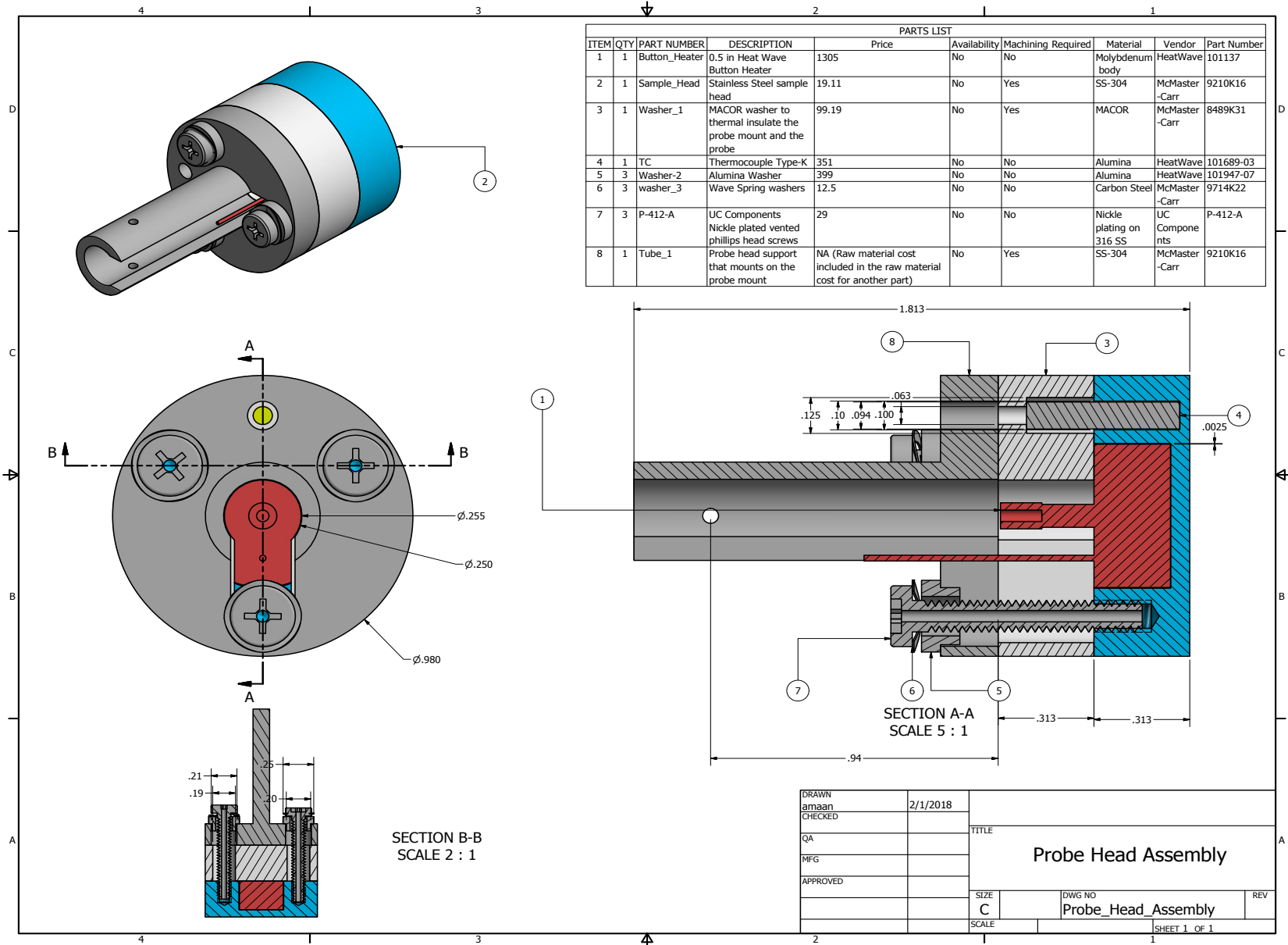
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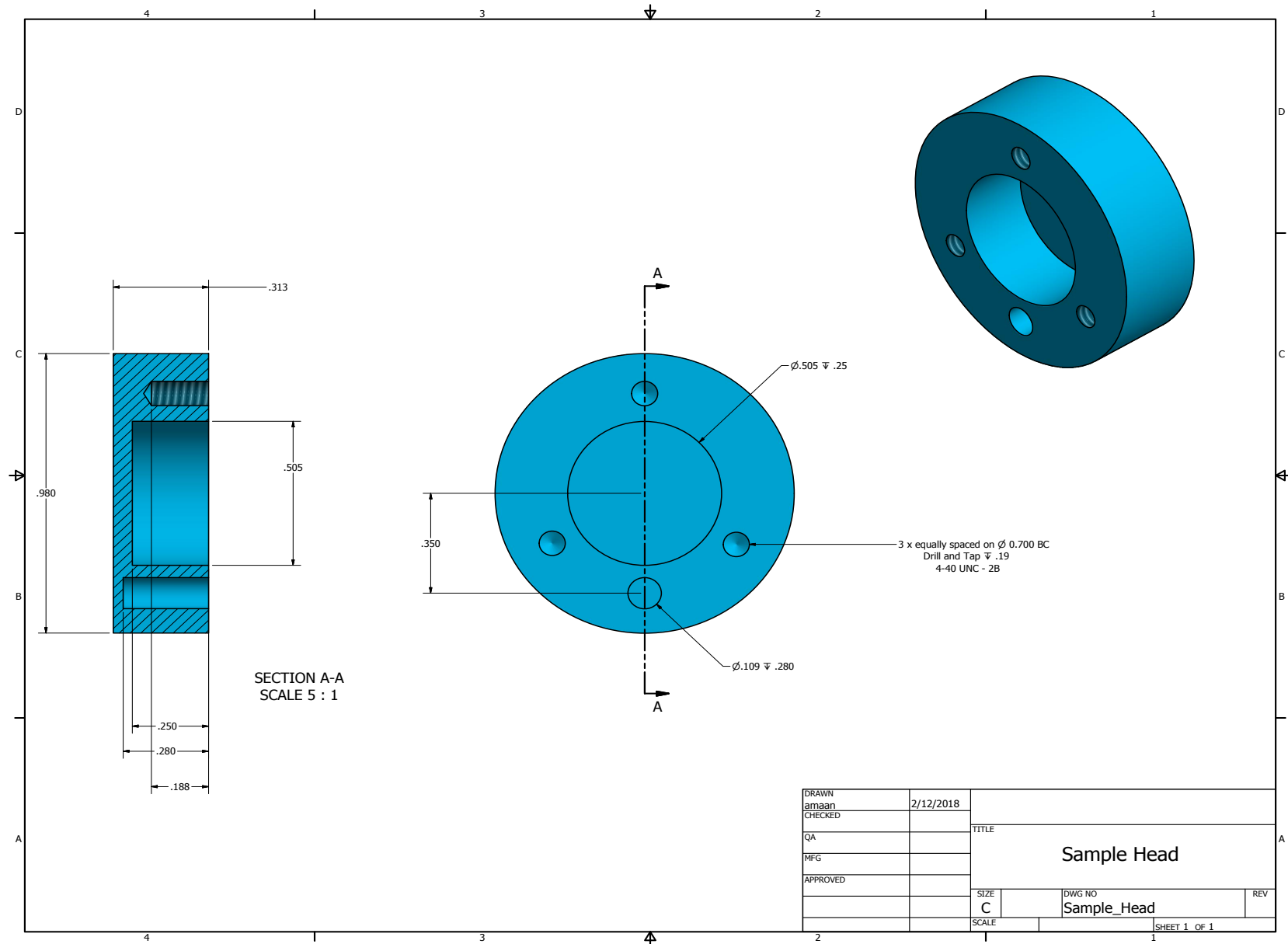
Appendix

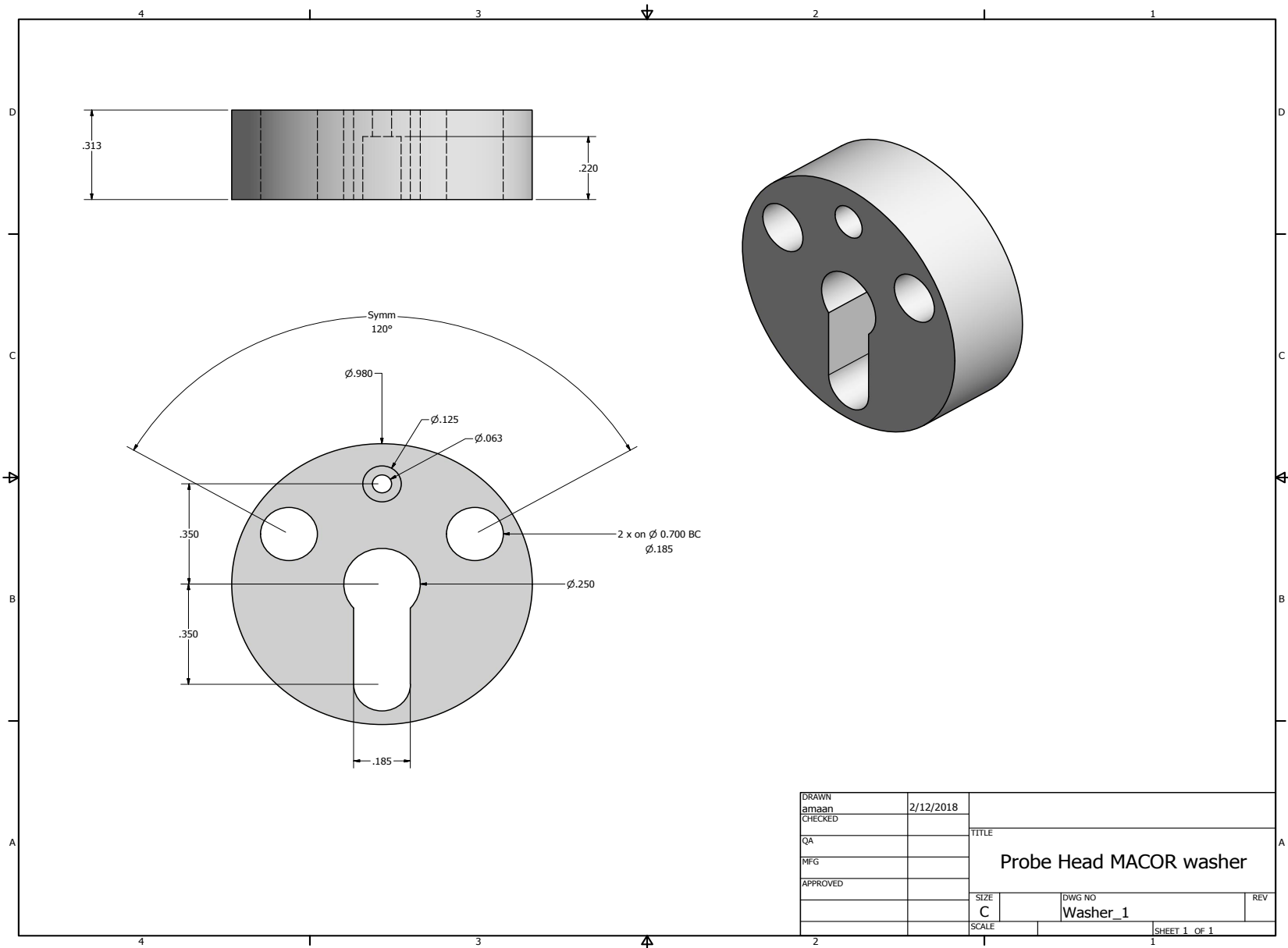
A Sample Exposure Probe Design, Drawings and CAD Assemblies

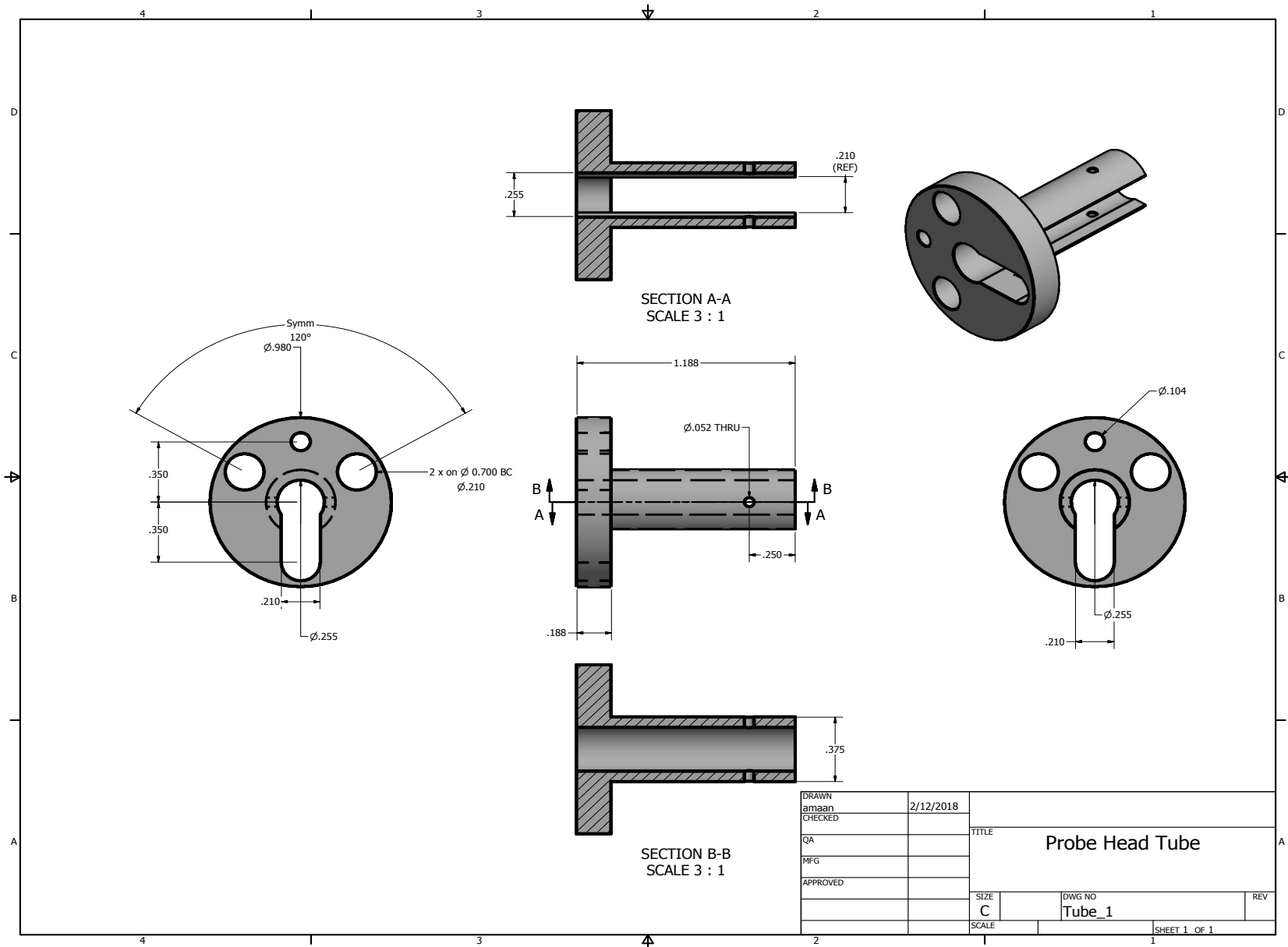


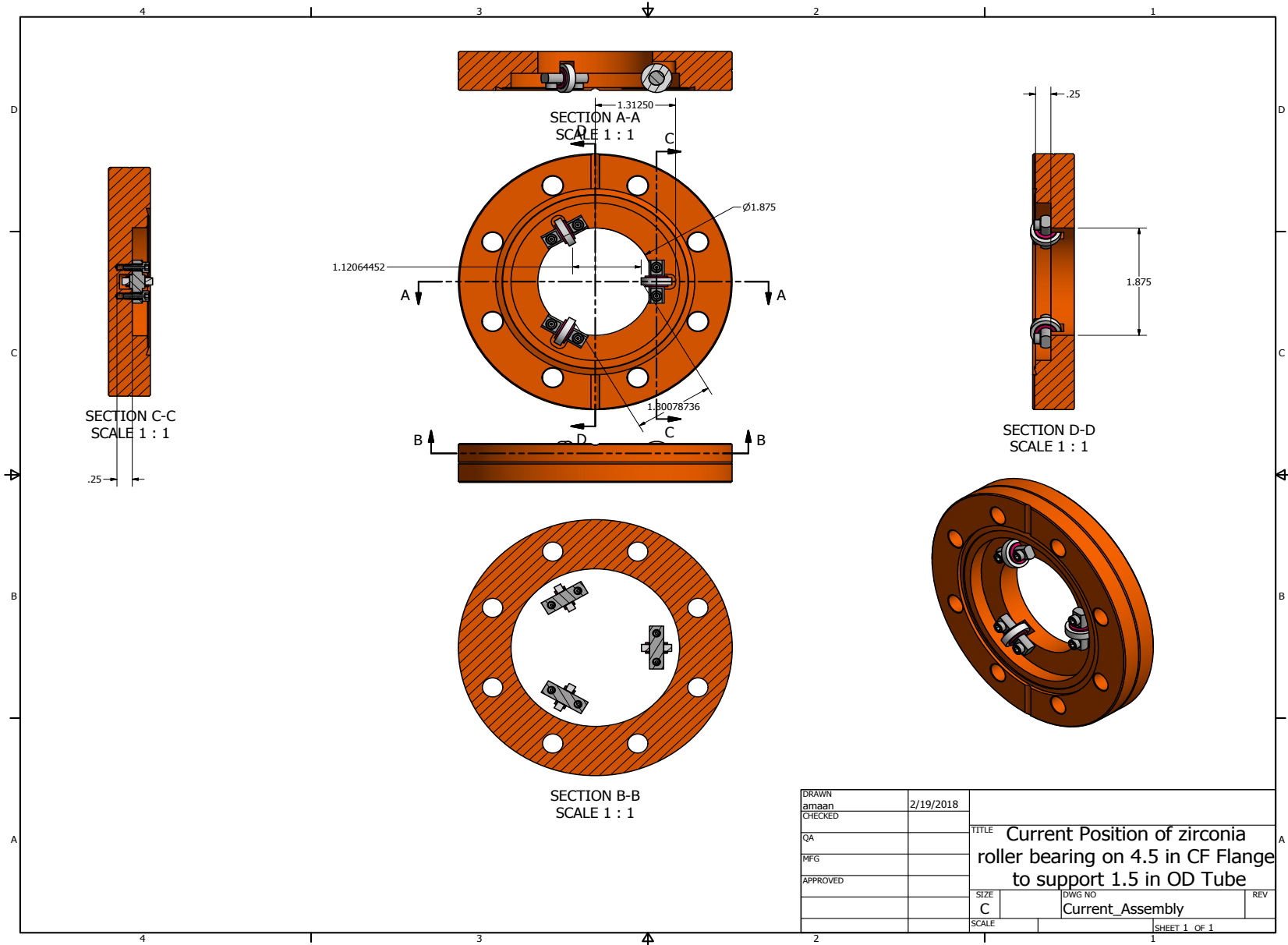


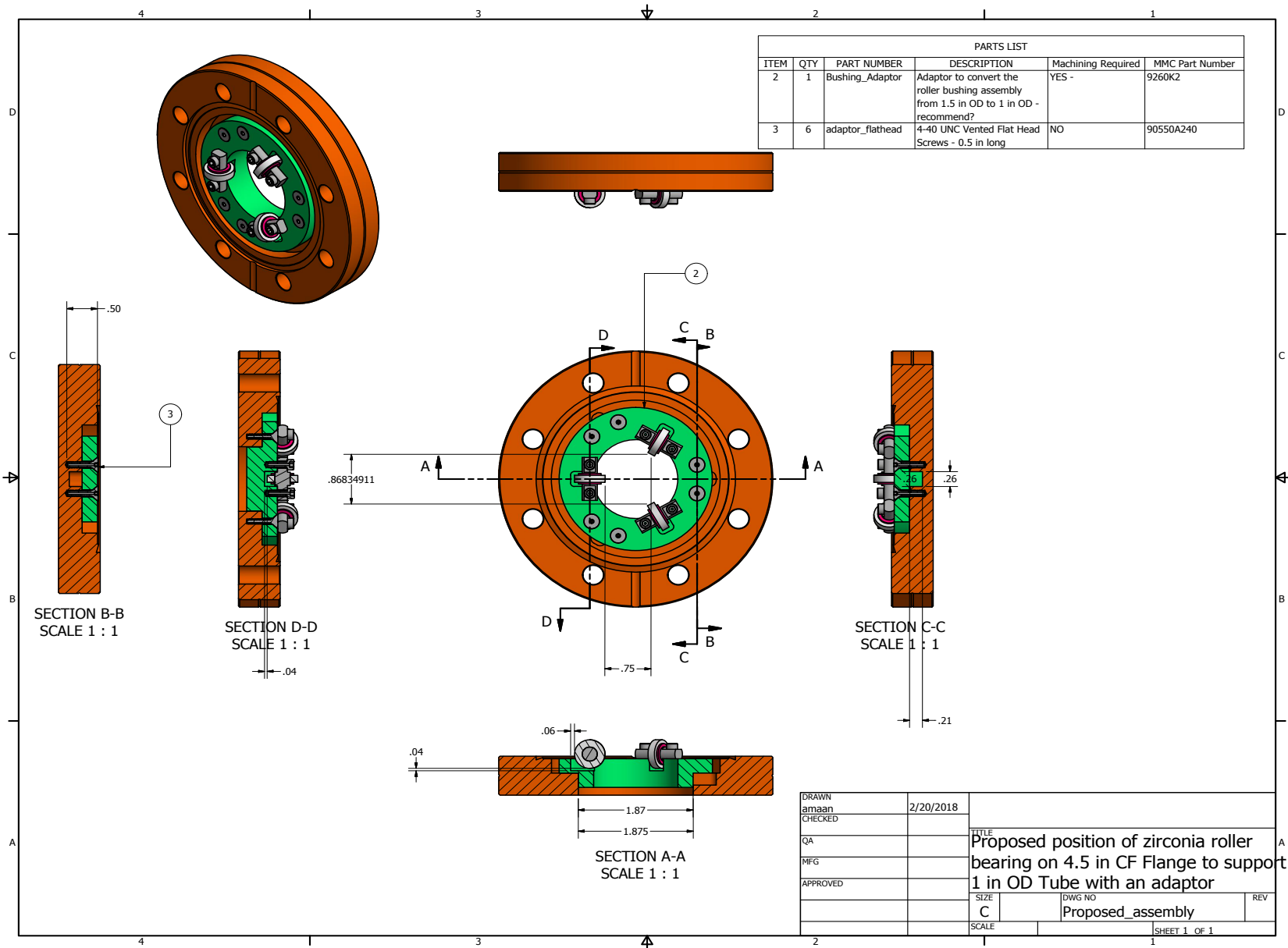


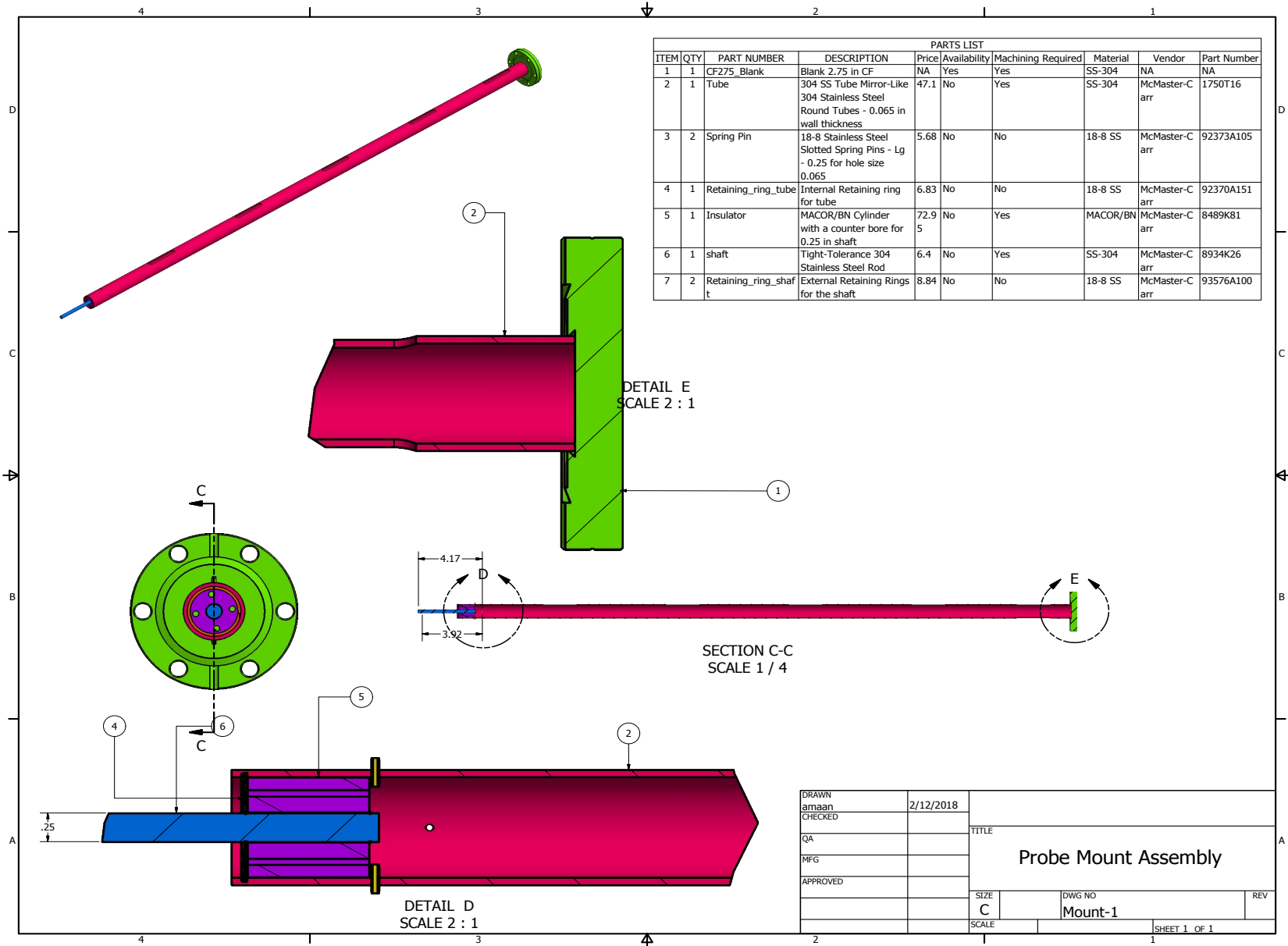


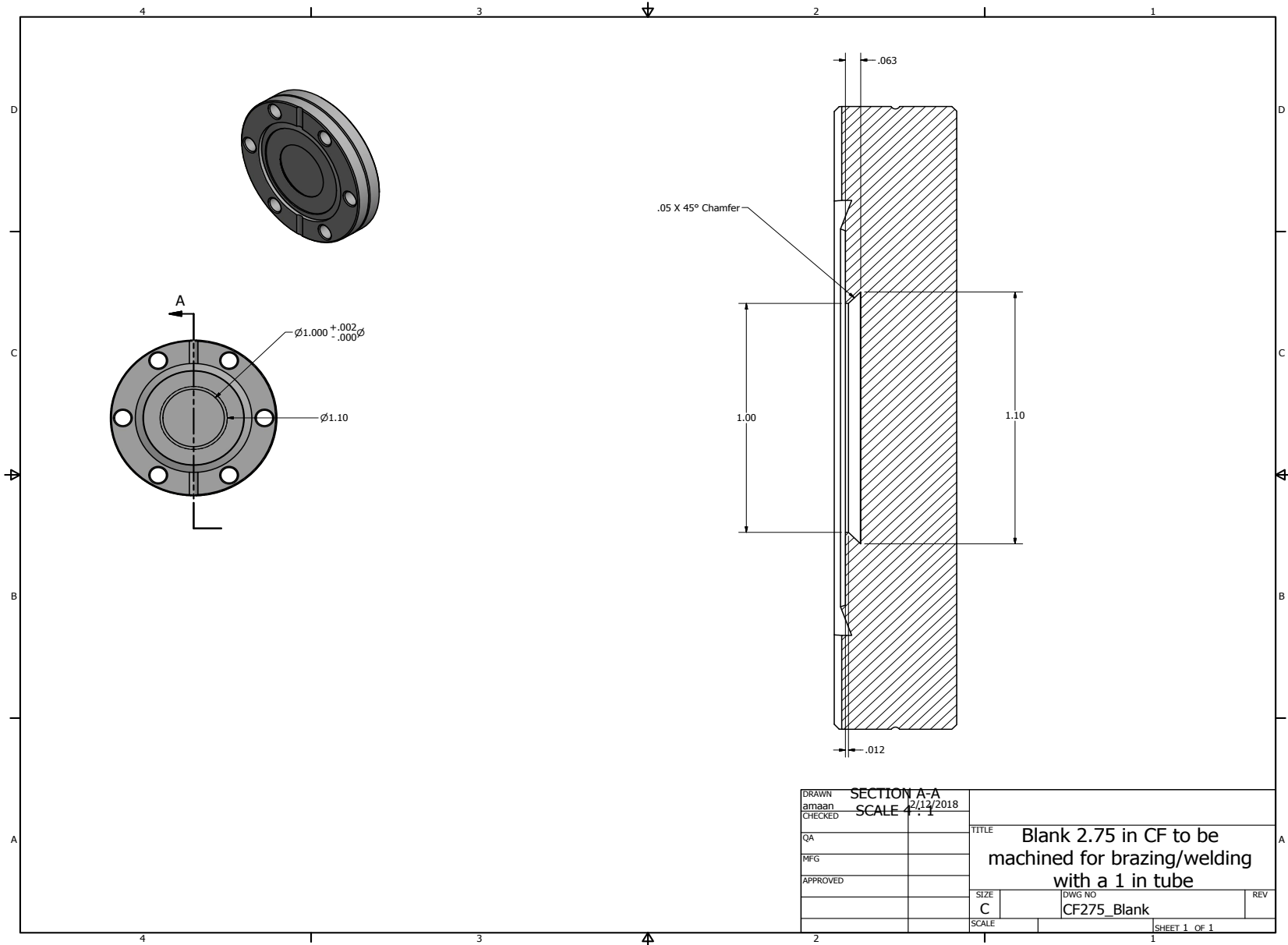


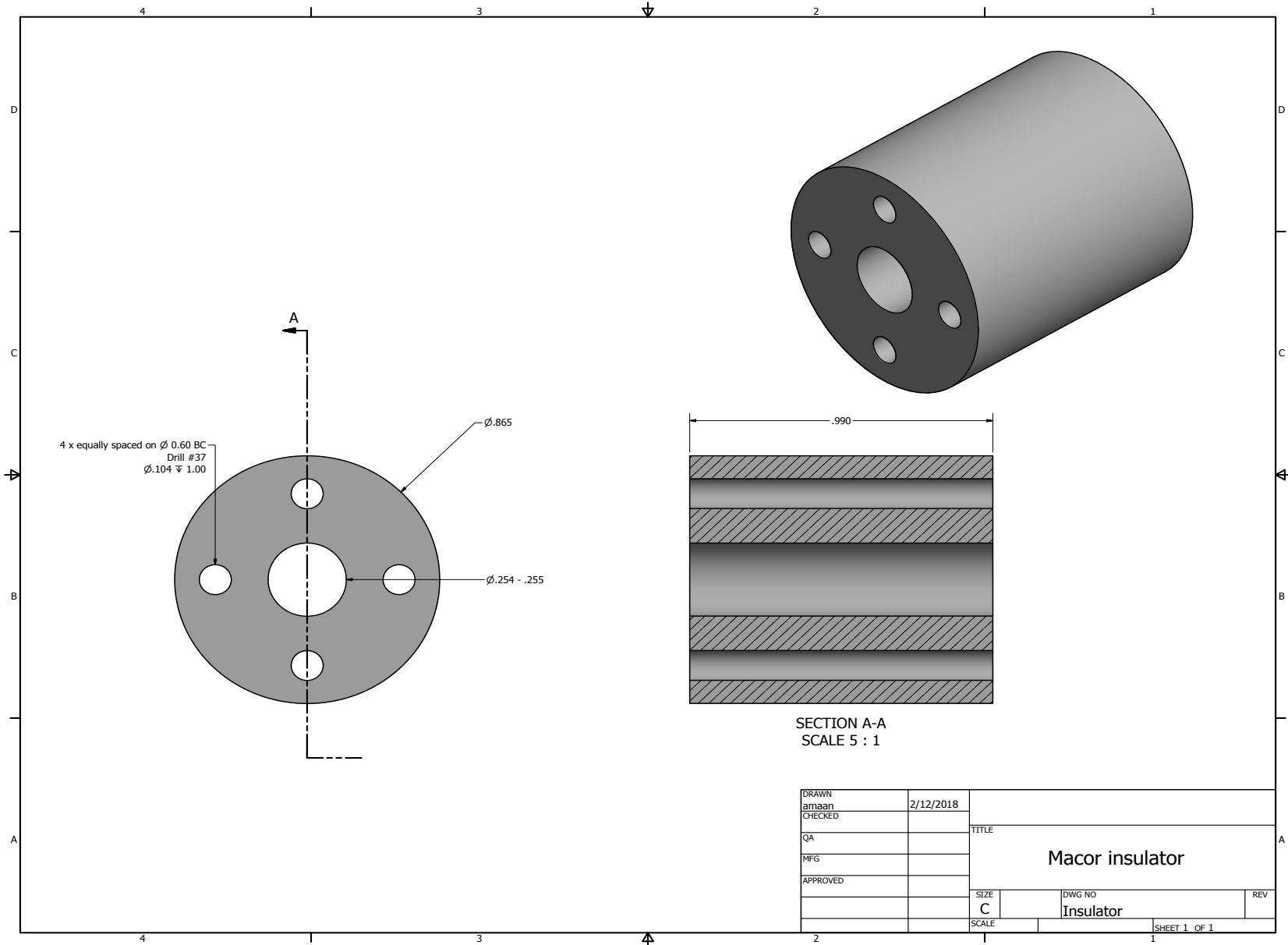


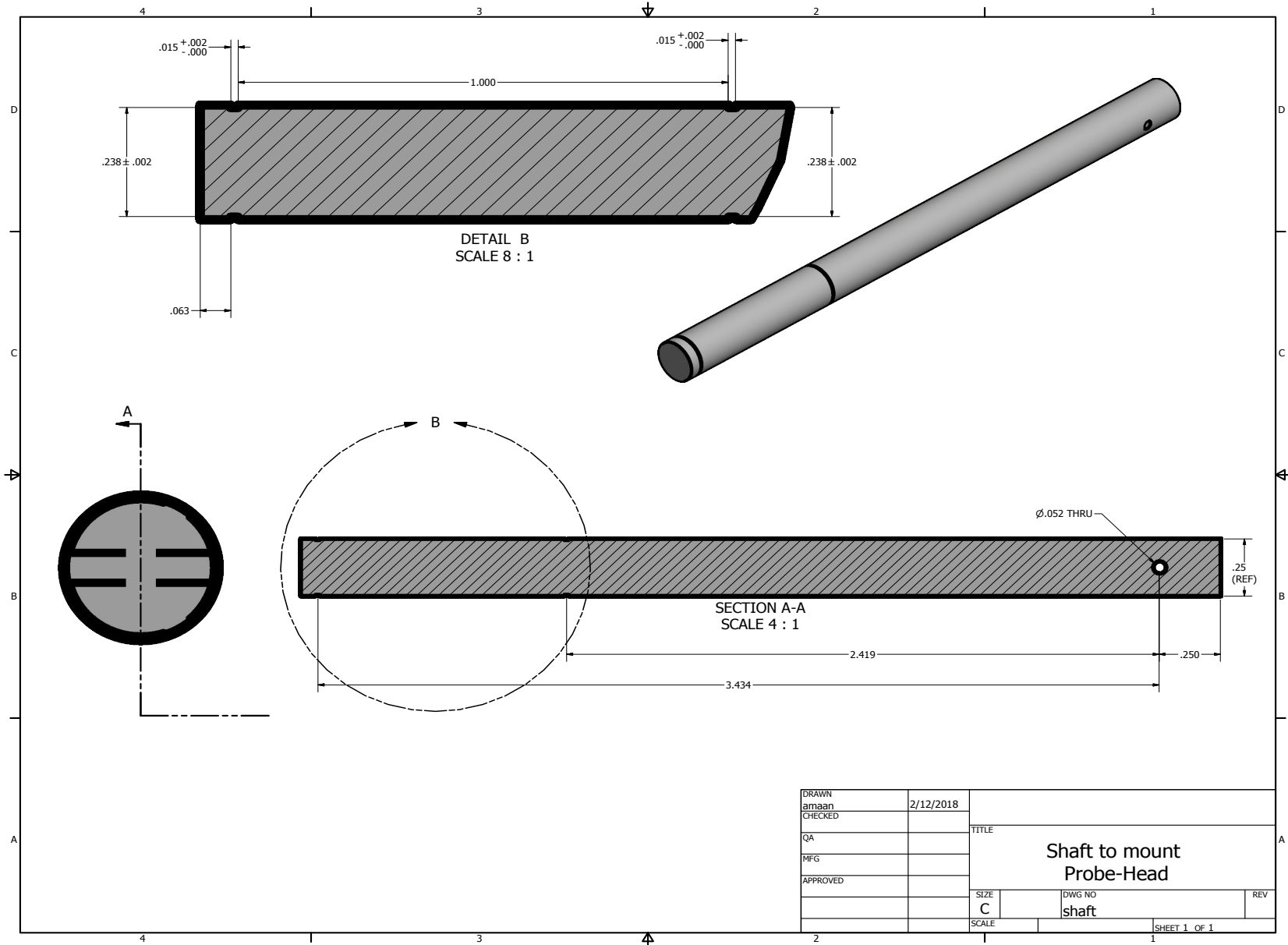


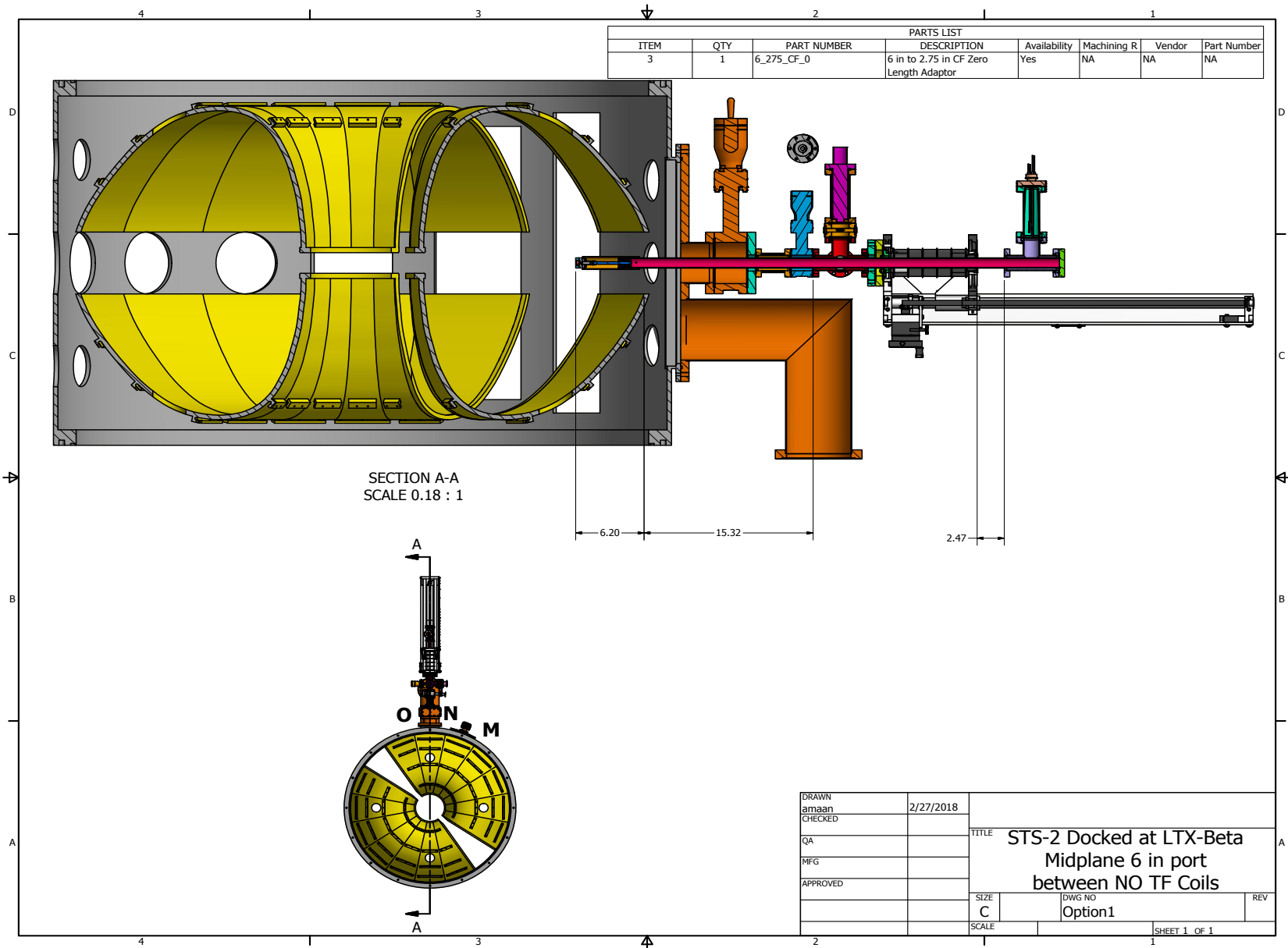


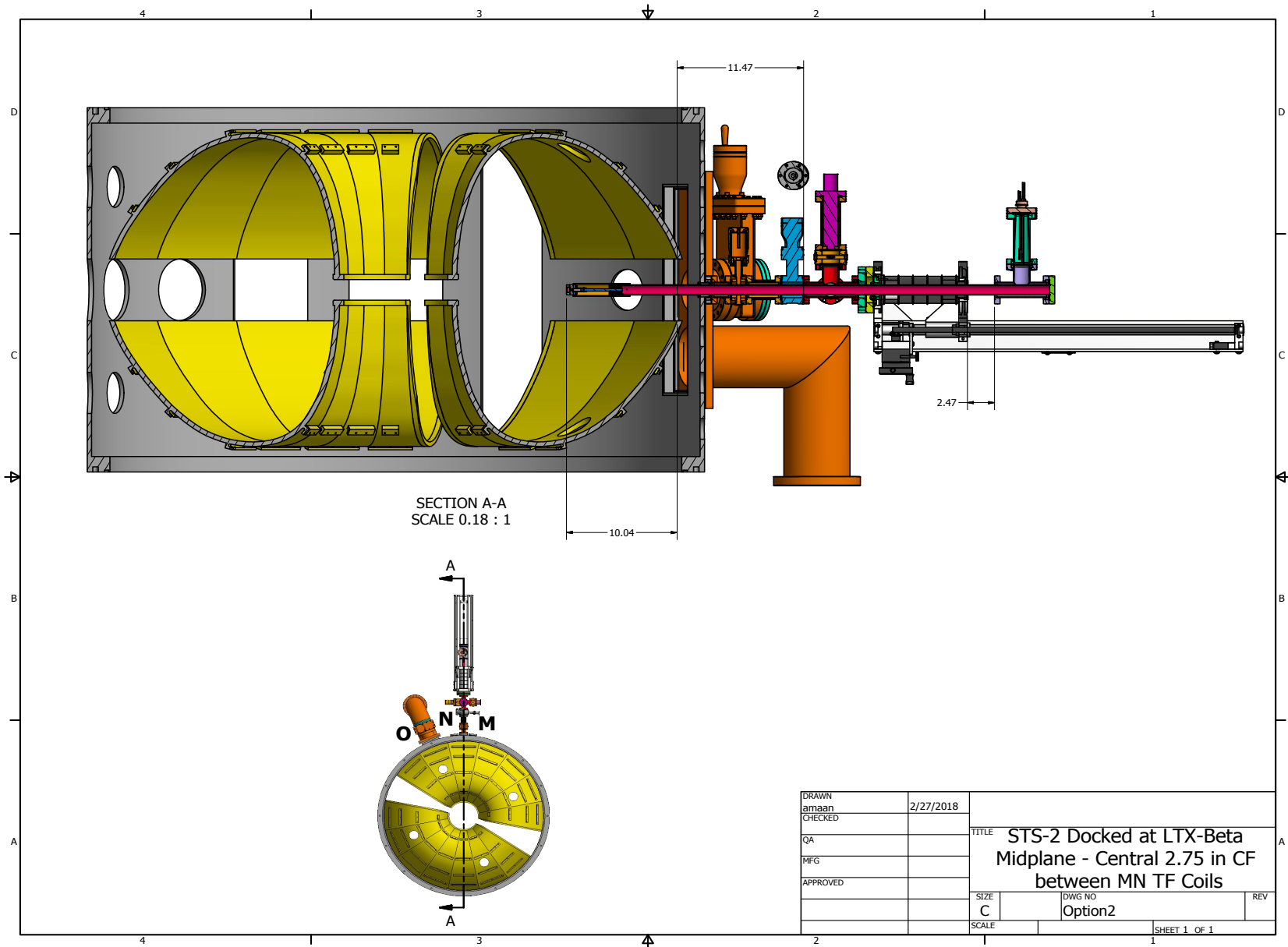


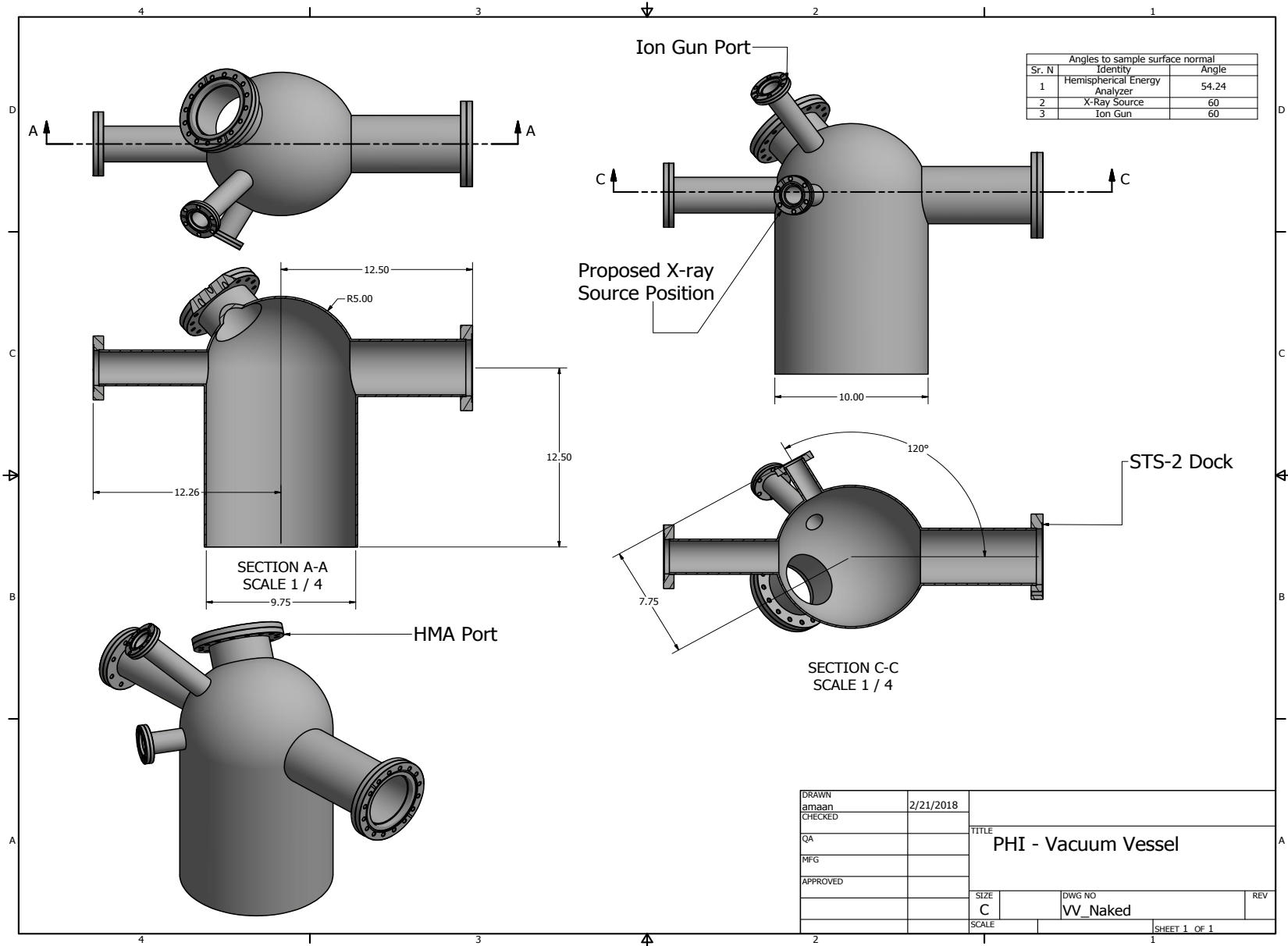


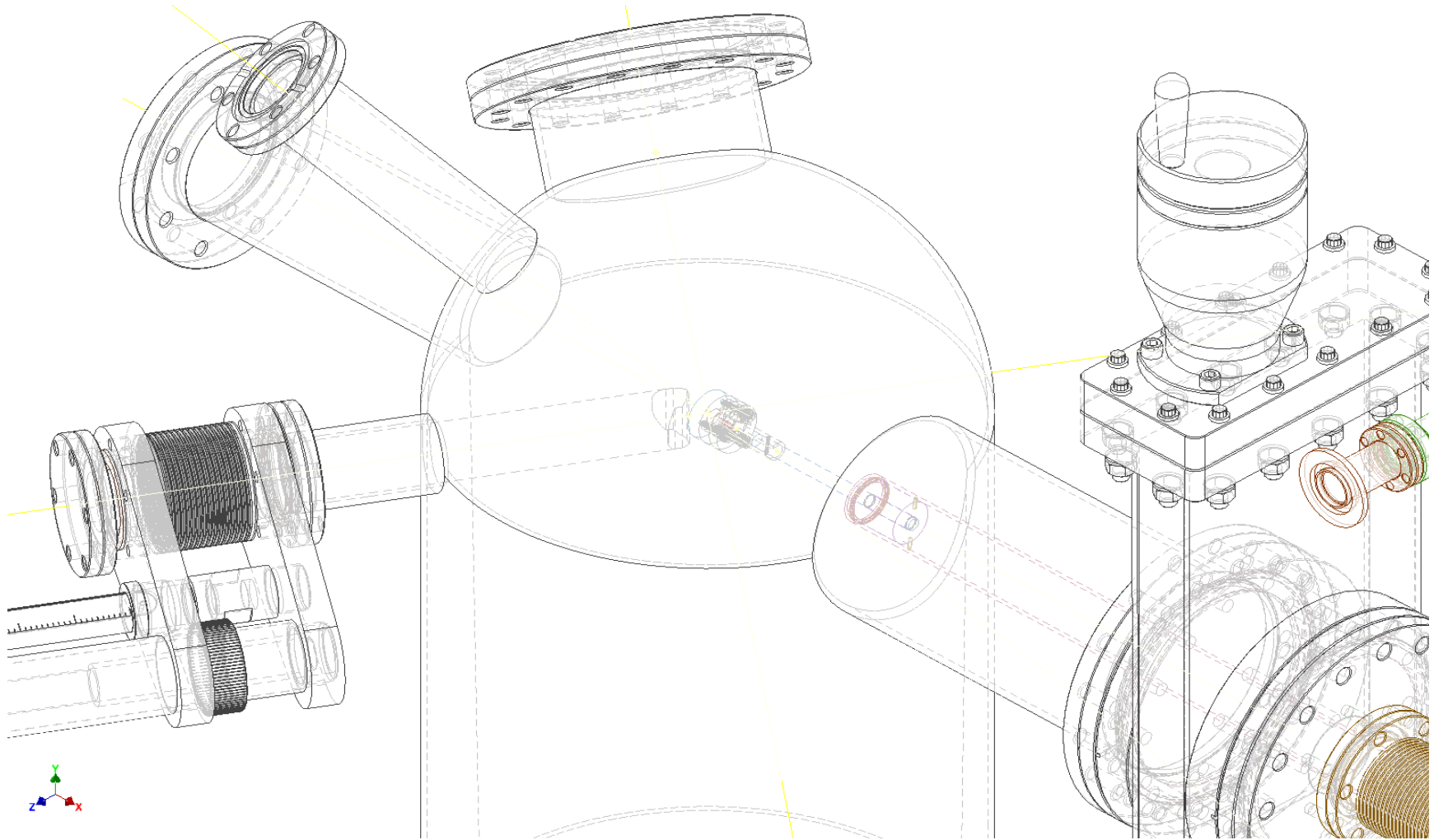


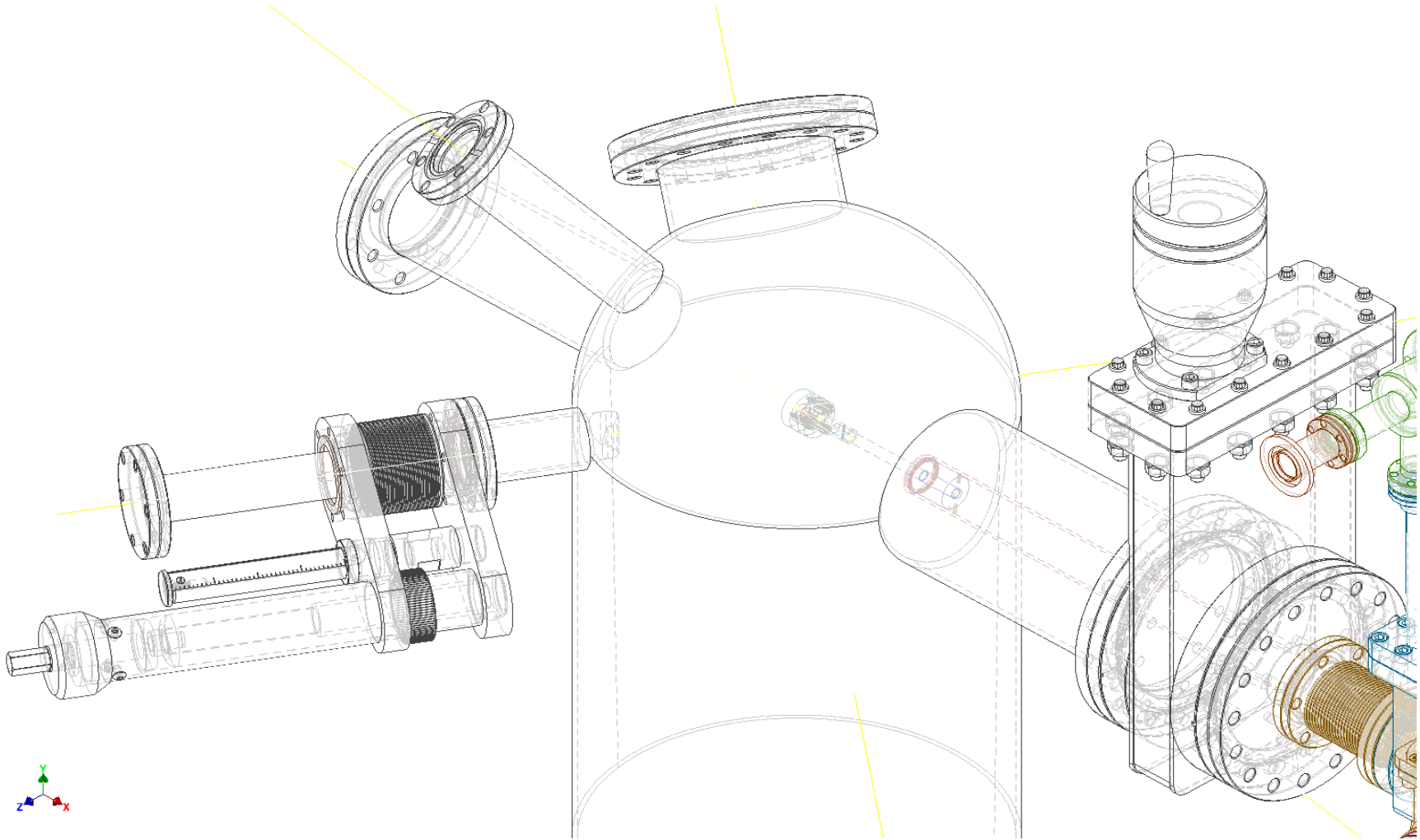


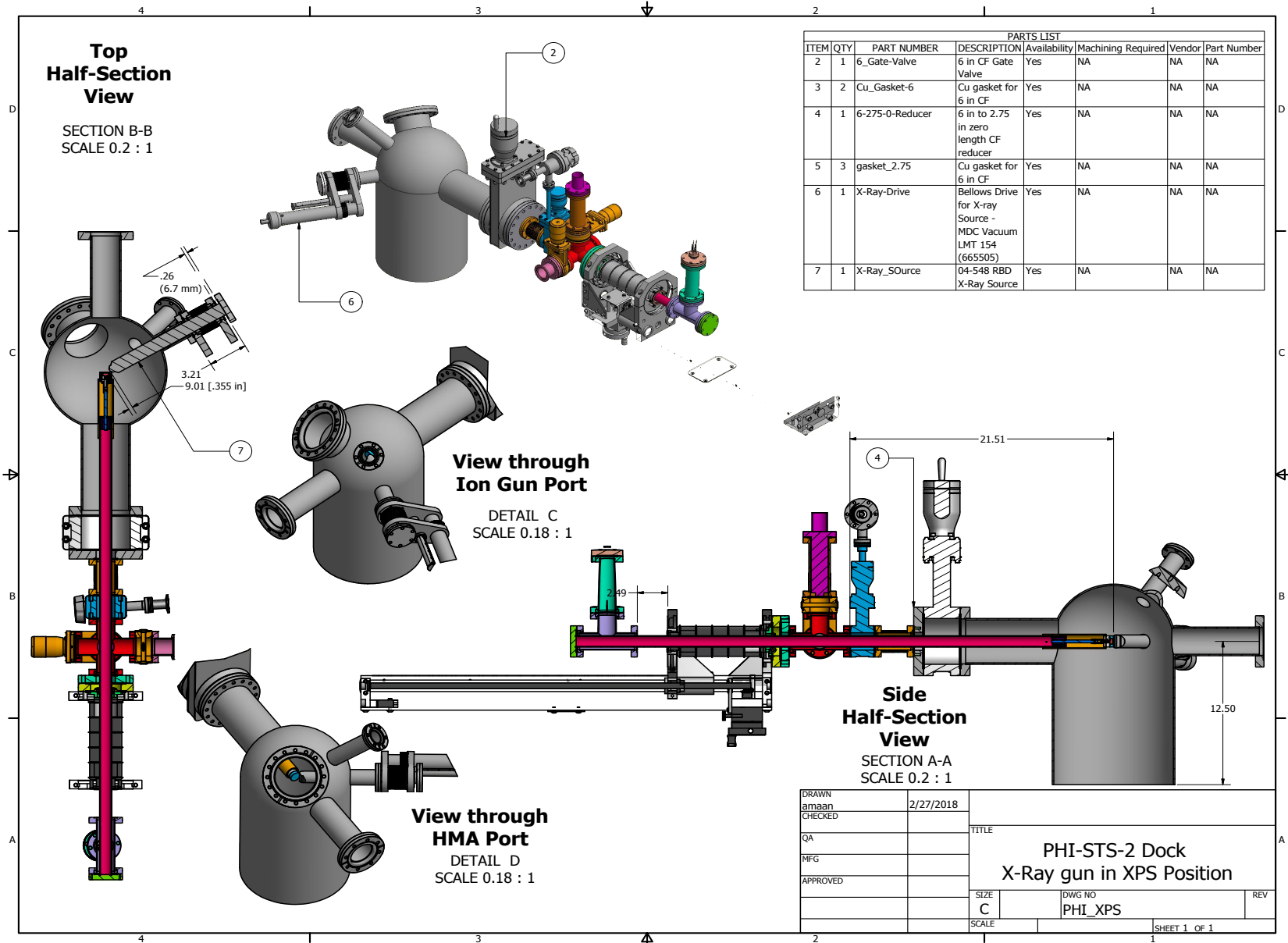


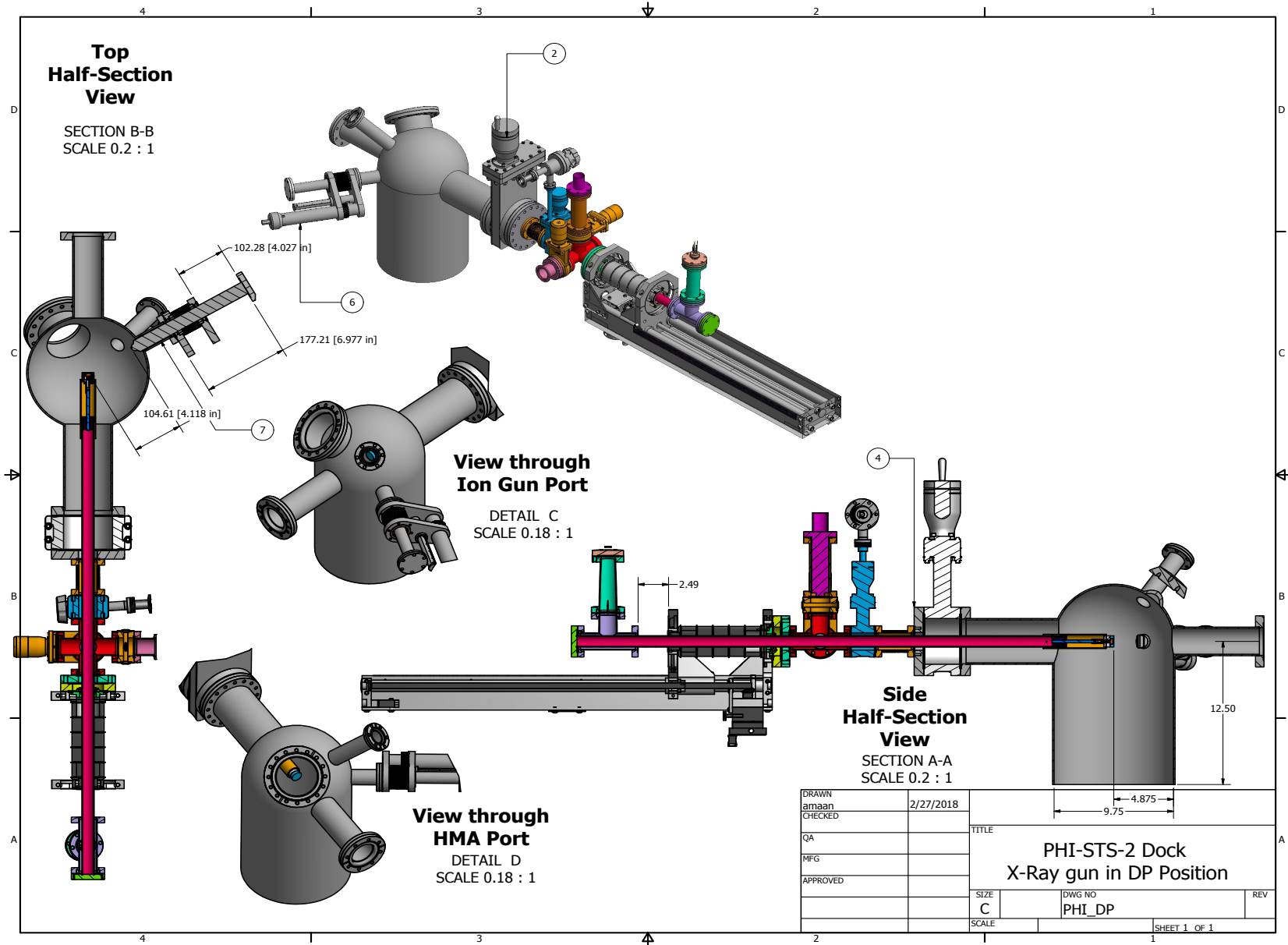












Vita

Anurag was born in India and went to school across the country. He did his Bachelor of Technology in Electrical Engineering from Walchand College of Engineering in Sangli, Maharashtra, India in 2011. He then got his Master of Technology from the Indian Institute of Technology, Kanpur in Nuclear Engineering in 2014, his master's thesis explored error estimates for tomographic reconstructions using frequency domain techniques. In 2014 he enrolled in the PhD program under the guidance of David Donovan in the Nuclear Engineering Department at the University of Tennessee, Knoxville (UT-K). At UT-K, he briefly served as a Teaching Assistant for the Radiological Engineering Laboratory and Nuclear Engineering Laboratory course before moving to Princeton, New Jersey to collaborate on the Lithium Tokamak eXperiment (LTX) and its upgrade LTX- β at the Princeton Plasma Physics Laboratory. His role at LTX was supported by a joint UT-K and Oak Ridge National Laboratory grant. His contribution in designing and commissioning diagnostics for LTX- β is the subject of this thesis.