ELECTRON TRANSPORT IN PLASMAS WITH LITHIUM-COATED PLASMA-FACING COMPONENTS

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Abstract

The Lithium Tokamak Experiment (LTX) is a spherical tokamak designed to study the low-recycling regime through the use of lithium-coated shells conformal to the last closed flux surface (LCFS). A lowered recycling rate is expected to flatten core $T_e$ profiles, raise edge $T_e$, strongly affect $n_e$ profiles, and enhance confinement.

To study these unique plasmas, a Thomson scattering diagnostic uses a $\leq 20$ J, 30 ns FWHM pulsed ruby laser to measure $T_e$ and $n_e$ at 11 radial points on the horizontal midplane, spaced from the magnetic axis to the outer edge at a single temporal point for each discharge. Scattered light is imaged through a spectrometer onto an intensified CCD. The diagnostic is absolutely calibrated using a precision light source and Raman scattering. Measurements of $n_e$ are compared with line integrated density measurements from a microwave interferometer. Adequate signal to noise is obtained with $n_e \geq 2 \times 10^{18}$ m$^{-3}$.

Thomson profiles of plasmas following evaporation of lithium onto room-temperature plasma-facing components (PFCs) are used in conjunction with magnetic equilibria as input for TRANSP modeling runs. Neoclassical calculations are used to determine $T_i$ profiles, which have levels that agree with passive charge exchange recombination spectroscopy (CHERS) measurements. TRANSP results for confinement times and stored energies agree with diamagnetic loop measurements. Results of $\chi_e$ result in values as low as 7 m$^2$/s near the core, which rise to around 100 m$^2$/s near the edge. These are the first measurements of $\chi_e$ in LTX, or its predecessor, the Current Drive Experiment-Upgrade (CDX-U), with lithium PFCs.
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Contents

Abstract ................................................................. iii
Acknowledgements ................................................ iv
List of Tables ......................................................... x
List of Figures ......................................................... xi

1 Introduction .......................................................... 1
  1.1 Fusion ............................................................ 1
  1.2 Plasma-Facing Components .................................... 7
  1.3 Lithium as a Plasma-Facing Component ...................... 10

2 The Lithium Tokamak Experiment .................................. 17
  2.1 LTX Device ...................................................... 18
  2.2 Diagnostics ...................................................... 35
  2.3 Fueling Systems ................................................ 47
  2.4 Operations and Data Acquisition ............................. 49

3 The LTX Thomson Scattering Diagnostic .......................... 51
  3.1 Principles ....................................................... 51
  3.2 Laser ........................................................... 53
  3.3 Viewing Optics ................................................ 61
3.4 Viewing Optics Alignment and Spatial Calibration ........................................... 63
3.5 Spectrometer and CCD .............................................................................. 67
3.6 System Timing, Connections, and Grounding ................................................ 77
3.7 System Calibrations .................................................................................. 79
3.8 Data Processing ....................................................................................... 97

4 Results ........................................................................................................ 102

4.1 TRANSP .................................................................................................. 102
4.2 Relatively Heavy Full Shell Lithium Evaporation Results .............................. 115
4.3 Relatively Light Partial Shell Lithium Evaporation Results ............................ 131
4.4 Conclusions ............................................................................................ 153

5 Conclusions and Future Work ..................................................................... 164

A Thomson Scattering ................................................................................... 168

B Drawings .................................................................................................. 176

C Lithium Fill Records .................................................................................. 186

Bibliography ................................................................................................. 188
# List of Tables

1.1 Properties of candidate PFCs .......................... 10

2.1 LTX design parameters ................................. 19

2.2 Magnetic field coil parameters ............................ 23

2.3 Robicon power supplies and ratings ........................... 24

3.1 Laser head and capacitor bank parameters .................... 57

3.2 Lens elements used in the viewing optics ....................... 63

3.3 2010 run fiber mappings .................................. 69

3.4 2011 run fiber mappings .................................. 70

3.5 2013 run fiber mappings .................................. 71

3.6 Results of the interferometer cross-calibration ............... 95

4.1 Crucible evaporation estimates using temperature-based calculations . . . . . . . 117

4.2 Corrected crucible evaporation estimates using temperature-based calculations . . . . . 118

4.3 Crucible freezing plateau times .............................. 118

4.4 LTX shot numbers for Thomson profiles used for TRANSP run 103574 .......... 119

4.5 LTX shot numbers for Thomson profiles used for TRANSP run 105989 .......... 137

5.1 Filterset used in LTX edge Thomson polychromators .................. 165

C.1 Record of lithium fills in the evaporator and filler systems ................. 187
# List of Figures

1.1 Fusion reaction rates ................................................. 2
1.2 Plasma recycling diagram ............................................ 12
1.3 Dependence of electron temperature profiles on wall recycling coefficient .... 13
1.4 CDX-U tray limiter ..................................................... 13
1.5 CDX-U \( \tau_E \) versus IPB98(y,1) scaling .......................... 14

2.1 The Lithium Tokamak Experiment .................................. 18
2.2 LTX vacuum vessel and shell assembly ............................ 19
2.3 Lithium evaporator assembly ........................................ 27
2.4 Evaporator temperature and heater currents during evaporation .............. 28
2.5 Lithium filler assembly ............................................... 31
2.6 Shells prior to lithium operations during a vent ........................ 31
2.7 Diamagnetic and compensation loop wiring diagram ..................... 39
2.8 High field side Langmuir probe ..................................... 44
2.9 The high field side puffer ........................................... 48

3.1 A conceptual diagram of Thomson scattering ...................... 52
3.2 The layout of the optical table for the ruby laser .................... 54
3.3 Fast photodiode response of the laser ................................ 57
3.4 The flight tube baffles prior to installation ........................ 59
3.5 Custom viewing optics raytracing using OSLO
3.6 The fiber holder with fibers
3.7 The viewing optics and fiber holder
3.8 Viewing optics alignment and spatial calibration
3.9 The CAD model used for the 2013 mapping
3.10 An image of the interior of the spectrometer
3.11 Manufacturer-supplied ruby light notch filter transmission
3.12 Manufacturer-supplied H-α light notch filter transmission
3.13 Thomson scattering diagnostic triggering connections
3.14 Helium line calibration for a helium gas lamp
3.15 CCD curvature calibration
3.16 Raw digitized signal from the Gentec energy meter for a 13.23 J laser pulse
3.17 Measurements of the laser energy and results of the laser energy calibration
3.18 \( G\eta T \) as measured for the 2012 viewing optics configuration
3.19 The transmission of the polarizer
3.20 Raman scattering calibration factors as a function of wavelength
3.21 Raman scattering calibration factors as a function of major radius
3.22 Line integrated density for shot 111091437
3.23 Data fitting from shot 1209141738
3.24 The results of data fitting from shot 1209141738

4.1 A comparison of the plasma composition \( Z_{\text{eff,p}} \) and the PMDE \( Z_{\text{eff,md}} \)
4.2 \( T_e \) initialization and evolution
4.3 Bolometer inversion geometry
4.4 Fitted and smoothed \( T_e \) profiles for the 1111081819 shot series
4.5 Fitted and smoothed \( n_e \) profiles for the 1111081819 shot series
4.6 Temperature and evaporated lithium mass during the November 8, 2011 evaporation
4.7 Lithium mass remaining and plateau time following several evaporations
4.8 Shot 1111081819 plasma current, loop voltage, and fueling
4.9 A comparison of coil currents for shots 1111081819 and 1112061424
4.10 CHEASE model equilibrium for the 1111081819 shot series
4.11 A comparison of $T_i$ from CHERS and TRANSP
4.12 Thermal diffusivity for the no-radiation power profile case for the 1111081819 shot series
4.13 Thermal diffusivity results for the no-radiation power profile case for the 1111081819 shot series at 449.5 ms
4.14 $W_{\text{kin}}$ and $\tau_E$ for the 1111081819 shot series
4.15 Calculated radiation power profiles for the 1111081819 shot series
4.16 $\chi_e$ results normalized to the no-radiation case for the 1111081819 shot series at 449.5 ms for calculated and flat $p_{\text{rad}}$
4.17 $\chi_e$ normalized to the base case at 449.5 ms for the 1111081819 shot series for high and low $n_e$ uncertainties
4.18 A comparison of $\chi_e$ calculated using the model equilibrium at $Z_0 = -4.6$ cm and $Z_0 = -2.3$ cm
4.19 Temperature and evaporated lithium mass during the September 14, 2012 evaporation
4.20 A comparison of $I_P$ signals for the same shot programming for 14 day passivated lithium (1209131646) and the one-side evaporation (1209141413)
4.21 Shot 1209141619 plasma current, loop voltage, and fueling
4.22 Plasma currents for the 1209141619 shot series
4.23 Fitted and smoothed $T_e$ profiles for the 1209141619 shot series
4.24 Fitted and smoothed $n_e$ profiles for the 1209141619 shot series
4.25 LRDFIT reconstructions for shot 1209141619 at 457 ms, 458 ms, and 459 ms
4.43 A comparison of $\chi_e/\chi_{e,neo}$ for the 1111081819 shot series and the 1209141619 shot series ................................................. 162

4.44 Comparisons of $\chi_e$ to model predictions ................................................. 162

4.45 Comparisons of $T_e$ and $\eta_e$ ..................................................................... 163

A.1 Thomson scattering .................................................................................. 169

B.1 Thomson scattering entrance flange .......................................................... 177

B.2 Thomson scattering exit flange ................................................................. 178

B.3 Flight tube assembly ................................................................................ 179

B.4 Spectrometer fiber holder ........................................................................ 180

B.5 Spectrometer entrance slit ..................................................................... 181

B.6 Baffle 1 .................................................................................................... 182

B.7 Baffle 2 .................................................................................................... 183

B.8 Baffle 3 .................................................................................................... 184

B.9 Baffle 4 .................................................................................................... 185
Chapter 1

Introduction

1.1 Fusion

Achieving economical fusion energy presents a great challenge. For fusion reactions to occur, atomic nuclei must be sufficiently energetic to overcome the Coulomb barrier, while at the same time must be confined well enough for reactions to occur. At temperatures high enough for fusion, matter is in a plasma state. Plasmas may be confined gravitationally, magnetically, or inertially. Gravitational confinement is only possible in massive systems such as stars. Magnetic confinement is an active area of research, and several magnetic configurations, such as the tokamak, stellarator, field-reversed configuration, reversed field pinch, and mirror machine are possible. Perhaps the most broad measure of magnetic fusion progress is the fusion energy gain factor

\[ Q = \frac{P_{\text{fusion}}}{P_{\text{heating}}} \]  

(1.1)

where \( P_{\text{fusion}} \) is the power produced by fusion and \( P_{\text{heating}} \) is the heating power applied to the plasma. Tokamaks currently hold the highest record for \( Q \), as the Joint European Torus (JET) achieved \( Q = 0.66 \) in 1997 [1]. Inertial confinement can be created by ion and electron beams, but
Figure 1.1: Fusion reaction rates averaged over Maxwellian distributions for the deuterium-tritium, deuterium-deuterium, and deuterium-helium-3 reactions as a function of temperature based off fitted data [3].

is most commonly done using high-power lasers. The highest power laser-based inertial confinement device is the National Ignition Facility (NIF) [2].

As shown in Figure 1.1, the deuterium-tritium reaction [4]

\[
D + T \rightarrow ^4\text{He} + n + 17.589 \text{ MeV}
\]  

(1.2)

has the highest cross-section of all fusion reactions. Applying conservation of energy and momentum to the fusion products gives four fifths of the energy to the neutron and one fifth to the helium nucleus. The helium nuclei can be thermalized in a plasma as a form of self-heating. Many other fusion reactions are possible, but those relevant to fusion energy are the deuterium-deuterium reaction [4]
and the deuterium-helium-3 reaction [5]

\[
D + ^3\text{He} \rightarrow ^4\text{He} + p + 18.353\text{ MeV.}
\] (1.4)

Deuterium is a naturally-occurring isotope of hydrogen with \(155.76 \pm 0.05 \times 10^{-6}\) fractional abundance [6]. Tritium is unstable with a half life of 12.32 years [7], so no natural resources of tritium exist. However, tritium may be bred by bombardment of a lithium breeding blanket by fusion neutrons. The two reactions that can occur are

\[
^6\text{Li} + n \rightarrow T + ^4\text{He} + 4.8\text{ MeV}
\] (1.5)

and

\[
^7\text{Li} + n \rightarrow T + ^4\text{He} + n - 2.5\text{ MeV.}
\] (1.6)

Note that the latter reaction is endothermic. The natural abundance of \(^7\text{Li}\) is 92.6\% and \(^6\text{Li}\) is 7.4\% [8]. Since \(^6\text{Li}\) has a significantly higher neutron cross-section below 5 MeV, a breeding blanket will likely use \(^6\text{Li}\). Note that a neutron multiplier and moderator can be used to convert 14.1 MeV fusion neutrons to lower energies. Lithium may be used in conjunction with other elements in a blanket. Some materials under consideration are \(\text{Li}_2\text{O}\) [8], a lead-lithium eutectic, LiF, \(\text{Li}_4\text{SiO}_4\), and FLiBe (a mixture of LiF and BeF\(_2\)) [9]. There are ideas to use a thick (0.55 m - 1.6 m) fast flowing liquid metal (FLiBe, Li, \(\text{Li}_{17}\text{Pb}_{83}\)) as both a plasma-facing component (PFC), for shielding, and for tritium breeding [10]. It is worth noting that helium-3 is rare on earth, but is present in concentrations on the order of \(10^{-8}\) in lunar regolith [11] and could serve as a source of fuel for space exploration or colonization.
For a fusion plasma to be self-sustaining, self-heating from thermalization of charged fusion products $P_{\text{self}}$ must overcome any power losses $P_{\text{loss}}$ (note that neutrally charged products can not be confined by magnetic fields, so they can not heat a plasma). This ignition condition can be written as

$$P_{\text{self}} > P_{\text{loss}}.$$  \hfill (1.7)

The total self-heating power for a plasma with $N$ ion species is

$$P_{\text{self}} = \sum_{i=1}^{N} \sum_{j=i}^{N} n_i n_j \langle \sigma v \rangle_{ij} E_{ij,\text{charged}} dV$$ \hfill (1.8)

where $n_i$ and $n_j$ are the number density of the $i^{\text{th}}$ and $j^{\text{th}}$ ion species, respectively, $\sigma$ is the fusion cross-section of two ion species, $v$ is the particle relative velocity, the bracket denotes the average over velocities, $E_{ij,\text{charged}}$ is the energy of the charged fusion products of the $i+j$ reaction, and $dV$ is the volume element. Note that the fusion cross-section $\langle \sigma v \rangle_{ij}$ may be very small for some ion combinations, such as minority or impurity species interactions. The power loss can be characterized from the energy confinement time $\tau_E$, defined as

$$\tau_E = \frac{W_{\text{kin}}}{P_{\text{heat}} - \frac{dW_{\text{kin}}}{dt}}$$ \hfill (1.9)

where $P_{\text{heat}}$ is the heating power, which in steady-state, can be assumed equal to $P_{\text{loss}}$. $W_{\text{kin}}$ is the kinetic energy of the plasma, which is the sum of the kinetic energies of each species integrated over the plasma volume

$$W_{\text{kin}} = \frac{3}{2} \int \left( n_e T_e + \sum_{i=0}^{N} n_i T_i \right) dV$$ \hfill (1.10)
where \( n_e \) is the electron number density, \( T_e \) is the electron temperature, \( n_i \) is the number density and \( T_i \) is temperature of ion species \( i \). For a quasineutral plasma,

\[
    n_e = \sum_{i=0}^{N} Z_i n_i
\]  

(1.11)

where \( Z_i \) is the atomic number of the \( i \)th ion species. Assuming a steady-state plasma such that \( dW_{\text{kin}}/dt = 0 \), yields the general condition

\[
    \sum_{i=1}^{N} \sum_{j=1}^{N} \int n_i n_j \langle \sigma v \rangle_{ij} E_{ij,\text{charged}} dV > \frac{3}{2T_E} \int \left( T_e \sum_{i=0}^{N} Z_i n_i + \sum_{i=0}^{N} n_i T_i \right) dV.
\]  

(1.12)

If a purely deuterium and tritium plasma is chosen, \( n_D = n_T = \frac{1}{2} n \) such that the fusion rate is maximized, and assuming spatial homogeneity with all temperatures equal to some temperature \( T \), this condition becomes the Lawson criterion \[12\]

\[
    n \tau_E > \frac{12T^2}{E_{\alpha} \langle \sigma v \rangle_{\text{DT}}}
\]  

(1.13)

where \( E_{\alpha} = 3.5178 \) MeV is the energy of fusion alpha particles. Since \( \langle \sigma v \rangle \) is a function of temperature, the criterion is sometimes expressed as a triple product by multiplying the equation by the temperature to obtain

\[
    n_e \tau_E T > \frac{12T^2}{E_{\alpha} \langle \sigma v \rangle_{\text{DT}}}
\]  

(1.14)

By minimizing \( T^2/\langle \sigma v \rangle \) and performing a more careful calculation using parabolic density and temperature profiles, the minimum value of the triple product for deuterium-tritium fusion is at

\[
    \hat{n} \hat{T} \tau_E > 5 \times 10^{21} \text{ keV s m}^{-3}
\]  

(1.15)

---

\[1\] The International System of Units (SI) is used exclusively for all equations (but not necessarily values) in this document, with the exception that the Boltzmann constant \( k_B \) has been absorbed into temperatures, which are measured in units of energy, as is the convention in plasma physics.
where \( \hat{n} \) and \( \hat{T} \) are the peak density and temperature, respectively [8]. Similar calculations can be performed for other fusion reactions, but yield larger minimum values of the triple product.

Note that the triple product demands high temperatures, densities, and confinement times. In magnetically-confined plasmas, the temperature of a plasma can be increased by various heating methods, such as Ohmic heating, neutral beam injection, radio frequency heating, and self-heating from charged fusion products. However, plasmas can lose energy by impurity radiation, Bremsstrahlung, cyclotron radiation, instabilities, and interaction with PFCs. The density can be raised by various fueling methods including gas puffing, supersonic gas injection, pellet injection, and neutral beam injection. However, in tokamaks, the density can only be raised up to the vicinity of the Greenwald density limit [13]

\[
n_G = \frac{10^{20}}{\text{MA} \cdot \text{m} \, \pi a^2} \quad \text{(1.16)}
\]

where \( I_P \) is the plasma current and \( a \) is the minor radius. While this limit is empirical, it is consistent with a limit imposed by the power balance between radiative loss and Ohmic heating in magnetic islands [14]. The energy confinement time is a function of many parameters that often lack flexibility. For example, the IPB98(y,2) scaling predicts

\[
\frac{\tau_E}{s} = 5.62 \times 10^{-2} \left( \frac{I_P}{\text{MA}} \right)^{0.93} \left( \frac{B_{T0}}{T} \right)^{0.15} \left( \frac{n_{\text{line}}}{10^{19} \text{m}^{-3}} \right)^{0.41} \times \left( \frac{P}{\text{MW}} \right)^{-0.69} \left( \frac{R_0}{\text{m}} \right)^{1.97} \kappa_a^{0.78} \left( \frac{a}{R} \right)^{0.58} \left( \frac{M}{u} \right)^{0.19}
\]

for H-mode tokamak plasmas with edge-localized modes (ELMs) [15]. The major radius \( R_0 \), minor radius \( a \), and elongation \( \kappa \) are limited by machine size and shape. Note that in the above equation, \( \kappa_a = A_P / \pi a^2 \) where \( A_P \) is the plasma cross-sectional area. The toroidal magnetic field on the plasma axis \( B_{T0} \) is limited by the cost and capabilities of magnetic field coils. The plasma

---

\( ^2 \text{This is sometimes referred to as the ITER98(y,2) or ITER98P(y,2) scaling.} \)
current $I_p$ is limited by the toroidal field such that the safety factor

$$q \approx \frac{r B_T}{R B_p}$$

is large enough to prevent instabilities. $R$ is the major radial coordinate, $r$ is the minor radial coordinate, $B_T$ is the toroidal magnetic field, and $B_p$ is the poloidal magnetic field. The average ion mass $M$ should be roughly constant for a deuterium-tritium plasma with some helium fusion products in steady state. $P$ is the loss power corrected for charge exchange and orbit losses and $n_{\text{line}}$ here is the line-averaged density. Plasma parameters are also affected by interactions between the plasma and non-plasma surfaces, which play an important role in fusion plasmas.

### 1.2 Plasma-Facing Components

Plasma-material interactions (PMIs) between a plasma and a PFC are complex and can have great effects on plasma performance [16]. Particles leaving the plasma can reflect off PFCs, back-scatter, implant within PFCs, or cause secondary electron emission. Sufficiently energetic plasma particles can sputter solid surface materials. Plasma particles and impurities can adhere to a solid surface through adsorption and can later desorb. A liquid PFC can similarly absorb and desorb particles. Another process that can occur is recycling. This is the process by which plasma ions leaving the plasma become neutralized by interaction with PFCs and then re-enter the plasma as neutrals.

The simplest boundary of a plasma would be open space. This can be approached in astrophysical systems such as stars, but terrestrial plasmas require some sort of vessel to maintain a vacuum in which a plasma can be created. The vacuum vessel is typically made of a metal, such as stainless steel or aluminum, but can also be made of glass and polycarbonate, among other materials.

In magnetically confined plasmas, a plasma may be bounded by either a limiter or a magnetic divertor. The limiter is a PFC in a vacuum vessel where the plasma intersects the last closed flux
surface (LCFS). In a diverted magnetic geometry, the LCFS does not intersect any PFCs, but rather interacts with a magnetic divertor through the scrape off layer (SOL), a region of a plasma with open field lines.

The search for suitable materials for PFCs is an important area of research in fusion science. PFCs should have a high thermal conductivity and an ability to withstand large heat fluxes at high temperatures. The divertor in ITER must be able to handle a steady power load of 10 MW/m$^2$, but the peak heat flux could be up to 20 MW/m$^2$ - 30 MW/m$^2$ [17]. Type I ELMs could deposit up to 1 GW/m$^2$ for 1 ms. A disruption in an ITER-scale device could deposit 10 MJ/m$^2$ - 100 MJ/m$^2$ in 1 ms - 10 ms, which will likely melt any solid material [17]. For reference, the heat flux on the surface of the sun is approximately 63 MW/m$^2$. Since fusion plasmas are energetic and must eventually approach steady-state operation, a PFC should have low erosion rates, or in the case of a liquid PFC, low evaporation rates. As most fusion research focuses on using deuterium-tritium reactions for power production, PFCs should be able to withstand high-energy neutron flux of up to 1.25 MW/m$^2$ [18]. The combination of plasma and neutron fluences strongly limits the lifetime of any solid used as a PFC. Additionally, PFCs should not be a source of detrimental impurities. Materials with a high atomic number have a high number of bound electrons. Collisions of sputtered wall materials and plasma particles can result in excitation of bound states that leads to impurity radiation, a mechanism for power loss in a plasma. Low-$Z$ particles can fully ionize at lower energies than high-$Z$ materials, so radiative loss from low-$Z$ materials occurs in the edges of the plasma instead of the core [16]. While high-$Z$ materials can cause large radiative losses, they have higher sputtering thresholds than low-$Z$ materials. Lower sputtering results in lower dilution of the plasma by impurities. Finally, PFCs should have low hydrogen affinity, such that the surface does not retain tritium.

Solid materials such as carbon, tungsten, beryllium, and molybdenum have been used for PFCs. Tungsten has a very high melting point at 3422 °C and is a high-$Z$ material ($Z = 74$), and as such, has a high physical sputtering threshold [19]. It can handle a high heat flux of at least
35 MW/m$^2$ [20], but it can melt and embrittle at high temperatures. Embrittlement is due to weakened intergranular boundaries at elevated temperatures [21]. A 10 mm thick W target is expected to last 800 - 2000 shots in ITER with 0.4 MJ/m$^2$ Type I ELMs occurring at a 1 Hz frequency. As a high-\(Z\) material, W can cause large radiative loss in the plasma core. Sputtering of high-\(Z\) materials can only be sufficiently low if the edge temperature is low (50 eV) [22]. Deuterium bombardment can result in the formation of blisters on a tungsten surface [23]. Additionally, tungsten between 1000 K and 2000 K, when exposed to helium ions with energies 20 eV or greater, can exhibit the growth of a fiberform structure layer in divertor simulators with a thickness greater than 1 \(\mu\)m for a 3400 s plasma exposure [24]. This phenomena has also been observed in Alcator C-Mod, where 50 nm to 100 nm thick nano-tendrils in a layer 600 ± 150 nm deep resulted [20]. These tendrils could result in unipolar arcing or tungsten dust formation. ITER will use W on divertor surfaces [17].

Carbon is used as a PFC in magnetic fusion devices in the form of graphite or carbon fiber composite (CFC). Graphite’s coefficient of thermal expansion is low, and it also has good compressive strength [22]. Carbon can handle large heat fluxes. CFC components with active cooling have handled thousands of cycles of 20 MW/m$^2$ heat flux [25]. A 20 mm thick CFC target is expected to withstand greater than 5000 ITER shots of Type I ELMs with energy densities up to 0.4 MJ/m$^2$ occurring at 1 Hz [17]. Carbon has a low atomic number (\(Z = 6\)), so it fully ionizes and doesn’t radiate in the core. It sublimes instead of melting [17]. However, the price for carbon’s ability to handle high heat fluxes is a low energy threshold for chemical erosion and high physical erosion rates. Carbon erosion is as high as 16 nm/s for a 2 MW/m$^2$ heat flux [26]. In a steady-state fusion reactor operating under these conditions, a 1 cm thick tile would completely erode in 7 days. Carbon has a high retention for hydrogen isotopes and produces dust, which present issues for tritium retention [17].

Beryllium is a low-\(Z\) material, and as such, it does not contribute to large radiative power loss. Beryllium has the capability to getter oxygen. However, it has a relatively low melting point and
1. Introduction

Material properties are crucial for the design and operation of plasma-facing components (PFCs). Table 1.1 summarizes key properties of candidate materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>$Z$</th>
<th>$T_{\text{melt}}$ [°C]</th>
<th>$T_{\text{boil}}$ [°C]</th>
<th>$T_{\text{sublime}}$ [°C]</th>
<th>$\rho$ [g cm$^{-3}$]</th>
<th>$\lambda$ at 27 °C [W m$^{-1}$ K$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium</td>
<td>3</td>
<td>180.50</td>
<td>1342</td>
<td>-</td>
<td>0.534</td>
<td>84.7</td>
</tr>
<tr>
<td>Beryllium</td>
<td>4</td>
<td>1287</td>
<td>2468</td>
<td>-</td>
<td>1.85</td>
<td>200</td>
</tr>
<tr>
<td>Carbon (Graphite)</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>3915-4020</td>
<td>2.267</td>
<td>119-165</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>42</td>
<td>2622</td>
<td>4639</td>
<td>-</td>
<td>10.2</td>
<td>138</td>
</tr>
<tr>
<td>Tungsten</td>
<td>74</td>
<td>3414</td>
<td>5555</td>
<td>-</td>
<td>19.3</td>
<td>174</td>
</tr>
</tbody>
</table>

Table 1.1: Properties of candidate PFCs. $T_{\text{melt}}$ is the melting point, $T_{\text{boil}}$ is the boiling point at atmospheric pressure, $T_{\text{sublime}}$ is the sublimation point, $\rho$ is the mass density and $\lambda$ is the thermal conductivity. Values for carbon from Lange’s Handbook of Chemistry [29]; all other values from the CRC Handbook of Chemistry and Physics [30].

is toxic. Be has a relatively high sputtering rate. Hot beryllium can react with steam to produce hydrogen gas, which presents a risk of explosion [27]. ITER will use Be for the first wall and the startup limiter [17].

Molybdenum is a high-$Z$ material and thus has a high sputtering threshold and is resistant to erosion, but can lead to large impurity losses in the plasma if ionized [17]. It has a fairly high melting point as shown in Table 1.1. Like tungsten, it has relatively low deuterium retention [28]. TZM, a molybdenum alloy with 0.1 % zirconium and 0.5 % titanium, is sometimes used because it has a high recrystallization temperature.

Clearly, there are many issues to address for solid PFCs. Development of advanced alloys for solid PFCs may alleviate some problems associated with their use. However, no clear candidate for a solid PFC has emerged.

1.3 Lithium as a Plasma-Facing Component

Many of the difficulties associated with solid PFCs can be overcome by instead using liquid metal PFCs. Liquid PFCs have the advantage of being self-healing, so any transient events that deposit large heat fluxes do not damage PFCs. Melting is no longer an issue, but evaporation and ionization
rates must be considered. A liquid PFC can be as simple as a thin layer of liquid on a substrate, or as complex as a fast-flowing thick surface. Candidate materials include gallium, tin, and lithium, along with eutectics.

Liquid lithium is an attractive PFC. Lithium has a relatively low melting point of 180.50 °C. As a low-\(Z\) material (\(Z = 3\)), lithium has a low ionization potential, so lithium from PFCs is not expected to deeply penetrate into the plasma, but is instead reionized and rapidly redeposited onto PFCs. Indeed, experiments on the National Spherical Torus Experiment (NSTX) with lithium wall coatings showed lithium densities in the core to be less than 0.10 % of the electron densities [31]. Lithium which does enter the core plasma is fully ionized and does not cause large levels of radiative loss.

Perhaps one of the best features of the use of liquid lithium as a PFC is that it leads to large reductions in recycling. The recycling rate \( R \) is defined as

\[
R = \frac{\Gamma_{\text{wall} \to \text{plasma}}}{\Gamma_{\text{plasma} \to \text{wall}}} \tag{1.19}
\]

where \(\Gamma_{\text{wall} \to \text{plasma}}\) is the neutral particle flux from the wall to the plasma, and \(\Gamma_{\text{plasma} \to \text{wall}}\) is the ion flux from the plasma to the wall. These fluxes are illustrated in Figure [1.2]. The recycling rate is typically unity for solid wall surfaces, but can be significantly lowered with liquid lithium walls. While recycling helps maintain the plasma’s particle inventory, neutrals from the wall have very low energies; thus their reintroduction to the plasma edge has a cooling effect. The edge temperature is brought down, increasing the thermal gradient, which can drive instabilities and degrade confinement. Lithium is able to lower the recycling rate because it forms hydrides when exposed to hydrogen isotope plasmas. This stops many hydrogenic neutrals from leaving the lithium PFC and recycling into the plasma. A gram-atomic weight of lithium can retain up to 0.5 gram-atomic weight of hydrogen [32].

\[^3\]A gram-atomic weight is an amount of an element equal to its atomic weight measured in grams.
As shown in Figure 1.3, a UEDGE \[33\] calculation based on an equilibrium from the Current Drive Experiment-Upgrade (CDX-U), where $T_e$ and $T_i$ is fixed at 200 eV in the plasma center indicates that lowering the recycling rate will increase the edge electron temperature. The presence of lithium walls is predicted to result in more stable plasmas with better energy confinement, which are crucial for developing a viable fusion reactor \[34\].

Previous experiments have studied the effects of using lithium PFCs. The Tokamak Fusion Test Reactor (TFTR) conditioned a graphite limiter with lithium pellet deposition to increase $\tau_E$, $Q$, and the Lawson triple product \[35\] \[36\]. Similar experiments in the Doublet III-D (DIII-D) tokamak also demonstrated increases in plasma performance \[37\]. While using a liquid lithium toroidal tray limiter shown in Figure 1.4, CDX-U obtained a low recycling rates; one study reported $R$ from 0.50 to 0.60 \[38\], while another reported $R = 0.75$ \[39\]. Lithium walls also resulted in a strong reduction in impurities and an increase in the plasma core temperature \[38\] \[40\].
Figure 1.3: Calculated dependence of the electron temperature profile on the recycling coefficient at the wall $R_w$ for a CDX-U equilibrium using UEDGE. $T_e$ and $T_i$ are fixed at 200 eV at the plasma center.

Figure 1.4: The CDX-U tray limiter (a) prior to lithium injection and (b) partially filled with liquid lithium.
Figure 1.5: Experimentally measured confinement times (in seconds on the vertical axis) versus those predicted by IPB98(y,1) scaling on CDX-U. Discharges with passivated lithium appear as blue circles; discharges following lithium evaporation resulting from an electron beam incident on the lithium are shown as red squares.

Figure 1.5 shows enhanced confinement over the IPB98(y,1) scaling in CDX-U in discharges with active lithium [44]. The study used the results of magnetic reconstructions to measure the confinement time using a global power balance approach. Lithium in the tray limiter was heated by resistive heaters beneath the tray and evaporation was the result of an incident electron beam between each shot. The resulting energy confinement time was found to be a factor of two to three over IPB98(y,1) scaling following lithium evaporation. Experiments on the T-11M and Frascati Tokamak Upgrade (FTU) devices have studied the feasibility of using a liquid lithium limiter in tokamaks [45, 46]. NSTX studies evaporated lithium onto both carbon tiles and a liquid lithium divertor with a plasma-sprayed molybdenum surface atop a copper plate substrate. Increases in $T_e$, $T_i$, confinement, and magnetohydrodynamic (MHD) stability were observed [47]. Furthermore, $T_e$ profiles exhibited broadening, the electron thermal diffusivity $\chi_e$ was reduced in outer plasma regions, the L–H mode power threshold was 40 % lower, and ELMs were fully suppressed [48].
A substantial fraction of the carbon PFCs remained uncoated with lithium, however, and the intercalation of the lithium into the carbon also limited its effectiveness.

Liquid PFCs can control a reactor’s tritium inventory. As the gas inventory in a solid wall can be large, implanted tritium becomes an issue \[\text{[8]}\]. Tritium can be recovered from solid PFCs through baking. However, liquid PFCs allow for the possibility of continuous tritium recovery. Liquid lithium used in a flowing wall configuration or breeding blanket can be sent through a tritium recovery system. Such a system is expected to remove tritium down to a concentration of 1 atomic part per million (appm) \[\text{[49]}\].

The recovery of tritium from lithium is an important challenge since lithium must be used to breed tritium for use in a D-T reactor. One possible method of tritium recovery uses a molten salt recovery process \[\text{[50]}\], in which a lithium halide eutectic is added to the tritium-contaminated lithium, which removes tritium. Electrochemical oxidation then converts tritides to tritium gas, which is collected and purified. Lithium halides are removed by mass separation and clean lithium could be reintroduced into the reactor. Another method is removal using a cold trap \[\text{[51]}\]. A cold trap normally has a hydrogen isotope saturation concentration of about 400 appm, but the addition of \(H^+\) to the contaminated lithium can cause tritium to precipitate out. The mixture of LiH and LiT in the cold trap is then heated to raise the partial pressure of hydrogen and tritium. Mass separation removes the tritium from the hydrogen. Tritium can also be removed by yttrium sorption \[\text{[52]}\], permeation through a zirconium-palladium window \[\text{[53]}\], or distillation \[\text{[54]}\]. It is possible that these processes may be performed at different stages of tritium removal to achieve high rates of recovery.

It should be noted that lithium is not without its disadvantages. It is highly corrosive, and as a conductive fluid, is subject to MHD forces. Lithium is very reactive and presents an explosive risk due to the production of hydrogen when exposed to water by the reaction

\[
2\text{Li} + 2\text{H}_2\text{O} \rightarrow 2\text{LiOH} + \text{H}_2. \tag{1.20}
\]
LiOH is strongly basic and corrosive. Li$_2$O can also be formed, which is corrosive as well. Lithium’s performance may degrade at higher temperatures. When lithium reaches temperatures above 400 °C, hydrogen retention ceases [55], lithium sputtering increases [56], and evaporative flux increases [57]. This could lead to undesirably large levels of lithium in the plasma, and could pose challenges related to maintaining adequate amounts of lithium on PFCs. However, a vapor shielding effect mitigates some of these concerns. For sufficiently high PFC temperature, lithium vapor pressure dominates the neutral pressure level. An increased lithium vapor pressure will result in a reduced plasma pressure at the PFC target, reducing the heat flux to the PFC. This is deemed a vapor-shielded target [58]. FTU has observed that a radiative lithium ring in the plasma edge converted plasma power flux to radiation that kept PFC heat loads reasonable [59]. Continued research is necessary to address the advantages and disadvantages of liquid lithium PFCs.
Chapter 2

The Lithium Tokamak Experiment

The Lithium Tokamak Experiment (LTX) is a spherical torus specifically designed to further studies of the low-recycling regime [60–63]. The unique feature of the experiment is the presence of shells conformal to the last closed flux surface (LCFS). The bottom of the shells may be filled with lithium, or lithium may be evaporated onto the plasma-facing side of the shells.

LTX extends the work of CDX-U in a cost-effective manner by reusing the vacuum vessel, center stack, power supplies, and other infrastructure and hardware. However, significant upgrades to CDX-U including the addition of the shells, an enhanced set of diagnostics, a new data acquisition system, a new ohmic heating power supply, and most importantly, a focus on the study of the low-recycling regime using lithium PFCs that almost completely surround the plasma have made the experiment worthy of a new name.

An isometric projection and a cross section of LTX are shown in Figure 2.1. The vacuum vessel and several of the flanges are gray. The shells are a copper color externally and gray on their plasma-facing surfaces. The toroidal field coils are green, the poloidal field coils are either orange, yellow, red, green, or blue, and the ohmic compensation coil is dark purple. LTX is designed to have \( R_0 = 0.40 \) m, \( a = 0.26 \) m, and \( \kappa = 1.55 \). The design toroidal field is \( B_{T0} = 0.34 \) T, but currently operates at \( B_{T0} = 0.17 \) T. The poloidal field system and Ohmic power supply is designed
to drive $I_F$ up to 400 kA with a flat-top over 100 ms long, and has presently reached $\sim 80$ kA with durations of $\sim 30$ ms. Peak $T_e$ is expected to exceed 300 eV. Design parameters are summarized in Table 2.1.

### 2.1 LTX Device

#### 2.1.1 Vacuum Vessel

The LTX vacuum vessel is the same as was used for CDX-U, except for slight changes. The vessel consists of four parts. The outer cylindrical wall is made of 3/8 inch thick stainless steel with an inner radius of 70.2 cm [39]. There are also two circular endcaps at the top and bottom of the vessel. The endcaps were sealed with a double O-ring seal on CDX-U, but during the conversion
to LTX, the innermost O-ring seal had to be removed to allow the installation of the internal coilset. The center stack also provides a vacuum interface.

The volume of the vacuum vessel, excluding the shells and including the pump duct, is 1.607 m$^3$ (D. Lundberg, personal communication, September 28, 2011). This value was determined by monitoring the pressure in the vessel during the addition of a known quantity of gas, and was compared with a geometric calculation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$</td>
<td>0.40 m</td>
</tr>
<tr>
<td>$a$</td>
<td>0.26 m</td>
</tr>
<tr>
<td>$B_{T0}$</td>
<td>0.34 T</td>
</tr>
<tr>
<td>$I_p$</td>
<td>400 kA</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>1.55</td>
</tr>
<tr>
<td>$T_{e, max}$</td>
<td>$&gt;$300 eV</td>
</tr>
<tr>
<td>$\tau_{\text{flat-top}}$</td>
<td>$&gt;$100 ms</td>
</tr>
</tbody>
</table>

Table 2.1: LTX design parameters.


2.1.2 Shells

LTX has a set of four internal shells designed to be conformal to the LCFS. Lithium wall conditions are achieved through lithium evaporation onto the plasma-facing side of the shells or by filling the shell bottoms or reservoirs with lithium. The approximately 200 pound shells are made of 3/8 inch oxygen-free high thermal conductivity (OFHC) copper to facilitate thermal uniformity. Additionally, the large amount of copper provides a high thermal mass so that lithium can remain in a liquid state during a discharge. Since lithium reacts with copper, the shells have been explosively bonded to 1/16 inch 304 stainless steel on the plasma-facing side, and are nickel plated on the back side. There are four shells instead of one large shell to prevent large-scale currents from flowing toroidally or poloidally, and also to allow diagnostic access. Gaps between the shells exist on the midplane for sightlines to the plasma core. Each shell also has two circular penetrations or ducts that allow vertical sightlines for optical diagnostics, electron beams, or gas injection closely coupled with the plasma.

Resistive heaters driven by 240 V AC power can heat the shells to 350 °C. The temperatures of the top and bottom shell pairs are separately controlled using a pair of variable autotransformers. An interlock system disconnects the heaters during each plasma discharge and also turns off the heaters in the case of an accidental vessel vent. Shell temperatures are monitored by eight thermocouples on each shell and are automatically cataloged using a Laboratory Virtual Instrument Engineering Workbench (LabVIEW) program. Experiments with heated shells have shown alterations in plasma performance [64].

The shells are held in place by four supports each. These supports exit the vessel through a bellows seal and are attached to an external support structure. Ceramic breaks provide electrical insulation between the vacuum vessel and the shell support structure. However, in December 2010, large-amplitude mechanical oscillations of the shells during plasma discharges were discovered. As seen on a fast camera, the shells had both toroidal and vertical motion with a full amplitude of
approximately 1 cm. This vibration caused ceramic pieces protecting magnetic flux loops to break, littering the shells and vacuum vessel. LTX was vented and cleaned. Additional supports were installed in the first half of 2011 to dampen this destructive motion, and the support structure for the flux loops was modified to allow some motion without breaking remaining ceramic insulators. Originally, the shells were designed to be mechanically and electrically isolated from the vacuum vessel, but the nature of the repair caused the loss of electrical isolation. Tests after the repair showed that the vertical motion was attenuated, but large-amplitude toroidal oscillations persisted.

A set of four limiters are installed on the lower shells near the toroidal gaps. The individual limiters are made of two pieces of molybdenum sandwiched together. There is a small gap in between the pieces, which encourages capillary action that brings liquid lithium into interaction with the plasma. There are also small lips on the toroidal ends of the lower shells that act as dams for the lithium reservoir. The toroidal ends of the shells are covered by a tungsten-coated stainless steel band to prevent lithium wetting that could cause lithium to flow over the edge of the shells. The band also supports the Mirnov coil in the gap between shell segments.

The inner surface area of the shells calculated directly from a Computer-Aided Design (CAD) model of the experiment is 3.71 m$^2$. This includes the shell ducts, the inner welded ring, the outboard flat area, and end faces. The volume of the region defined by the shells is calculated to be 0.707 m$^3$. This includes the volume in the toroidal gaps and thus represents an upper limit on the plasma volume.

### 2.1.3 Magnetic Field Coils and Power Systems

The toroidal magnetic field (TF) in LTX is generated by a set of 16 rectangular coils, evenly spaced 22.5° toroidally. Each coil has eight turns of copper conductors (four layers of two turns each) for a total of $N_{TF} = 128$ turns. The conductors are hollow to allow water cooling. Each coil consists of a bracket piece that forms the bottom, outer side, and upper legs of the rectangle, which is attached
to the center stack where an inner leg completes the loop. The outer bracket section of the coil is enclosed in an aluminum casing. Typical currents $I_{TF}$ during plasma discharges are 2.7 kA, which produces a TF on the plasma axis of

$$B_{T0} = \mu_0 \frac{N_{TF} I_{TF}}{2\pi R_0} = 0.17 \text{T}$$  \hspace{1cm} (2.1)

where $\mu_0$ is the vacuum permeability. The TF current will eventually be increased to 5 kA, which will increase $B_{T0}$ by a factor of 1.9. This requires additional cooling on the center stack and the addition of another power supply to achieve voltages large enough to drive the requisite current. The sixteen TF coils are lettered A through P. The ports between TF coils are then identified by the two adjacent coils. For instance, the Thomson scattering beam entrance port is on the HI midplane.

There are six pairs of poloidal field (PF) coils. Five coil pairs are outside the vacuum vessel, and are given monikers based on the color of their insulation. The blue coil pair is the largest and provides the main poloidal field. The yellow coil pair cancels the poloidal field on startup to allow the formation of a vertical field null necessary for breakdown. The orange coil pair allows for vertical plasma positioning and curvature control. The green coil pair cancels eddy currents generated by the ohmic solenoid. The red coils provide additional shaping. An internal coil pair in the vacuum vessel allows for fast control of the poloidal field as the resistive skin time of the vessel is not a factor. Coil parameters are given in Table 2.2.

The TF, blue, orange, red, and internal coilsets are powered by six Robicon power supplies. The power supplies rectify 12-phase alternating current to direct current. Some temporal ripple is present in the output of the power supplies due to difficulties adjusting gain and rise times for the power supply control circuits. These circuits were not intended for pulse lengths found on LTX, but rather $\sim 0.5$ ms pulses on the Princeton Beta Experiment-Modification (PBX-M) \[66\]. Resistor banks with fifteen 1 $\Omega$ resistors in parallel were installed in series with the output of the T2, T3, and T4 supplies in 2013 to reduce the ripple by increasing the overall impedance of the system.
<table>
<thead>
<tr>
<th>Coil</th>
<th>Radial Layers</th>
<th>Vertical Layers</th>
<th>Turns</th>
<th>$R$ [m]</th>
<th>$Z$ [m]</th>
<th>$w$ [m]</th>
<th>$h$ [m]</th>
<th>$L$ [$\mu$H]</th>
<th>$R$ [mΩ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal Field</td>
<td>-</td>
<td>-</td>
<td>128</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5600</td>
<td>148.2</td>
</tr>
<tr>
<td>Ohmic Solenoid OH1</td>
<td>1</td>
<td>74</td>
<td>74</td>
<td>0.07465</td>
<td>0.00</td>
<td>0.0127</td>
<td>1.067</td>
<td>114.310924</td>
<td>7.81*</td>
</tr>
<tr>
<td>OH2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0.513</td>
<td>+1.02085</td>
<td>-1.02085</td>
<td>0.0127</td>
<td>0.0254</td>
<td>10.773</td>
</tr>
<tr>
<td>OH3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0.154</td>
<td>+0.51135</td>
<td>-0.51135</td>
<td>0.0127</td>
<td>0.0254</td>
<td>2.3053</td>
</tr>
<tr>
<td>Yellow</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0.724</td>
<td>0.730</td>
<td>0.8</td>
<td>-0.787</td>
<td>0.0137</td>
<td>12.8</td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td>0.1</td>
<td>0.094</td>
<td>0.4862</td>
<td>-0.49</td>
<td>0.0368</td>
<td>300</td>
</tr>
<tr>
<td>Blue</td>
<td>3</td>
<td>4</td>
<td>12</td>
<td>0.8618</td>
<td>0.8618</td>
<td>0.4064</td>
<td>-0.4128</td>
<td>0.0504</td>
<td>336.</td>
</tr>
<tr>
<td>Orange</td>
<td>2</td>
<td>10 and 9</td>
<td>19</td>
<td>0.4248</td>
<td>0.3962</td>
<td>0.8136</td>
<td>-0.8137</td>
<td>0.0088</td>
<td>520</td>
</tr>
<tr>
<td>Red</td>
<td>6</td>
<td>2</td>
<td>12</td>
<td>0.673</td>
<td>0.673</td>
<td>0.4937</td>
<td>-0.4969</td>
<td>0.0631</td>
<td>146.5</td>
</tr>
<tr>
<td>Internal</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>0.6318</td>
<td>0.6318</td>
<td>0.3667</td>
<td>-0.3667</td>
<td>0.03175</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 2.2: Magnetic field coil parameters summarized from Berzak [65]. * Note that the $R = 7.81$ mΩ for the all OH coils in series.
Power supply ratings are summarized in Table 2.3. The IF Robicon supply always powers the TF coils, but other connections between supplies and coils are changed occasionally. A capacitor bank drives the yellow coil pair.

The ohmic heating (OH) system for LTX consists of an ohmic solenoid, an ohmic compensation coil, and a power supply. The ohmic solenoid has 74 turns in a single layer, and two pairs of additional coils to cancel the ohmic field externally. The OH power supply is made of a capacitor bank which is discharged by duty cycle modulation of insulated gate bipolar transistors (IGBTs) in an H-bridge configuration. Ideally, this system is capable of driving an arbitrary waveform in the ohmic solenoid. However, it is presently run by setting the duty cycle over millisecond scale time bins. Modulation of the current results in switching noise, which is picked up by nearly all digitized diagnostics.

The green coils are powered by both a dedicated capacitor bank and also a transformer driven by the OH. This allows closely-matched currents as a function of time to cancel eddy currents driven by the OH.

Electron Cyclotron Heating (ECH) is used to facilitate tokamak startup. The electron cyclotron frequency is

\[
\nu = \frac{eB}{2\pi m_e}
\]  

(2.2)
where $e$ and $m_e$ are the magnitudes of the electron charge and mass, respectively. A resonant surface exists where

$$B = \frac{2\pi \nu m_e}{e}. \quad (2.3)$$

Since the toroidal magnetic field has the form

$$B_T = \frac{\mu_0 N_{TF} I_{TF}}{2\pi R} = \frac{B_{T0} R_0}{R}, \quad (2.4)$$

this surface is at

$$R = \frac{e B_{T0} R_0}{2\pi \nu m_e}. \quad (2.5)$$

LTX currently has a $\nu = 5.6$ GHz system that can pulse for 5 ms. With $B_{T0} = 0.17$ T, the resonant surface is at $R = 35$ cm. Future plans to increase the toroidal field by reconfiguration of power supplies will produce $B_{T0} = 0.34$ T, with an associated resonance at $R = 64$ cm. Since this is close to the outboard edge, a constant waveform $\nu = 10$ GHz system will be used instead. This produces a resonance at $R = 19$ cm for $B_{T0} = 0.17$ T and $R = 36$ cm for $B_{T0} = 0.34$ T.

A filament is also used for startup. The filament provides a population of seed electrons through the process of thermionic emission. These seed electrons are accelerated by the electric field from the Ohmic solenoid, which then create a breakdown through collisions with neutral particles. The filament itself is a 0.015 inch diameter tungsten wire mounted on an insertable bellows. It is powered by standard 120 V AC power controlled by a variable autotransformer. Additionally, the filament can be given a DC bias to enhance electron emission, but this capability is not generally used. Both ECH and the filament are necessary for startup when the walls are uncoated, but when the walls are lithium-coated, only ECH is necessary.
2.1.4 Lithium Delivery Systems

Lithium can be introduced into LTX in one of two ways. The primary method of lithium deposition is through the use of two evaporative crucibles. As shown in Figure 2.3, the evaporators consist of yttria (Y$_2$O$_3$) crucibles typically filled with 8 g solid lithium. The crucibles are slightly tapered cylinders, with an inner diameter of 3.04 cm at the bottom, 3.36 cm at the top, and depth of 4.87 cm. Resistive tantalum heaters surround the exterior of the crucibles. A small basin is in place below the crucible to catch any debris that could fall if a crucible were to fracture. The crucible, heater assembly, and basin are mounted on a translation stage and sealed with a welded bellows. This allows the crucibles to be driven into the interior of the shells for evaporation, then removed during plasma operations while maintaining vacuum. The evaporators are attached to the vessel using a double gate valve configuration that acts as an air lock. The evaporators are supported by carts, which allows them to be loaded in a separate lithium laboratory room. To prevent the lithium from reacting with water, oxygen, and nitrogen in the atmosphere, the crucibles are loaded with lithium in a glove bag with an argon atmosphere. The interior of each evaporator is filled with argon during transportation to prevent passivation of the lithium.

The evaporator heaters are powered by external power supplies. The evaporator that connects to the six inch LM port on the north side of the vessel is connected to a programmable DC power supply$^1$. The evaporator on the eight inch DE port on the south side of the vessel is connected to a separate DC programmable power supply$^2$. Both power supplies operate in current-controlled mode. During evaporation, the current is initially set to 50 A and is typically increased by 50 A every ten minutes until 250 A is achieved; however, currents as high as 350 A have been used. The slow rise in current is intended to ensure even heating of the lithium. The temperature of the lithium is measured using a pair of thermocouples in each crucible. The target temperature for evaporation is between 500 °C and 600 °C. The heater current is modified to ensure a lithium

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1 American Reliance Inc. ePower SPS5-600-K022
2 Magna-Power Electronics TSAii8-600
Figure 2.3: A lithium evaporator assembly. The yttria crucible is the white piece in the middle, which is surrounded by the heater and heat shields. The rectangular basin under the crucible is intended to catch lithium in case of a spill.
Figure 2.4: South 8 inch evaporator temperature in red and heater power supply current in blue for the January 4, 2012 evaporation. Note the plateau in temperature of 180.5 °C at $t = 205$ minute due to the latent heat of fusion during cooling of the lithium.

temperature within this range. Once the crucibles reach the target temperature range, the current is typically kept constant for one hour while evaporation occurs. The power supplies are then turned off and the evaporators are allowed to cool. Then, the evaporators are retracted from the vessel prior to plasma operations. During evaporation, many gate valves on the vessel are closed to prevent lithium deposition onto optical windows or diagnostics.

Thermocouple measurements are monitored and saved using a LabVIEW interface. Example measurements are shown in Figure 2.4. This data allows two ways of estimating the amount of lithium evaporated. Due to the latent heat of fusion, the amount of time the lithium is at its freezing point during cool-down is indicative of the amount of lithium remaining in the crucible. Comparing this time with freezing times from previous evaporations and taking into account the initial amount of lithium added to the crucibles can give an estimate of the total amount evaporated.
The other method of estimating the evaporated amount is to use a curve for the evaporation rate as a function of temperature using the temporal history of the crucible temperature. The vapor pressure of lithium is [67]

\[
P = \exp \left( 13.0719 \pm 1.8424 - \frac{18880.659 \pm 347.220 \text{ K}}{T} 
- (0.4942 \pm 0.2208) \ln \left( \frac{T}{\text{K}} \right) \right) \times 10^6 \text{ Pa.}
\]

(2.6)

The evaporation rate is related to the partial pressure by [68]

\[
\Gamma = P \sqrt{\frac{1}{2\pi mT}}
\]

(2.7)

and the total evaporated mass \( m \) is

\[
m = A \int \Gamma \, dt
\]

(2.8)

where \( A \) is the surface area of the exposed lithium in the crucible. Neither of these techniques is precise, but allow simple observations such as an asymmetry in the evaporation rate between the two evaporators. Typical evaporation cycles result in 2 g evaporation per crucible per hour at full temperature.

Normally, the vessel is filled with 5 mTorr of helium in order to ensure the evaporative deposition is as uniform as possible. Using the DEGAS 2 neutral particle transport code, the pressure range of 1 mTorr - 10 mTorr was found to give the most uniform deposition in both toroidal and poloidal directions [69, 70]. This is because in the limit of low pressure, the evaporation becomes more of a line-of-sight cone and preferentially deposits lithium on the upper shell directly above the crucible. In the high-pressure limit, the mean free path of a lithium atom is short enough that deposition is dominantly onto the evaporator assembly itself, which is clearly not desired.

Initially, evaporations were performed during helium glow discharges. Since lithium glows a bright red color in these conditions, this technique allowed visual inspection of the uniformity of
the evaporation. Glow discharges were discontinued after it was ascertained that the deposition was reasonably uniform.

The other system for introducing lithium into LTX is the lithium filler. As shown in Figure 2.5, this system is the same as the evaporator assembly except the ceramic crucible is replaced by a tungsten crucible with an inner diameter of 4.98 cm and a depth of 5.73 cm, with a 0.94 cm hole in the bottom. A hole is also punched in the basin below the crucible. Typically, 15 g of solid lithium is loaded as previously described, and a cylindrical tungsten plunger with diameter of 4.98 cm, height of 1.93 cm, and mass of 716 g sits within the crucible atop the lithium. During the reservoir fill, the heaters melt the lithium, which is then forced out of the hole in the bottom of the crucible and into the shell reservoirs by the tungsten plunger, which provides a pressure equal to column of lithium ∼ 0.5 m high. These reservoirs are the bottommost part of the lower shells bounded by small lips on the toroidal shell gaps that act as dams for the lithium. During the fill, the lower shells are kept at 300 °C so that the lithium remains in a liquid state when it hits the shells. Lithium fill occurs in a 200 Torr argon background atmosphere, which inhibits oxidation.

Over time, lithium reservoirs will form an oxide layer from passivation. As on CDX-U, the oxide layer is stirred into solution with the lithium by targeting the surface with an electron beam mounted on a port directly above one of the shell penetrations. The electron beam is created by a 4.2 kV electron gun capable of currents up to 140 mA. The beam is directed to the lithium reservoirs by applying toroidal and vertical magnetic fields. A Biot-Savart code is used to calculate necessary coil currents to properly guide the electron beam. The operating currents are 50.5 A in the TF coils, 457 A on the lower red coil, and 335 A on the blue coils.

An image of the shell interiors at the beginning of the 2012-2013 vent is shown in Figure 2.6. Lithium was deposited in the shell reservoirs, but they were not full. The white substance on the shells is lithium carbonate, which results from the lithium hydroxide reacting with carbon dioxide after the vent. The darker substance on the left and right sides is lithium nitride. The lithium-
Figure 2.5: A lithium filler assembly. The tungsten crucible is in the center of the assembly. Note the hole in the bottom of the crucible.

Figure 2.6: A composite image of the shells during the Winter 2012 vent. Thick lithium deposits in the shell reservoirs were scraped off but the shell interiors had not yet been cleaned with vinegar.
nitrogen reaction is strongly temperature dependent, and the proximity of the shells to the hot evaporators or fillers results in more lithium nitride deposition near the center of the shells.

Lithium, lithium carbonate, and lithium nitride are cleaned from the shells during vents using consumer grade distilled vinegar (about 5% acetic acid). Lithium acetate is formed, which is water-soluble and easily removed. Only a small amount of vinegar is added to the vessel at a time by a spray bottle. After the vinegar finishes reacting, lint-free wipes are used to clean the liquid in the vessel. The process is repeated until the shells are clean. To avoid accumulation of hydrogen and to contain vinegar fumes, the vessel volume is exhausted by a high-volume blower. Final cleanings with distilled water and then ethanol are also used.

2.1.5 Vacuum Systems and Wall Conditioning

LTX is kept at a low base pressure using a system of several pumps. These pumps are connected to a pump duct on the vessel. The main pump for the LTX vacuum vessel is a rotary vane vacuum pump\(^3\) which has a maximum pumping speed of 65 m\(^3\)/h. This pump is capable of pumping the vessel to approximately \(10^{-3}\) Torr. The exhaust of the pump is routed outdoors. From summer 2011 until its failure in October 2012, an oil-free scroll vacuum pump\(^4\) was used. This pump had a maximum pumping speed of 1200 L/min. It was chosen for use because there seemed to be evidence of carbon in the vessel while using a previous oil-sealed roughing pump. The rotary vane vacuum pump is connected to the outlet of a turbomolecular pump\(^5\) with a maximum pumping speed of 1500 L/s. The turbomolecular pump is used to reach pressures in the range of \(10^{-7}\) Torr. A cryogenic pump\(^6\) is used at low base pressures to remove water vapor and other contaminants from the vacuum vessel.

\(^3\)Leybold Trivac D 65 B  
\(^4\)ISP-1000 Anest Iwata Scroll Meister  
\(^5\)Leybold-Heraus Turbovac 85381  
\(^6\)Helix Technology Corporation CTI-Cyrogenics Cryo-Torr 8
A roots blower backed by a rotary vane vacuum pump is used in order to keep vessel pressure in the ~ 100 Torr range even if a small vacuum window is completely fractured, or a larger window is cracked. Liquid lithium will not burn in air at pressures less than 200 Torr. The inlet of the roots blower is connected to the vessel by a duct and pneumatic gate valve that is set to automatically open if the pressure rises above a setpoint. The pump is also used to quickly pump down the vessel after a vent or backfill.

An auxiliary pumping system provides additional pumping and serves as a backup in case of the failure of the main pumping system. This system consists of a turbomolecular pump (maximum pumping speed 500 L/s) and a rotary vane vacuum pump (maximum pumping speed of 30 m$^3$/h). The auxiliary pumping system is connected to an uninterruptible power supply to provide operation in case of a short power outage.

Several methods of leak checking are employed on the device. During initial pumpdown, any large-scale leaks can be heard as an audible hissing. Smaller leaks can be found with the aid of an ultrasonic leak checker. A method useful at intermediate pressures is to squirt pure ethanol onto vessel flange connections. A leak allows some ethanol to enter the vessel, which vaporizes and causes the pressure to rise. At low pressures, helium leak checking can be used. In this technique, a small amount of helium gas is released near a flange. A helium leak checker is connected to the outlet turbomolecular pump, and detects helium levels present in the vessel using a small mass spectrometer.

In order to achieve the high vacuum necessary for plasma operation, numerous techniques of vacuum vessel conditioning are used. One method is to bake the shells at an elevated temperature for a long period of time in order to desorb water and other impurities inside the vessel. The shells have been baked for several days in a row at 180 °C, and for shorter periods as high as 350 °C. To prevent gas desorbed from the shells from simply redepositing on the vacuum vessel walls, the

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7Leybold Trivac D65BCS
8Arthur Pfeiffer TPU 510
9Leybold-Heraus D 30 A
vacuum vessel may be heated through copper lines in contact with the vacuum vessel and pump duct, through which heated water from a 9 kW heater\(^\text{10}\) at up to 90 °C is circulated. A 5 kW chiller\(^\text{11}\) can also be used to cool the vessel below 20 °C during operation to keep impurities on the vessel walls.

Another method to condition the vacuum vessel is to run a glow discharge for several hours. Typically, helium at a pressure of approximately 20 mTorr is used, but argon and neon have been used as well. The glow is driven by an insertable probe biased with respect to the vacuum vessel by 480 V AC power. The glow is initiated using a Tesla coil. Additionally, the shells may be purposely or inadvertently cleaned during plasma operation since disruptions drive the plasma into the shells. On bare shells, plasma performance has improved after repeatedly firing plasma shots that terminated on the shells. Base pressures in LTX may be as low as \(\sim 5 \times 10^{-8}\) Torr after wall conditioning.

LTX has two residual gas analyzers (RGAs) to monitor partial pressures as a function of mass to charge ratios of main and impurity gasses in the vacuum chamber. A Stanford Research Systems, Inc. RGA200 with an electron multiplier is connected to a short, six inch Conflat port behind one of the lower shells. In addition to being highly sensitive, it is closely coupled to the main vacuum chamber so that it can be used for helium leak checking. The other unit is a Stanford Research Systems, Inc. RGA100 with a less sensitive Faraday cup, which is connected to the main vessel on a 2 3/4 inch Conflat port at the end of a long tube. This unit is not as closely coupled with the vacuum chamber, but may be kept on during machine operation because it is far enough away from magnetic field coils so as not to be damaged. While these RGAs are not absolutely calibrated, comparisons between relative levels of impurities can be made to characterize effects of lithium walls on vacuum conditions.

\(^{10}\)Mokon Hydrotherm II HY40090EF

\(^{11}\)Thermo Scientific Neslab ThermoFlex 5000
2.2 Diagnostics

LTX has a wide range of diagnostics necessary to study magnetically-confined plasmas. These include magnetic diagnostics, two interferometers, a Langmuir probe, X-ray detectors, a fast camera, several spectroscopic diagnostics, and a Thomson scattering system.

2.2.1 Magnetic Diagnostics

The collection of magnetic diagnostics on LTX is made of 102 Mirnov coils, 27 flux loops, two Rogowski coils, and a diamagnetic loop with a compensation coil [65].

Following Hutchinson [71], a Mirnov coil measures the voltage across a small coil of wire with $N$ turns and an area $A$, which is proportional to the time derivative of the magnetic field perpendicular to the coil plane:

$$V = -\frac{d\Phi}{dt} = -\frac{d}{dt} (NBA) = -NAdB \frac{dt}{dt}.$$  \hspace{1cm} (2.9)

To measure the magnetic field at a given time, the voltage must be integrated. Typically, this is done with an integrating circuit which has a time constant $\tau = RC$, where $R$ is the effective resistance and $C$ is the effective capacitance, so that the output of the integrator is

$$V = \frac{NAB}{RC}.$$  \hspace{1cm} (2.10)

LTX has 102 Mirnov coils: 30 coils on the internal or plasma-facing side of the shells, 10 coils on the external side, 36 coils in the shell gaps, and 26 coils in a rectangular array at the edge of the vacuum vessel.

Rogowski coils are used to measure the toroidal plasma current. If a solenoidal coil is bent into a torus that nearly connects to itself, but has a return wire that does not form an enclosed loop, it
will enclose a magnetic flux

\[ \Phi = n \oint_A dA \mathbf{B} \cdot d\mathbf{l} \]  

(2.11)

where \( d\mathbf{l} \) is along the solenoidal axis, and it is assumed that the magnetic field changes little between turns. As

\[ \mathbf{B} = \frac{\mu_0 I}{2\pi r} \hat{\theta} \]  

(2.12)

where \( I \) is the enclosed current, \( r \) is the major radius of the coil, and \( \theta \) is the angular measure around the coil. This integrates as

\[ \oint_I \mathbf{B} \cdot d\mathbf{l} = \frac{\mu_0 I}{2\pi r} 2\pi r = \mu_0 I \]  

(2.13)

and the flux is then simply

\[ \Phi = nA \mu_0 I. \]  

(2.14)

The electromotive force induced in the coil is then

\[ V = -\frac{d\Phi}{dt} = -nA \mu_0 \frac{dI}{dt} \]  

(2.15)

where \( n \) is the number of turns per unit length of the coil and \( A \) is the cross-sectional area of the coil. Rogowski coils poloidally encircling the plasma cross section provide a measurement of \( I_p \). LTX has a Rogowski coil to measure the plasma current and a second to measure eddy currents in the vacuum vessel.

A toroidal circular flux loop produces a signal

\[ V = -\frac{\partial \psi}{\partial t} \]  

(2.16)
where $\psi$ is the flux enclosed by the loop. LTX has 11 flux loops internal to the center stack. There are also 16 shell flux loops, which are on the exterior side of the shells, plus two saddle loops on the upper shell toroidal gaps with corresponding pairs for the lower toroidal gap that measure error fields. Further information on LTX magnetic diagnostics are given by Berzak [65, 72].

The measurements from the magnetic diagnostics are used for reconstructions of the magnetic field in the experiment [73] and estimations of eddy currents in the shells. This is done by matching experimental data to parameters in the Grad-Shafranov equation [74]

$$\Delta^* \psi = -\mu_0 R^2 \frac{dP}{d\psi} - \frac{1}{2} \frac{dF^2}{d\psi}$$

(2.17)

where $F = RB_T$ and

$$\Delta^* = R \frac{\partial}{\partial R} \left( \frac{1}{R} \frac{\partial}{\partial R} \right) + \frac{\partial^2}{\partial Z^2}.$$  

(2.18)

The magnetic field is given by

$$\mathbf{B} = \frac{1}{R} \nabla \psi \times \hat{e}_T + \frac{F}{R} \hat{e}_T$$

(2.19)

and the current is given by

$$\mu_0 \mathbf{j} = \frac{1}{R} \frac{dF}{d\psi} \nabla \psi \times \hat{e}_T - \frac{1}{R} \Delta^* \psi \hat{e}_T.$$  

(2.20)

The diamagnetic effect can be used to measure poloidal beta $\beta_p$ and the energy confinement time $\tau_E$. A diamagnetic loop is a flux loop that encircles the plasma poloidally, which measures a diamagnetic flux

$$\phi_{\text{dia}} = \int \mathbf{B} \cdot d\mathbf{A} = \pi a^2 \langle B_\phi \rangle.$$  

(2.21)

This picks up components from both the vacuum magnetic field and the field from the plasma. Since the plasma is paramagnetic, the overall toroidal field is stronger than the vacuum field. In order to measure the vacuum magnetic field during a shot, a compensation coil is used. This coil
is located on the atmospheric side of the bottom of the vacuum vessel, but within the toroidal field coils. The number of turns multiplied by the area of each loop is roughly equal. The compensation coil has dimensions of 36.6 cm by 9.0 cm with 17.1 turns. As shown in Figure 2.7, one side of the first turn of the diamagnetic loop is set to be the positive differential input to a digitizer. The other side of that turn is connected to the first half of a compensation loop such that toroidal field is subtracted. The center of the compensation loop is grounded to reduce noise. The other half of the compensation loop is connected to the other turn of the diamagnetic loop. The far side of the diamagnetic loop is connected to the negative differential input. Thus, the signals from the two loops are subtractive so that only the signal due to the plasma and not due to the TF or other coils is digitized.

Following Hutchinson [71], measurements of \( \delta \phi_{\text{dia}} = A_P (\langle B_T \rangle - B_T(a)) \) can then be used to measure

\[
\beta_P = \frac{2\mu_0 \langle P \rangle}{B_{Pa}^2}.
\]  

(2.22)

In the limit of low \( \beta_P \) and \( B_T \gg B_P \) this becomes

\[
\beta_P \approx 1 + \frac{2B_{Ta}(B_{Ta} - \langle B_T \rangle)}{B_{Pa}^2}.
\]  

(2.23)

Writing \( B_{Pa} = \mu_0 I_P/\ell \), where \( \ell \) is the circumferential length of the poloidal cross-section of the plasma, results in

\[
\beta_P = 1 - \frac{2\ell^2 B_{Ta}}{(\mu_0 I_P)^2} A_P \delta \phi_{\text{dia}}.
\]  

(2.24)

In the limit that \( \ell = 2\pi a \) and \( A_P = \pi a^2 \), the form of the above equation is

\[
\beta_P = 1 - \frac{8\pi B_T}{(\mu_0 I_P)^2} \delta \phi_{\text{dia}}.
\]  

(2.25)
Figure 2.7: Diamagnetic and compensation loop wiring diagram.
However, typically $\ell$ and $A_P$ must be calculated from a magnetic equilibrium. For example, in plasmas with $R_0 = 0.40$ m, $a = 0.25$ m, $\kappa = 1.4552$, and $\delta = 0.30$, the values are $\ell = 1.95$ m, $A_P = 0.282$ m$^2$, and $V = 0.677$ m$^3$. This results in a slight correction of $\ell^2/4\pi A_P = 1.07$. Note that if $\beta_p < 1$ ($\delta \phi_{\text{dia}} > 0$, so excess toroidal field is produced), then the plasma is paramagnetic. If $\beta_p > 1$ ($\delta \phi_{\text{dia}} < 0$, so less toroidal field is produced), the plasma is diamagnetic. The total stored energy $W_{\text{kin}}$ is

$$W_{\text{kin}} = \frac{3}{2} \langle P \rangle 2.26 {}
\rightleftharpoons

Using the definition of $\beta_p$, this becomes

$$W_{\text{kin}} = \frac{3V\mu_0 I_P^2 \beta_p}{4\ell^2}. \quad (2.27)$$

In the circular plasma limit, this is

$$W_{\text{kin}} = \frac{3}{8} \mu_0 \beta_p I_P^2 R_0. \quad (2.28)$$

Note that here the correction is $2V/R_0 \ell^2 = 0.889$ for the same shaping parameters as listed previously. The energy confinement time for Ohmically heated plasmas

$$\tau_E = \frac{W_{\text{kin}}}{I_P V_{\text{loop}} - \frac{dW_{\text{kin}}}{dt}} \quad (2.29)$$

can then be calculated. More accurate analytic forms of these equations for non-circular plasmas exist, but require knowledge of additional plasma parameters such as pressures and bulk flow velocities [75].

Flux loop, Mirnov coil, and Rogowski coil data is available for plasma analyzed in Chapter 4. The compensated diamagnetic loop data is available for the September 14, 2012 dataset, but not the November 8, 2011 dataset.
2.2.2 Interferometers

Microwave interferometers allow measurements of the line integrated electron density in a plasma. The phase shift of a microwave signal of frequency $\nu$ passing through a plasma in the quasi-transverse ordinary mode is given by \[\Delta \phi = \frac{e^2}{4\pi \epsilon_0 m_e c \nu} \int n_e d\ell \] (2.30)

where the integral is along the path length, $\epsilon_0$ is the vacuum permittivity, and $c$ is the speed of light. The cutoff density

\[n_c = \frac{4\pi^2 \nu m_e \epsilon_0}{e} \] (2.31)

is the density above which the wave can no longer propagate.

LTX previously had a 140 GHz interferometer [76] that viewed the plasma on several horizontal radial chords that reflected off a mirror on the center stack. The interferometer height could be scanned between discharges, such that several chords could be viewed over the course of several plasma shots. With knowledge of the shape of flux surfaces, this allowed Abel inversions to be performed to produce $n_e$ profiles [77]. The output signal from the 140 GHz interferometer undergoes a fringe shift if the phase becomes greater than $\pi$ or less than $-\pi$, such that the detector has a full span of $2\pi$ [78]. Since a fringe shift can happen very quickly, a fast digitizer must be used in order to distinguish a phase shift from noise. The 140 GHz system used a two-channel 200 MS/s GaGe CompuScope digitizer card to directly measure the reference and output signals from the interferometer. The phase was then determined from these signals using a digital phase comparator algorithm [79]. Following this, fringe shifts were removed by another procedure that either added or subtracted $2\pi$ from the phase after a fringe shift. Each $2\pi$ fringe shift represented a line integrated density $\int n_e d\ell = 1.04 \times 10^{18}$ m$^{-2}$. The cutoff density for this system was $2.43 \times 10^{20}$
While this system produced excellent measurements for years, the difficulty in replacing its failed Gunn diodes rendered it impractical to maintain.

LTX has a second interferometer operating at 282 GHz that uses a frequency-chirped source and heterodyne detector [80]. Originally, this system viewed the plasma on a fixed vertical chord. The beam entered the vessel from the bottom on a viewing chord through one of the shell ducts, passed through the plasma, reflected off a mirror on the top of the vessel, and returned on the same path. After the failure of the 140 GHz system, the 282 GHz system was moved to the main interferometer port, and now views a fixed radial chord on the midplane. Each phase shift of the phase comparator output is equal to \( \int n_e d\ell = 2.10 \times 10^{18} \text{ m}^{-2} \). The cutoff density for this interferometer is \( 9.86 \times 10^{20} \text{ m}^{-3} \).

Interferometer data is not available for plasmas analyzed in Chapter 4, however, as described in Section 3.7.5, a comparison between the 140 GHz interferometer data and Thomson scattering measurements is used to correct the Thomson scattering electron density measurements.

### 2.2.3 Langmuir Probes

LTX has several Langmuir probes for the measurement of edge electron temperatures, electron densities, and the floating potential. In the ion saturation and transition region of the probe characteristic, where the bias voltage \( V \) is less than the space potential \( V_{sp} \), the current \( I \) collected by the probe is

\[
I = A n_e \left( c_s \exp \left( -\frac{1}{2} \right) - \sqrt{\frac{T_e}{2\pi m_e}} \exp \left( -\frac{e(V_{sp} - V)}{T_e} \right) \right)
\]

where \( A \) is the surface area of the probe tip, and \( c_s \) is the sound speed [81]. Fitting the data from the probe characteristic to the above equation produces measurements of \( n_e, T_e \), and the floating potential \( V_f \) at the probe location. The first term in Equation 2.32 is the ion saturation current.
a sufficiently negative bias, only ions are collected and the current becomes

\[ I = A n_e e_a \exp\left(-\frac{1}{2}\right) = A e \Gamma \]  

(2.33)

where \( \Gamma \) is the ion flux. This quantity is used to determine the flux of particles out of the plasma needed to estimate the recycling rate.

A single-tip Langmuir probe is mounted on the midplane of LTX. It is made of a cylindrical tungsten probe tip (1 mm diameter, 5 mm long) insulated in an alumina tube. The probe is sealed using a welded bellows such that the tip location can be changed without breaking vacuum. The probe can be driven in as far as \( R = 65.5 \) cm, which is just inside the shell. To measure the probe characteristic, the voltage of the probe is typically swept with a 25 V amplitude, -25 V offset triangular wave at 1 kHz. The time resolution of \( n_e, T_e, \) and \( V_f \) measurements is thus determined by the sweep frequency.

During the 2012-2013 outage, four additional Langmuir probes were installed. Two are mounted on the underside of the vacuum vessel and pass through the shell ducts. The other two probes are mounted on the edge of the shells in the interferometer gap on the high field side of LTX. These are all triple-tip probes, which sample Equation 2.32 at three voltages to measure \( T_e, \) and \( V_f \). One tip is floating and the other two are biased. As no voltage sweep is required, this setup allows continuous measurements. The electronics used for these probes is based off an existing design [82]. An image of a high field side Langmuir probe is shown in Figure 2.8.

A four-tip Langmuir probe is also available, but is not used due to a lack of supporting electronics. A four-tip probe has one tip biased negatively enough to measure the ion saturation current, another two tips biased at different voltages in the transition region, and a final tip which is kept floating. Equation 2.32 is measured at four points, which then determines \( n_e, T_e, \) and \( V_f \). Like triple-tip probes, measurements are limited only by the digitizer sampling rate.

Only data from a single-tip low field side probe is available for shots analyzed in Chapter 4.
Figure 2.8: A high field side Langmuir probe, which is mounted on the center stack between the shells. Note that while four tips could be used, only three are in place to prevent magnetic shadowing.
2.2.4 Passive Spectroscopy

Passive spectroscopic measurements are used to measure impurity ion levels, Bremsstrahlung radi- dation, and recycling coefficients.

LTX has three filterscopes \[83, 84\], which are diagnostics that measure the intensity of a single spectral line along a chord. Light is imaged into fiber optics, and is then sent to a narrow bandpass optical interference filter. The intensity of the filtered light is measured by a photomultiplier tube. One filterscope images emission from the the upper shell inner lip on the inboard side, another views a lower shell, and the last views a molybdenum limiter. These can be fitted with a variety of spectral filters to measure intensities \(I_\lambda\) of various emission lines. With additional measurements of the local \(T_e\) and \(n_e\), the \(S/XB\) coefficients can be determined, where \(S\) is the ionization rate, \(X\) is the excitation rate, and \(B\) is the branching ratio. These coefficients are retrieved from the Atomic Data and Analysis Structure database \[85\] and are then used to determine impurity ion fluxes

\[
\Gamma_{\text{wall}\rightarrow\text{plasma}} = 4\pi \left( \frac{S}{XB} \right)_{\lambda, T_e, n_e} I_\lambda.
\]  

Two spectroscopic arrays measure Lyman-\(\alpha\) emission at 121.6 nm on several vertically-fanned chords. One views the plasma-facing inboard sides of two shells on a radial midplane port, and the other views the plasma-facing outboard side of two shells on a tangential port. The inboard-viewing array also has bolometric channels. Two single channel Lyman-\(\alpha\) detectors also view molybdenum limiters. Lyman-\(\alpha\) emission is viewed instead of H-\(\alpha\) emission since lithium is much less reflective at lower wavelengths, which simplifies interpretation of measurements \[39, 84\].

LTX also has three Ocean Optics HR2000+ spectrometers that are used to obtain low-resolution spectra over the 390 nm - 590 nm range on the same viewing chords as the filterscopes. The spectrometers produce a spectrum 600 times per second \[84\].

A grazing-incidence spectrometer, known as the Long Wavelength and Extreme Ultraviolet Spectrometer (LoWEUS) \[86, 87\], and previously called the Silver Flat Field Spectrometer...
(SFFS) [88], is used to assess impurity levels in the plasma (the wavelengths are long relative to other Lawrence Livermore National Laboratory extreme ultraviolet instruments). The system views a radial chord through the midplane of the experiment. The imaged spectral band can be scanned by changing the location of a liquid nitrogen cooled charge-coupled device (CCD). Light from 25 Å to 450 Å within a 200 Å band can be imaged. As light is collected for the full discharge, data is cumulative over the duration of the plasma. LoWEUS is kept at vacuum with a dedicated pumping system.

Passive spectroscopic diagnostic data are available for the plasmas analyzed in Chapter 4.

2.2.5 Fast Camera

A Vision Research Phantom V210 monochrome 1280 × 800 pixel complimentary metal-oxide semiconductor (CMOS) camera is used to image the plasma on a tangential port. The camera can operate at 2000 frames per second at full spatial resolution, although typically the resolution is reduced and the camera produces a frame every 100 µs. An H-α filter is often used in conjunction with the camera, which provides information on the plasma location and shape. Fast camera data is available for plasmas analyzed in Chapter 4.

2.2.6 Charge Exchange Recombination Spectroscopy

In order to measure ion temperature, ion density, and plasma rotation profiles, LTX has a charge exchange recombination spectroscopy (CHERS) diagnostic. While the system has undergone some changes in configuration, the viewing optics are currently comprised of a \( f = 85 \) mm, \( f/1.8 \) lens that illuminates a 17 fiber toroidal array, and a 12 fiber and lens poloidal array. The light is dispersed in a Kaiser Optical Systems Holospec \( f/1.8 \) spectrometer and then imaged in a Princeton Instruments ProEM electron-multiplying charge-coupled device (EMCCD) capable of 1.5 ms frame rates. Due to limitations on the spectrometer, only 11 fibers can be imaged at one time.
The system is currently being run to collect passive emission of the Li III line at 516.689 nm [89]. However, active charge exchange emission measurements will be possible once a diagnostic neutral beam is added to the experiment. Passive CHERS data is available for plasmas analyzed in Chapter 4.

### 2.3 Fueling Systems

LTX is fueled using a variety of techniques. The main neutral gas prefill is delivered by one of two puffers. Typically, gas injection occurs 300 ms before plasma startup in order to provide a uniform background of neutral particles. During discharges, the plasma may be fueled using a supersonic gas injector. A third technique for fueling uses a molecular cluster injector (MCI) [78]. A diagnostic neutral beam may eventually provide some fueling, but is primarily intended to be for use in CHERS.

#### 2.3.1 Low Field Side Puffer

A low field side puffer (LFSP) with a Maxtek MV-112 piezoelectric valve feeds gas through a 2.25 inch long, 1/2 inch inner diameter guide tube ending about an inch from the plasma edge on the midplane [78]. The low field side puffer is often used for pre-fueling the vacuum vessel before discharges, and also for fueling during discharges. The LFSP is used to fuel plasmas for the November 8, 2011 data analyzed in Chapter 4.

#### 2.3.2 High Field Side Puffer

A high field side puffer (HFSP) was installed during the 2012-2013 vent. It is comprised of a 1/4 inch molybdenum tube mounted on the center stack 3.2 inches below the lower shell upper inboard lip. It is fed by a bellows segment routed under the lower shell and connected to an external gas
Figure 2.9: The high field side puffer. The lower shells are on either side of the puffer, and the gas line bellows drops vertically from the nozzle.

line through a 2 3/4 inch port on the vessel bottom. A High Vacuum Products, Inc. PEV-1 valve connected to a gas valve driver is controlled with a gate signal by the operator. An image of the high field side puffer is shown in Figure 2.9. The HFSP was not yet installed for use in plasmas analyzed in Chapter 4.

2.3.3 Supersonic Gas Injector

A supersonic gas injector (SGI) [78] is also available for plasma fueling. It is made of a Vecco PV-10 piezoelectric pulse valve and a stainless steel supersonic converging-diverging nozzle (Mach 5.5, 4.5° half angle) mounted on a bellows drive.
2.3.4 Molecular Cluster Injector

LTX has a Molecular Cluster Injector (MCI), which is a SGI with a cryogenically cooled nozzle, a skimmer, and a ballast volume [78, 90, 91]. By cooling hydrogen, molecules can form small clusters held together by intermolecular forces, which are intended to act like fueling pellets. The system uses a Series 99 Parker fast solenoid valve and a Mach 3, 45° nozzle. A stainless steel skimmer allows the backing pressure to be increased without over-fueling plasma. The system has a large ballast volume pumped by 200 L/s turbomolecular pump, which is backed by dry scroll pump. A 2000 L/s SAES getter pump removes hydrogen from the system.

2.4 Operations and Data Acquisition

LTX operation is performed in a dedicated control room for the experiment. The machine operator requests currents for the Robicon power supplies, controls programming of the OH capacitor bank, selects charge levels of other power supply capacitor banks, and changes gas fueling programming. Presently, there is no feedback control based on the fields generated by the coils or the plasma current; all currents in coils follow only the requested currents waveforms.

The bulk of data acquisition is performed in either the LTX test cell or an adjacent room. LTX has two D-tAcq Solutions, Ltd. 96 channel 500 kS/s digitizers. Additionally, a D-tAcq Solutions Ltd. 96 channel 500 kS/s, 32 channel analog output, 64 channel digital output digitizer both records signals and controls some timing. While most signals are digitized using these systems, a Computer Automated Measurement And Control (CAMAC) rack has two LeCroy 8212A/8TP Fast Data Loggers, and four Joerger TR612/3 Transient Recorder modules. Two Jorway Model 221 Timing and Sequence units and two Jorway Model 222 TTL Buffers also control experimental timing. Additionally, a two channel 200 MS/s GaGe CompuScope digitizer card is used to digitize interferometer signals.
Most of the data acquired during a shot is stored using a central data management system called MDSplus. MDSplus was designed with fusion research experiments in mind as large amounts of raw data can be stored directly from digitizers. Processed data and simulation results are also stored within the same hierarchy. Data from LTX is stored in a division of the MDSplus server called a tree. Data stored from each shot on the experiment is organized into the “ltx” data tree, and calibration data that remains constant over many shots is stored in the “ltxcal” tree [92]. The shot numbers for the experiment are based off the date and time of the shot, in YYMMDDhhmm format. For example, a shot on July 1st, 2011 at 12:02 pm (Eastern time) would be 1107011202.
Chapter 3

The LTX Thomson Scattering Diagnostic

3.1 Principles

Thomson scattering is the elastic scattering of an incident electromagnetic wave due to the oscillation of a charged particle. Thomson scattering is the low-energy or classical limit of Compton scattering, when $h\omega \ll mc^2$, where $\omega$ is the angular frequency of the incident wave and $m$ is the mass of the particle. When there is a large phase difference between the light scattered from an electron and the light scattered off particles within its shielding cloud, such that the Debye length $\lambda_D = \sqrt{\varepsilon_0 T_e/e^2 n_e}$ is much greater than the incident light wavelength ($k_0 \lambda_D \gg 1$, where $k_0$ is the wavenumber of the incident light), there are no collective effects and Thomson scattering is incoherent [71]. This criterion is satisfied for

$$n_e \ll \frac{4\pi^2 \varepsilon_0 T_e}{e^2 \lambda_0^2} \quad (3.1)$$

where $\lambda_0$ is the wavelength of incident light. For a plasma with $T_e = 100$ eV, as is typical in LTX, and incident light at $\lambda_0 = 694.3$ nm from a ruby laser, incoherent Thomson scattering occurs when $n_e \ll 5 \times 10^{23}$ m$^{-3}$. The maximum measured density in LTX is far below this limit. Being
Figure 3.1: A conceptual diagram of Thomson scattering. Incident light with some wavevector \( \mathbf{k}_i \) and electric field \( \mathbf{E}_i \) scatters at an angle \( \theta \) off a charged particle moving at velocity \( \mathbf{v} \) to produce a scattered wavevector \( \mathbf{k}_s \) and electric field \( \mathbf{E}_s \).

able to incoherently Thomson scatter light is convenient since the distribution of scattered light from a collection of particles is the same as that of a single particle, and therefore the intensity of scattered light is directly proportional to the number of particles. If \( k_0 \lambda_D \ll 1 \), collective effects are important and scattering is coherent.

As derived in Appendix A, the total Thomson scattering cross section is

\[
\sigma = \frac{8\pi}{3} r_e^2
\]

where \( r_e = \sqrt{e^2/4\pi\varepsilon_0 m_e c^2} = 2.8179403267(27) \times 10^{-15} \) m is the classical electron radius [93].

Since this cross section is so small, Thomson scattering is a very inefficient process, and any diagnostics designed to observe Thomson scattered light require an intense light source and sensitive collection optics.

Light scattered from a moving charged particle will be Doppler shifted, and the spectral dependence of the scattered light will reveal information about the particle velocities. As derived in Appendix A, a Thomson scattering diagnostic comprised of a monochromatic polarized light source,
such as a laser, incident on a plasma comprised of nonrelativistic electrons with a Maxwellian velocity distribution produces a number of photoelectrons \( N_{pe} \) equal to

\[
N_{pe} = \frac{N_i G \eta T n_e \pi r_e^2 L \Delta \Omega \Delta \lambda}{\lambda_1 \sin (\theta/2)} \sqrt{\frac{m_e c^2}{8 \pi T_e}} \exp \left( -\frac{(\lambda - \lambda_i)^2 m_e c^2}{8 \lambda_i^2 T_e \sin^2 (\theta/2)} \right)
\]  

(3.3)

where \( N_i \) is the number of incident photons, \( G \) is the detector gain, \( \eta \) is the detector quantum efficiency, \( T \) is the system’s optical transmission, \( n_e \) is the electron density, \( L \) is the length of the laser beam imaged, \( \Delta \Omega \) is the solid angle of collection, \( \Delta \lambda \) is the wavelength band, \( m_e \) is the electron mass, \( \lambda_i \) is the wavelength of incident light, and \( \theta \) is the scattering angle [94].

Fitting a measured scattered light spectrum to Equation 3.3 allows simultaneous measurement of \( T_e \) and \( n_e \). The spectral width of the scattered line directly gives \( T_e \). Scattering intensity is directly proportional to \( n_e \), which makes arbitrary density measurements easy. However, absolute density measurements require accurate values of all the variables in Equation 3.3.

Thomson scattering diagnostics have been used for over 50 years. In 1958, radio waves scattered off electrons in the ionosphere were observed [95]. Thomson scattered light was detected from a ruby laser incident on an electron beam in 1963 [96]. In 1968, the Russian Tokamak T-3 produced plasmas with \( T_e \) between 100 eV and 2000 eV as measured by a soft X-ray diagnostic. The following year, a British team used Thomson scattering measurements to confirm that \( T_e \) was between 100 eV and 1000 eV [97]. A review of Thomson scattering was written by DeSilva in 2000 [98].

### 3.2 Laser

The Thomson scattering system on LTX [99] uses a four-stage pulsed ruby laser (694.3 nm) as the light source for its Thomson scattering diagnostic. The optics for the laser beam are mounted on a four foot by nine foot optical table, as shown in Figure 3.2. The optical table is covered by
Figure 3.2: The layout of the optical table for the ruby laser.
a custom 32 inch high enclosure made by MiniTec. The primary purpose of the enclosure is to prevent unwanted light from leaving the optical table, which would result in unwanted signals on the system’s detector. While door interlocks provide ultimate personnel protection, the enclosure serves as an additional barrier to contain laser light within the optical table. The enclosure also protects optical components and helps maintain a more stable thermal environment. The room is cooled by an air conditioner that runs intermittently, and the shell and vessel heaters can heat up the room, and exhaust from other systems can blow on the table. The enclosure prevents thermal expansion or contraction of optical components, which could cause misalignment of the laser optics. The enclosure has removable panels made of sandwiched plastic and aluminum to allow access to the optical components while blocking light from leaving the optical table when the panels are in place. The enclosure also has a shelf suspended from the top such that optical equipment can be stored conveniently.

The laser heads are typically kept at 10 °C using deionized water cooled by a NESLAB RTE-7 chiller. In order to prevent condensation, the setpoint must be kept above the dew point of the air in the test cell. During the humid summer months, this limits the cooling temperature to 15 °C. During the dry winter months, the dew point drops below the freezing point of water, becoming a frost point. Then, the cooling temperature can be set at any point above 0 °C. The cooling loop runs continuously to prevent thermally stressing the system and to prevent the growth of algae.

The oscillating cavity is bounded by two mirrors: the rear fully reflective to ruby light and the other partially reflective. The rear mirror has a radius of curvature $R_2 = 5.5$ m, while the other mirror is flat. As this is a plano-concave resonator $[100]$, it has a laser beam waist of

$$w_0^2 = \frac{\lambda}{\pi} \sqrt{L (R_2 - L)}$$

(3.4)

where the cavity length $L \approx 1$ m, which gives $w_0 = 0.7$ mm. Inside, a ruby rod is optically pumped using four xenon flashlamps. Ruby consists of Al$_2$O$_3$ crystal with a small portion of Al$^{3+}$ replaced
by Cr$^{3+}$. Light from the flashlamps optically pumps the Cr$^{3+}$ ions in the ruby from the $^4A_2$ state to the broad band $^4F_1$ and $^4F_2$ states. These transitions absorb violet and green light, respectively. The ions rapidly decay to the metastable $^2E$ state. From this state, light is emitted via stimulated emission as the electrons transition to the original $^4A_2$ state, producing light at 694.3 nm. Such a configuration is referred to as a three-level laser.

The combination of a quarter-wave plate, a Glan prism polarizer, and a Pockels cell allows Q-switching. When voltage is applied to the Pockels cell, it becomes birefringent. Linearly polarized light passing through will undergo a $\pi/2$ relative phase shift, thereby becoming elliptically polarized. A quarter-wave plate further shifts the relative phase by $\pi/2$, making the light linearly polarized but with the polarization rotated by $\pi/2$. After reflecting at the rear mirror, light passes through the elements again and gains another $\pi/2$ polarization rotation. The total rotation is then $\pi$, which allows amplification in the rod. When the Pockels cell is off, the total rotation is only $\pi/2$, blocking amplification [100]. A Glan prism passes only horizontally polarized light. Thus, only horizontally polarized light from the ruby rod is amplified while vertically polarized light is rejected. The polarization of the laser beam was examined using a photodiode and polarized filters placed at the oscillator exit and it was found that the vertically polarized light carried roughly 10% of the energy of the horizontally polarized light. A 2 mm aperture inside the oscillator constrains the initial laser beam diameter.

From the oscillator, the laser beam travels through a piece of glass that diverts approximately 4% of the laser’s energy toward an energy meter. The remaining light then passes through a 3.0 mm aperture, then through an expanding doublet, and then a variable width aperture. The laser then enters the preamplifier, which is simply another ruby rod with many atoms excited by flashlamps fired at a time delay. Additional stimulated emission of the incident laser amplifies the pulse by a factor of $\sim 10$. After passing through a 13.8 mm aperture, two more amplification stages add energy to the laser, as summarized in Table [3.1]. Final laser energy was designed to be up to 15 J, however energies as high as 20 J have been achieved. The pulse duration at the exit of the
oscillator was measured using a photodiode to be approximately 36 ns full width at half maximum (FWHM), as shown in Figure 3.3. After passing through the final amplifier, a focusing doublet focuses the laser in the center of the collection region to a spot about 0.5 mm in diameter. A beam splitter samples a portion of the laser after the second amplifier stage so that a laser power meter can measure the laser energy for each shot. The laser is then elevated and aimed toward the vessel using a system of mirrors.

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<td>325</td>
<td>320</td>
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<td>Preamplifier</td>
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<td>4</td>
<td>1820</td>
<td>350</td>
<td>1800</td>
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</tr>
<tr>
<td>Amplifier 1</td>
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<td>6</td>
<td>1900</td>
<td>225</td>
<td>1840</td>
<td>7</td>
</tr>
<tr>
<td>Amplifier 2</td>
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<td>8</td>
<td>1900</td>
<td>225</td>
<td>1280</td>
<td>15</td>
</tr>
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</table>

Table 3.1: Laser head and capacitor bank parameters.
The flashlamps for each of the four stages of the laser are powered by a set of independently-controlled capacitor banks. Several Quantel CB302 capacitor bank units are used to form the capacitor bank. Four Quantel PU420 units control the charge and the firing delay time on each bank. Parameters for the capacitor banks are shown in Table 3.1. The Thomson scattering capacitor bank control unit interfaces with each of the PU420 units. This allows a single bank enable, charge, and fire signal for all four units. Due to the 10 s recharge time of the capacitor banks, the system is only capable of a single pulse per plasma shot. An additional interlock box ensures that the power supplies can be enabled only when all doors of the test cell are closed, no emergency stop buttons are depressed, and the master key for the system is engaged.

From the laser table, the laser transits a four inch air gap. It then passes through a BK7 anti-reflection-coated laser window custom made for a ruby laser with a $7^\circ$ incidence angle. The damage threshold of the window is quoted for a single wavelength 15 J/cm$^2$, 20 ns, 20 Hz at 1064 nm. The spot size of the laser at the entrance window is approximately 2.5 cm$^2$ in area, giving a maximum laser pulse energy of 37 J. Initially, the entrance window was a BK7 ARB-3 broadband-coated window, but during a machine vent it was discovered that the anti-reflection coating showed signs of damage. The air gap between the optical table enclosure and the laser entrance window is surrounded by thick black cloth for safety, to prevent ambient light from entering the vessel, and to prevent dust from accumulating on the window. As the windows must remain free of lithium for good optical transmission, pneumatic gate valves on the flight tubes are kept closed when lithium in LTX is in a liquid state, and open for a few seconds when a shot is fired. Additionally, the intrinsic length of the laser flight tubes prevents evaporation onto windows.

After passing through the laser entrance window, the laser traverses the entrance flight tube, which is a 50 inch long, three inch diameter stainless steel tube with vacuum flanges on both ends. The laser then passes through a six inch long vacuum bellows segment and a pneumatic gate.

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1. CVI Melles Griot W2-PW1-4037-C-694-7
2. Linos Qioptiq 390044000 100 mm diameter 10 mm thick
valve before encountering the laser entrance flange, as pictured in Appendix B. This flange forms the interface between the LTX vacuum vessel and the laser entrance assembly. The laser passes through the vacuum vessel on a non-radial chord with a 11.8 cm radius of tangency. The laser exits the vessel through an exit flange and then passes through a second pneumatic gate valve, a small eight inch long tube necessary to avoid vacuum hardware for other systems, a second six inch long vacuum bellows segment, and a flight tube and laser window identical to those previously traversed. The laser path length from the vacuum side of the entrance flange to the vacuum side of the exit flange is 1.52 m.

To reduce stray laser light levels, four baffles were added to the flight tubes during the 2012 - 2013 outage. An image of the baffles is shown in Figure 3.4. The baffles are made of 316 stainless steel turned down to fit inside the flight tubes. One side of the baffles is tilted 10° off normal incidence and has been given a reflective polishing. The other side of the baffles is unpolished and
is tilted $60^\circ$ off normal incidence. The polished side of the baffles always points away from the vessel. In this manner, stray laser light from the main laser and any reflections off the beam dump are prevented from reaching the measurement volume. The aperture size of the baffles is designed to be six mm larger than the laser size at the baffle location as determined by the size of a burn on laser burn paper. Each flight tube has a baffle just interior to the laser window and also next to the vacuum seal on the far side. Set screws hold the baffles in place inside the flight tubes. Drawings of the baffles are included in Appendix B.

The beam dump for the system is made of a wedge of two pieces of absorptive glass located on the air side of the laser exit window. The beam dump and laser exit window are kept in an aluminum box for the same reasons the black cloth is used on the entrance window.

Two Helium-Neon laser beams are used for alignment. The first is an unpolarized 2.5 mW laser set up such that the laser enters the oscillator cavity from the rear. This is only possible because the mirrors used in the system are fully reflective only to ruby light, so some of the HeNe light passes through. This allows rough alignment of the first three stages of the laser. Practically, the laser is aligned as well as possible with the HeNe laser, then finer alignment is performed by actually pulsing the ruby laser. A second laser from a horizontally polarized 2.5 mW laser is injected into the laser path after the first amplifier stage. It is mainly used for aligning the laser as it passes through the vessel and ensuring that it hits the beam dump.

On a historical note, many components of the laser were used previously on the PBX-M. While additional maintenance is required for the aging equipment, there were substantial cost savings as compared to purchasing a new system. The first measurements from the system were in 2010, during LaserFest’s Year of the Laser, which commemorated the 50th anniversary of Theodore Maiman’s invention of the laser.

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3CVI Melles Griot model 25-LHR-691-249
4CVI Melles Griot model 25-LHP-691-249
3.3 Viewing Optics

The viewing optics for the LTX Thomson scattering diagnostic collect scattered light through a viewing port on top of the vacuum vessel. The viewing geometry is not directly above the laser axis; there is a 3.1° (for the 2013 alignment, formerly 3.6° for the 2011 alignment) tilt of the viewing optics toward the laser beam line. The viewing window for the system is a 150 mm diameter, 10 mm thick piece of N-BK7 glass coated with ARB3 VIS broadband anti-reflective coating manufactured by Linos Qioptiq (part number G730-717-000). A shutter internal to the vacuum vessel protects the viewing window from lithium deposition during evaporation cycles. The shutter is opened and closed by a pneumatic rotary vane actuator made by Turn-Act Inc. The window is mounted on a gate valve which allows the window to be removed without venting the vacuum vessel in case the window is inadvertently coated with lithium. To date, the shutter has been excellent at protecting the window and no cleaning has been necessary.

A linear polarizer is in place between the viewing window and the optics. The polarization axis is oriented perpendicular to the laser to allow Thomson scattered light to pass while reducing unpolarized plasma background light by approximately a factor of two. Originally, Edmund Optics polarizer film was used. However, the film did not lie flat and transmission was determined to be subpar, so the polarizer was replaced by a superior 150 mm diameter Edmund Optics polarizer, which is rigid.

To prevent vibrations during plasma discharges from moving the system out of alignment, the viewing optics are mounted above the vessel on the arm of a support tower mounted on the floor and not at all connected to the vacuum vessel. The optics are stabilized against vibrations perpendicular to the mounting arm by a pair of guy wires and a threaded rod connected to supports in the test cell ceiling. This setup also provides some means of thermal isolation during vessel bakes.

\[5\] 8.5 in, Part number 4668 000 SM3 PO 062351
\[6\] Part number 86-203, 150 mm Diameter Linear Plastic Polarizer, Unmounted
The optics used in the system are a five element $f/3.8$ lens set which was custom designed for LTX using Lambda Research Optics Software for Layout and Optimization for optical systems (OSLO) raytracing software, as shown in Figure 3.5 and tabulated in Table 3.2. The optics were built by JML Optical Industries, Inc. The viewing optics are mounted 59 cm above the laser beam line, which is almost directly above the viewing window. The lens set is designed to collect a solid angle of 0.012 sr directly below the lens, which drops to 0.01 sr for the outermost possible views.

The optics image light scattered from the laser beam line onto a fiber holder with a radius of curvature of 10.3 cm. As shown in Figure 3.6, the fiber holder has 25 grooves to hold the fibers in place. The fibers for the system are 16 circular quartz-core fibers with a 800 $\mu$m diameter, 900 $\mu$m cladding diameter, and 1000 $\mu$m overall diameter manufactured by Fiberguide Industries, Inc.\(^7\) In CDX-U, square plastic fibers were used, which resulted in a high packing fraction, but their transmission was too low for continued use on LTX.\(^{[103]}\) Fibers can be configured to either

\[^7\]Part number SPC 800/900/1000
### Table 3.2: Lens elements used in the viewing optics. Lens 1 is closest to the plasma and lens 5 is farthest away. Parameters displayed are diameter $d$, central thickness $t$, spacing to next lens face $s$, front radius of curvature $R_1$, and rear radius of curvature $R_2$.

<table>
<thead>
<tr>
<th>Lens</th>
<th>Manufacturer / Part Number</th>
<th>Material</th>
<th>$d$ [mm]</th>
<th>$t$ [mm]</th>
<th>$s$ [mm]</th>
<th>$R_1$ [mm]</th>
<th>$R_2$ [mm]</th>
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<tbody>
<tr>
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<td>Spindler-Hoyer 312364</td>
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<tr>
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<td>Spindler-Hoyer 312243</td>
<td>Silica</td>
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<td>10.0</td>
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<td>BK7</td>
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<tr>
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<td>Spindler-Hoyer 312390</td>
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<td>100.1</td>
<td>24.0</td>
<td>-</td>
<td>68.786</td>
<td>-</td>
</tr>
</tbody>
</table>

view scattered light from the laser or to look slightly off the laser axis to image background plasma light. An image of the viewing optics, fiber holder, and fiber assembly is shown in Figure 3.7.

### 3.4 Viewing Optics Alignment and Spatial Calibration

In order to align the viewing optics and accurately determine the spatial locations from which each channel collects light, light is sent in the reverse direction through the fibers onto a target within the vacuum vessel. The target is made of an adhesive ruler applied to a rigid square aluminum channel nearly three m long, which is then placed along the laser path through the vacuum vessel. The channel is held in place using cable ties connected to bolts in the laser entrance and exit flanges. Care is taken to ensure that the channel is centered on the laser path and that the uppermost side of the channel is even with the vessel midplane. To prevent the channel from bowing under its own weight, the far end of the ruler is externally supported. The fiber optics are back-illuminated using a halogen light. The resulting images on the ruler define the area of the light collection, as shown in Figure 3.8.
Figure 3.6: The fiber holder with fibers for the 2013 alignment. Fibers viewing the plasma core are on the right side of the image, and fibers viewing the edge are on the left. The top row of fibers is for off-laser beam viewing chords, and the bottom is for collecting scattered light.
Figure 3.7: The viewing optics and fiber holder with fibers for the 2013 alignment. The setup shown was used for calibrations.
Figure 3.8: Viewing optics alignment and spatial calibration as viewed through the edge Thomson viewing port for the 2010 alignment. The metal tube in the center of the image is a flux loop.
First, the viewing optics are aligned so that the images are collinear with the laser path, and so that there is no curvature of the images on the ruler. Then, the image locations are recorded, as is the location of the entrance flange face of the ruler. Using a CAD model of the experiment, the image locations can then be translated from measurements on the ruler to machine coordinates. The CAD model for the 2013 alignment and mapping is shown in Figure 3.9.

After alignment, the fibers are reinserted into the spectrometer. By illuminating each fiber with a flashlight from within the vessel, the mapping of each fiber to pixels on the CCD is determined.

The layout of the fibers in the fiber holder has been changed three times, and an alignment and spatial calibration was performed after each rearrangement. A summary of the results from each setup is shown in Tables 3.3, 3.4, and 3.5.

3.5 Spectrometer and CCD

Light from the collection optics travels through the fibers to a Kaiser Optical Systems HoloSpec VPT System spectrometer A photograph of the spectrometer interior is shown in Figure 3.10.

A custom fiber mount is used to hold 16 fibers at the entrance to the spectrometer. A drawing of the fiber holder is shown in Figure B.4. While the system was initially set up with hopes of imaging all 16 fibers, the width of the initial set of optics in the spectrometer limit the number of imaged fibers to 11. As a result, during the 2010 run, no light was seen from five of the fibers, two of which were in the core, and three of which were in the edge. During an extended vent, the fibers were remapped to ensure a full view of the plasma from core to edge. While the 16 fiber design was initially an oversight, it allows a way to secure spare fibers.

The spectrometer has optical mounts for two notch filters to pre-filter light from the fibers before it enters the diffraction grating. Laser light at 694.3 nm is blocked by a Kaiser Optical Systems Model HS-f/1.8i-VIS.
Figure 3.9: The CAD model used for the 2013 mapping shown. The vacuum vessel is viewed from the top and the laser beam line is shown in red. Measurement points are shown as red circles along the laser beam line.
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Table 3.3: 2010 run fiber mappings.
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Table 3.4: 2011 run fiber mappings.
Table 3.5: 2013 run fiber mappings.

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Figure 3.10: An image of the interior of the spectrometer. A metal cover has been removed for the photo. The fiber holder is normally connected to the right side of the spectrometer.
Systems notch filter,\footnote{Part number HSPF-694.3AR-2.0} and H-\(\alpha\) light at 656.28 nm is blocked by an additional Kaiser Optical Systems notch filter.\footnote{Part number HSPF-656.0AR-2.0} Manufacturer-supplied transmission curves are shown in Figures 3.11 and 3.12. Transmission is near \(10^{-5}\) at the bottom of the wells.

From here, the light travels through a custom-made entrance slit with a width of 800 \(\mu\)m as shown in Figure B.5. The entrance slit was designed to pass the largest amount of light possible, but also introduces a large instrumental function, which must be compensated for during data analysis.

There are two dispersion gratings available for use in the spectrometer. The low dispersion transmission grating is a Kaiser Optical Systems HFG-650. This grating is currently in use and disperses light onto the CCD from 547 to 764 nm. This spectral range is useful for measuring relatively high \(T_e\) values. A high dispersion transmission grating is also available, which views
light from 703 to 732 nm, which allows for more precise measurements of lower $T_e$ values. It is important to note that the spectrometer introduces a slight image curvature on the CCD since the angle of light incident on the grating is a function of height. This is corrected during data analysis.

After passing through the spectrometer, the light is imaged onto a Princeton Instruments IMAX Intensified CCD (ICCD) (512 by 512 pixels, 19 $\mu$m by 19 $\mu$m pixel size). The camera intensifier acts as both a fast electronic shutter and gain medium. It is comprised of a photocathode, a microchannel plate, and a phosphor screen inside a high voltage vacuum tube. Incident photons create photoelectrons on the photocathode, which are then accelerated to the microchannel plate, which multiplies the number of photoelectrons. These photoelectrons are further accelerated into the phosphor screen that converts them into photons. The intensifier is connected to a fiber optic faceplate that channels light to the CCD. To reduce noise, the CCD is cooled by a thermoelectric cooler set at -10 °C. The CCD can be operated in a high (1 MHz) or low (100 kHz) speed read
mode. The shortest readout time of the 512 by 512 pixel CCD is 0.28 s when reading in fast mode (1 MHz). As plasma durations are much shorter than this time, it is only possible to obtain one image per plasma discharge. Instead, the low speed mode is used, because less noise is introduced into the system. The manufacturer specifies read noise as 8 - 10 electrons in the low speed mode and 35 electrons in the high speed mode.

A Princeton Instruments ST-133 Controller both powers and reads out data from the CCD. It contains a 16 bit analog to digital converter. The controller is connected via a general purpose interface bus (GPIB) cable to a computer running WinSpec32, the software used for controlling light collection. Gain on the ICCD is controlled by changing the potential of the multichannel plate. While the gain can be set from 0 to 255 arbitrary units, the camera is always run with maximum gain.

Gating of the CCD intensifier is controlled by a Stanford Research Systems Digital Delay Generator (DG-535), which allows for precise gating with jitter less than 100 ps.

### 3.5.1 Spectral Instrumental Function

The spectral instrumental function is assumed to be a top hat distribution

\[
h(\lambda) = \begin{cases} 
0, & \lambda < -\frac{a}{2} \\
A, & -\frac{a}{2} \leq \lambda \leq \frac{a}{2} \\
0, & \lambda > \frac{a}{2}
\end{cases} \tag{3.5}
\]

where \(a\) is the full width. If the emission line is a Gaussian function

\[
f(\lambda) = Be^{-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}} \tag{3.6}
\]
then the resulting image will be the convolution of the two functions

\[
g(\lambda') = \int_{-\infty}^{+\infty} f(\lambda) h(\lambda - \lambda) \, d\lambda
\]

\[
= AB \int_{\lambda' - a/2}^{\lambda' + a/2} e^{-\frac{(\lambda - \lambda_0)^2}{2\sigma^2}} \, d\lambda
\]

\[
= AB\sigma \sqrt{\frac{\pi}{2}} \left( \text{erf} \left( \frac{\lambda' - \lambda_0 + a/2}{\sqrt{2\sigma}} \right) - \text{erf} \left( \frac{\lambda' - \lambda_0 - a/2}{\sqrt{2\sigma}} \right) \right). \tag{3.7}
\]

It is important to properly normalize the instrumental function such that the convoluted function retains the same integral, or else calculations of \( n_e \) will be off. The integral of the Gaussian function is

\[
\int_{-\infty}^{+\infty} \left( \lambda - \lambda_0 \right)^2 \, d\lambda = \int_{-\infty}^{+\infty} B e^{-\frac{(\lambda - \lambda_0)^2}{2\sigma^2}} \, d\lambda
\]

\[
= B\sqrt{2\pi\sigma^2} \tag{3.8}
\]

and the integral of the convoluted function is

\[
\int_{-\infty}^{+\infty} g(\lambda) \, d\lambda = \int_{-\infty}^{+\infty} AB\sigma \sqrt{\frac{\pi}{2}} \left( \text{erf} \left( \frac{\lambda' - \lambda_0 + a/2}{\sqrt{2\sigma}} \right) - \text{erf} \left( \frac{-\lambda' + \lambda_0 - a/2}{\sqrt{2\sigma}} \right) \right) \, d\lambda
\]

\[
= ABa\sqrt{2\pi\sigma^2}. \tag{3.9}
\]

Therefore, \( A = 1/a \).

The spectrometer entrance slit is 800 \( \mu \text{m} \) wide, which results in a fairly large instrumental function. The H-\( \alpha \) line from a hydrogen gas lamp is imaged in order to characterize this function. The line is fit to the above function, which results in a width of \( a = 8.0 \text{ nm} = 19 \text{ pixels} \).
3.6 System Timing, Connections, and Grounding

The capacitor banks are charged at least 10 s before the main machine trigger at $t_0$. The Thomson scattering trigger time $t_{TS}$ is specified by the machine operator. The capacitor banks discharge 225 ms to 325 ms after $t_{TS}$. The Pockels cell triggers at $t_{TS} + 850 \mu s$, which results in the actual firing of the laser. There is an additional delay before scattered light arrives in the spectrometer. Using Raman scattering measurements, this is determined to be 270 ns after the laser is fired. The delay is most likely due to time of flight of the laser, signal transmission through signal cables, and delays intrinsic to system electronics. The intensifier is gated for 110 ns after light arrives, so the true time of data collection is at $t_{TS} + 850 \mu s + 135 \text{ns} \pm 55 \text{ns}$. Previously, the initial delay in the arrival time of scattered light was set to be 290 ns, with an exposure time of 70 ns, but this tended to result in poor measurements due to some jitter in the firing of the laser. Laser jitter may be possible to overcome by triggering the SRS DG-535 delay generator off a photodiode sampling the laser. However, when this was attempted, light from the flashlamps triggered the photodiode early. A more careful setup using a ruby light filter or a way to geometrically block flashlamp light may be successful. A diagram of triggering connections between system components is shown in Figure 3.13.

Several measures are taken in order to prevent the formation of ground loops that can inject noise or spurious triggers into the system. The optical table, capacitor banks, charging supplies, delay generators, and other equipment for the laser firing system all share a single-point ground. To accomplish this, the AC power for the system is fed through an isolation transformer with no ground connection. Grounding cables from the mounting racks and optical table are connected to building ground through thick copper wires. The optical table for the spectrometer, CCD, Stanford Research Systems DG535, and Princeton Instruments ST-133 Controller is on a separate ground. To isolate the two grounds, the coaxial cable that triggers the SRS DG535 is first routed through
Figure 3.13: Thomson scattering diagnostic triggering connections. The computer running WinSpec32 is tstrickler-pc.
a Mini-Circuits coaxial RF transformer\(^\text{11}\) that permits the TTL triggering signal to be sent without connecting the grounds. Additionally, an optocoupler is used in the interface of the Berkeley Nucleonics delay generator and the Thomson scattering capacitor bank control unit. The system is isolated from the main data system by a fiber optic transmitter and receiver pair. This is especially important because the capacitor banks and Pockels cell are electrically noisy.

3.7 System Calibrations

3.7.1 Spectral Calibration

In order to provide a one-to-one correspondence between the wavelength of incident light into the spectrometer and the CCD pixels, the system is calibrated using known emission lines from gas lamps. The emission lines are fit to a sum of Gaussian, Lorentzian, skew-normal, or Voigt profiles\(^\text{12}\).

The skew-normal fit allows for alignment of the spectrometer. The location of the emission line is determined by fitting parameters which are matched to known emission lines from the National Institute of Standards and Technology (NIST) Atomic Spectra Database\(^\text{106}\). See Figure\(^\text{3.14}\) for an example of the fit to a set of helium lines.

Additional fits to correct for the curvature of the image on the CCD are also performed. Each vertical pixel line is fit to the H-\(\alpha\) line. The pixels that correspond to the center of the H-\(\alpha\) line are then fit to the radius of curvature and center of the circular function, as shown in Figure\(^\text{3.15}\). The final result for the CCD is

\[
\lambda = 0.423 \text{ nm} \left( x - 466 \times 10^1 + \sqrt{(466 \times 10^1)^2 - (y - 217)^2} \right) + 547 \text{ nm} \quad (3.10)
\]

\(^\text{11}\)Part number FTB-1-6*A15+

\(^\text{12}\)The Voigt profile is the convolution of the Lorentzian and Gaussian profiles of an emission line, and accounts for both the shortening of the duration of emission due to atomic collisions and the random thermal motions of the atom, respectively\(^\text{105}\).
Figure 3.14: Helium line calibration for a helium gas lamp.

Figure 3.15: CCD curvature calibration. $x$ and $y$ are the index of the horizontal and vertical pixels, respectively. Data in black are fits to the H-\(\alpha\) line for each vertical pixel slice. The green line is the fit to the circular function.
where \( \lambda \) is the wavelength of incident light and \( x \) and \( y \) are the horizontal and vertical pixel numbers of the spectrometer, respectively, which are numbered from 0 to 511. This indicates a spectral range from 547 nm to 764 nm across the center of the CCD.

### 3.7.2 Laser Energy Calibration

A beam splitter directs a portion of the final laser to a model ED-500 Gentec Joulemeter. The unit is calibrated for 2.4 V/J for a 1 M\( \Omega \) termination. The output of the energy meter is digitized by the main data system so that the laser energy for each laser pulse can be determined. In order to calibrate the energy meter, a Scientech 365 Power and Energy Meter with a model 380201 calorimeter is placed along the main laser beam path just past the beam splitter, and a series of laser pulses is fired. The Scientech energy meter has a precision of 1% of the full scale range. The full scale range is typically selected to be 20 J, but 20 mJ, 200 mJ, and 2 J ranges are also available.

Ideally, the peak voltage from the raw signal is directly proportional to the laser energy. However, the actual raw signal must first be processed before the laser energy can be determined. As an example, the raw digitized signal from the Gentec energy meter for a \((13.23 \pm 0.2)\) J pulse is shown in Figure 3.16. The main signal is the slowly rising and falling curve. For this shot, the laser trigger time was 454.150 ms. The signal is initially unaffected. Note that 225 \( \mu s \) later at 454.375 ms, the A1 and A2 amplification stages flashlamps fire, creating a noise spike larger than the main signal. A smaller second spike appears 325 \( \mu s \) after the laser trigger time as the oscillator and preamplifiers fire. As a result of the noise spikes, the offset voltage just before the Pockels cell firing time at 455.000 ms can be either higher, as is the case for this shot, or lower than its value prior to the laser trigger time. After the Pockels cell fires, the laser deposits some energy on the energy meter, causing the signal to rise. Some high-frequency noise is present in addition to the main signal, so clearly, a simple measurement of the peak voltage is not appropriate.
While several other techniques were tried, the best technique for processing the data is to subtract off the mean of the DC offset voltage from 360 \( \mu \)s to 800 \( \mu \)s after the firing time from the main signal, and then use a low-pass filter with a cutoff of 700 Hz to filter out high-frequency noise. The peak of the processed signal Pockels cell firing time is then considered to be the proper peak voltage \( V_{\text{peak}} \).

A series of laser pulses and measurements are used to fit corrected peak voltages to measured laser energies. For the 2013 setup, the result is that the laser energy is

\[
E_{\text{laser}} = (-0.513 \pm 0.106) \ J + (108. \pm 1.01) \ \frac{J}{V} V_{\text{peak}}
\]

with \( \chi^2 = 25.3 \) for \( \nu = 43 \) degrees of freedom (\( p = 0.986 \)). This suggests that laser energies below 513 mJ cannot be measured, but such levels are too low for adequate levels of scattering and are not an issue. A plot of the measurements and fit is shown in Figure 3.17.
3.7.3 Precision Light Source Calibration

The primary method of absolute density calibration uses a precision light source. A Labsphere URS-600 Uniform Radiance Standard precision light source is used to measure the overall transmission of the CCD, spectrometer, filters, fibers, viewing optics, and polarizer. The light source is comprised of a 45 W tungsten lamp imaged into an integrating sphere though a variable attenuator. The integrating sphere is internally coated with a material that provides many diffuse reflections, resulting in a Lambertian light source. A photopic detector measures the luminance in the integrating sphere. Light exits the sphere through an aperture. The spectral distribution of the light source is well known, which allows for precision calibrations of optical systems. The factory calibration of the Labsphere also provides a mapping between the luminance and the spectral radiance.

Ideally, the system viewing optics would be illuminated from the collection volume, so that the viewing window, polarizer, viewing optics, fibers, filters, spectrometer, and CCD would all be included in the calibration. However, it is impossible to fit the precision light source inside the LTX vacuum vessel. Instead, the viewing optics are removed from the support tower and set up on
an external test stand to image light from the precision light source. This allows a calibration of all system components except for the viewing window. This method has the disadvantage of not preserving the alignment of the viewing optics with respect to the laser beam path; the calibration must be performed during a vessel vent so that the optics can be aligned and spatially calibrated.

Since the fibers image light across a line approximately 24 cm long, and the aperture of the precision light source is 3.8 cm, only one or two channels can be illuminated at a time. To align the precision light source with respect to the viewing optics, the fibers are back-illuminated to ensure that the viewing area is completely within the aperture. Then, the fibers are reconnected to the spectrometer, and calibration frames are taken. To reduce noise, up to 16 frames are taken for each channel. The precision light source is then moved to illuminate the next channel or channel pair. The process is repeated until all channels are imaged.

The spectral radiance $L_\lambda$ of the imaged light is known from the calibration of the precision light source. The number of photoelectrons $N_{pe}$ at each pixel is measured by the CCD. The two quantities are related by

$$N_{pe} = L_\lambda \Delta \Omega \Delta A \Delta \lambda \frac{\lambda}{hc} \tau_{exp} G \eta T$$

where $\Delta \Omega$ is the solid angle of light collection, $\Delta A$ is the area of light collection, $\Delta \lambda$ is the wavelength range imaged on a pixel, $\lambda$ is the wavelength of a particular pixel, $\tau_{exp}$ is the exposure time, $G$ is the gain of the CCD, $\eta$ is the quantum efficiency of the CCD, and $T$ is the transmission of optics included in the setup. It is not possible to individually measure most of these quantities with this technique. Instead, the factor $\Delta \Omega \Delta \lambda \Delta AG\eta T$ is measured. Since the intensity of Thomson scattered light given by Equation 3.3 has common factors of $\Delta \Omega \Delta \lambda G\eta T$, it is not necessary to determine each quantity, but rather their product. This reduces error which would propagate and
increase the uncertainty in the measurement of $T_e$ and $n_e$. In practice, the flat field correction

$$F_{\text{flat}} = G\eta T \Delta \Omega \Delta A \Delta \lambda = \frac{N_{pe} h c}{L \lambda \tau_{\text{exp}}}$$  \hspace{1cm} (3.13)

serves as the calibration factor. Since the imaged area is circular, the area of the imaged area and the length of the laser across this area is simply related by $\Delta A = \pi L^2 / 4$.

To reduce uncertainty in the measurement, a calibration factor is measured for each frame at each pixel, and the results are averaged over frames to create the overall calibration factor. The standard deviation of the individual calibration factors for a fixed pixel across frames is also computed and is used for estimation of errors.

While not used for the density calibration, the product $G\eta T$ may be estimated using the best known values for $\Delta \Omega$, $\Delta A$, and $\Delta \lambda$. $\Delta \lambda$ is well known from the spectral calibration of the spectrometer and CCD. $\Delta A$ is known from spatial calibrations. $\Delta \Omega$ is difficult to measure, but can be calculated from raytracings of the optics. The product $G\eta T$ measured for the 2012 viewing optics configuration is shown in Figure 3.18. At its peak, $G\eta T \approx 13 \%$. The same procedure was repeated for the 2013 viewing optics configuration.

This technique can also be used to measure the transmission of the polarizer by repeating the calibration with the polarizer removed. The ratio of calibration factors with the polarizer to that without the polarizer serves as a measure of the transmission. The transmission of the polarizer for the calibration of the 2012 viewing optics configuration is shown in Figure 3.19. Apart from wavelengths affected by notch filters and pixels on partially illuminated channels, the transmission factor is fairly constant.

### 3.7.4 Raman Scattering Calibration

Raman scattering is an inelastic scattering process in which photons can either gain or lose energy as they interact with molecular vibrational, rotational, and electron energy states. Scattered light
Figure 3.18: $G\eta T$ [%] as measured for the 2012 viewing optics configuration.
Figure 3.19: The transmission $T\ [%]$ of the polarizer as measured by the ratios of the calibration factors for the system with and without a polarizer for the 2012 viewing optics configuration.
is emitted in lines greater than and less than the laser wavelength, which reduces inaccuracies due to stray light. Only scattering associated with rotational state transitions is accessible to the system’s spectrometer. This method of calibration works with a diatomic gas such as H$_2$ or N$_2$, and a precision pressure gauge capable of measuring pressures at several hundred Torr. Comparing the expected signal and the actual signal allows calibration of the efficiency of the optics.

For linear molecules, the rotational term value is

$$F_v(J) = B_v J (J + 1) - D_v [J (J + 1)]^2 + H_v [J (J + 1)]^3$$  \hspace{1cm} (3.14)

where, \( J \) is the rotational quantum number, and \( \nu \) is the vibrational state \[^{107}\]. The constant \( B \) is given by

$$B = \frac{\hbar}{8\pi^2 c I_B}$$  \hspace{1cm} (3.15)

where \( I_B \) is the moment of inertia for rotation perpendicular to the atomic axis. The \( D \) term is due to non-rigidity of the molecule due to centrifugal force from rotation. For rotational Raman scattering of a diatomic molecule, the selection rule

$$\Delta J = \pm 2$$  \hspace{1cm} (3.16)

applies. For \( \Delta J = +2 \), the molecule gains energy and the photon loses energy, resulting in a scattered wavelength longer than the incident wavelength. This is called Stokes scattering in analogy to Stokes’ Law for frictional drag. For anti-Stokes scattering, \( \Delta J = -2 \), the molecule loses energy and the photon gains energy, resulting in a shorter scattered wavelength.

The wavelength of the scattered photon that transfers a molecule from state \( J \) to state \( J' \) is \[^{108}\]

$$\lambda_{J \rightarrow J'} = \frac{1}{\nu_0 + \Delta\nu}$$  \hspace{1cm} (3.17)
where
\[ \tilde{\nu}_0 = \frac{1}{\lambda_0} \]  
(3.18)

and
\[ |\Delta \tilde{\nu}| = F(J) - F(J'). \]  
(3.19)

The intensity of rotational Raman scattering from \( J \) to \( J' \) is
\[ I_{J \rightarrow J'} = PnLF_J\sigma_{J \rightarrow J'} \]  
(3.20)

where \( P \) is the incident laser power, \( n \) is the gas density, and \( L \) is the length of the laser over which light is observed. The fraction of molecules in the state \( J \) given by
\[ F(J) = \frac{g_J (2J + 1)}{Q} e^{-\frac{E_J}{kT}} \]  
(3.21)

where \( Q \) is the rotational partition function and is a normalization factor such that
\[ \sum_{J=0}^{\infty} F_J = 1. \]  
(3.22)

\( g_J \) is a statistical weight factor. For \( N_2 \) gas, \( g_J = 6 \) for even \( J \) and \( g_J = 3 \) for odd \( J \). The Raman scattering cross section is
\[ \sigma_{J \rightarrow J'} = \frac{7 (2\pi)^4 S(J) \gamma^2}{45 \lambda_J^{4 J \rightarrow J'}} \]  
(3.23)

where \( \gamma \) is the anisotropy of the molecular polarizability. The Placzek-Teller coefficients are
\[
S(J) = \begin{cases} 
\frac{3(J+1)(J+2)}{2(2J+1)(2J+3)}, & J \rightarrow J + 2 \\
\frac{3J(J-1)}{2(2J+1)(2J-1)}, & J \rightarrow J - 2 
\end{cases}
\]  
(3.24)

for a simple linear molecule [109].
To perform a Raman scattering calibration on LTX, the vessel is filled with $N_2$ at pressures up to 400 Torr. A Baratron capacitance manometer (500 Torr full scale, 0.5% accuracy\textsuperscript{13}) is used in order to accurately measure vessel pressure $P$ in this range. Both $P$ and laser energy $E$ are varied, and several spectra at each setting are acquired. The ruby and H-\(\alpha\) filters are kept in the spectrometer. The number of incident photons is

$$N_i = \frac{E\lambda_i}{hc}$$

(3.25)

where $\lambda_i = 694.3$ nm is the incident light wavelength and $h$ is the Planck's constant. The gas density is

$$n = \frac{P}{T}$$

(3.26)

where the temperature is taken to be 293 K.

The number of Raman-scattered photoelectrons collected including the dark frame offset $N_{dark}$ is

$$N_{\text{Raman}} = G\eta T N_i n_n (F\sigma)_{\text{convolved}} L\Delta\Omega + N_{\text{dark}}$$

(3.27)

where $\Delta\Omega$ is the solid angle of light collection and $(F\sigma)_{\text{convolved}}$ is the convolution of $F\sigma$ and the entrance slit to incorporate the instrumental function of the spectrometer. Since the instrumental function is so large, individual Stokes and anti-Stokes lines cannot be resolved. Ideally, the product of the calibration factors

$$[G\eta T\Delta\Omega \Delta A\Delta\lambda]_{\text{Raman}} = \frac{(N_{\text{Raman}} - N_{\text{dark}}) \Delta A\Delta\lambda}{N_i n_n (F\sigma)_{\text{convolved}} L}$$

(3.28)

could be directly measured. Since scattered light is only incident on a small portion of the CCD, the Raman scattering calibration produces only a single calibration factor, not a full array of values for each CCD pixel. The calibration factors from the precision calibrated light source must also be

\textsuperscript{13}Part number MKS722B52TG2FA
used, so this calibration is not independent, i.e.,

\[
\frac{[G\eta T \Delta \Omega \Delta A \Delta \lambda]_{\text{Raman}}}{[G\eta T \Delta \Omega \Delta A \Delta \lambda]_{\text{Labsphere}}} = \frac{(N_{\text{Raman}} - N_{\text{dark}}) \Delta A \Delta \lambda}{N_i n_n (F\sigma)_{\text{convolved}} LF_{\text{flat}}}.
\] (3.29)

Additionally, since Raman-scattered light, Rayleigh-scattered light, and stray laser light are collected, the Raman contribution must be isolated.

To accomplish this, a set of Rayleigh calibration shots is taken in argon gas just following the Raman shots. The argon measurements are made at nearly the same pressure as with nitrogen. For each pixel, the master dark frame \(N_{\text{dark}}\), which is the mean of 83 individual dark frame responses, is subtracted from each raw Rayleigh frame \(N_{\text{Rayleigh}}\). Then, the data is normalized by the number of incident photons \(N_i\) and neutral gas density \(n_n\) as

\[
N_{\text{Rayleigh, normalized}} = \frac{N_{\text{Rayleigh}} - N_{\text{dark}}}{N_i n_n}.
\] (3.30)

Note that this still includes stray laser light. For each CCD image, the Raman calibration factor, which is the product of quantum efficiency and overall system transmission, is calculated as

\[
\frac{[G\eta T \Delta \Omega \Delta A \Delta \lambda]_{\text{Raman}}}{[G\eta T \Delta \Omega \Delta A \Delta \lambda]_{\text{Labsphere}}} = \frac{(N_{\text{Raman}} - N_{\text{dark}} - N_{\text{Rayleigh, normalized}} n_n N_i \sigma_{\text{Rayleigh, nitrogen}} \sigma_{\text{Rayleigh, argon}}) \Delta A \Delta \lambda}{N_i n_n (F\sigma)_{\text{convolved}} LF_{\text{flat}}}.
\] (3.31)

where the overbar denotes the mean. In this manner, both the Rayleigh-scattered and the stray laser light components of the signal are removed, leaving only the Raman-scattered component. Data is binned by wavelength and channel, and the mean value of the calibration factor over the 685 nm - 690 nm range is kept as the calibration factor.

The ratio of the Raman scattering calibration factor to the precision light source calibration factor is shown in Figure 3.20. There is variation in the ratio over wavelength, which is most likely due to uncertainties introduced in the convolution of the ideal Raman spectrum. The presence
of stray light and the ruby light filter make measurements of the calibration factor difficult for wavelengths close to the ruby laser wavelength. The Raman scattering spectrum becomes small at wavelengths below 685 nm and above 705 nm. A single calibration factor for each channel is determined from the mean of the calibration factors over an intermediate wavelength range, as indicated by a dashed-dotted line in Figure 3.20. This mean calibration factor ratio is used in Figure 3.21, which compares the ratios as a function of major radius. Due to the presence of stray laser light that does not completely subtract, channels 5, 6, and 7 at major radii 55.6 cm, 63.8 cm, and 62.8 cm, respectively, have a higher calibration factor ratio. Ignoring these channels, there is an overall trend of higher calibration factor ratios as major radius increases. Additionally, the ratio of the calibration factors for all channels is less than one. This suggests that the the viewing optics could slightly misaligned with respect to the laser, such that channels at a larger major radius are better aligned and those at a smaller radius are more poorly aligned. This analysis can be used to ensure proper alignment prior to a run.

### 3.7.5 Interferometer Cross-Calibration

There is a very limited set of data that includes both a functioning interferometer and good Thomson scattering measurements. However, a cross-calibration of the Thomson scattering density measurements is possible.

To compare Thomson measurements to interferometer measurements, the line integrated density of the measured Thomson density profile must first be calculated. In particular, since only the outboard side of the plasma is imaged in the Thomson viewing optics, there is no direct information about the inboard plasma. In order to calculate the inboard plasma density, some assumptions about plasma geometry must be made. No good LRDFIT reconstructions exist for shots with good interferometer data. However, a model CHEASE equilibrium may be used to map Thomson measurement points to flux surfaces (this equilibrium is described in Section 4.2). In this case, the
Figure 3.20: The ratio of Raman scattering calibration factor $G\eta T$ to the precision light source calibration factor as measured for the 2012 viewing optics configuration as a function of wavelength and channel. The black data points are the ratio without Rayleigh subtraction, and the blue points are the ratio with the subtraction. The dashed lines from 685 nm to 690 nm show the mean and standard deviation of the ratio in interval, and the dashed lines from 698 nm to 705 nm show the corresponding values for that interval with the uncorrected values in red and corrected values in green. The black points are actually used to correct the density.
Figure 3.21: The ratio of Raman scattering calibration factor $G\eta T$ to the precision light source calibration factor as measured for the 2012 viewing optics configuration as a function of major radius.
ideal equilibria is produced to match $I_P$ and the uncorrected peak $n_e$ to yield a reasonable Shafra-

Table 3.6: Results of the interferometer cross-calibration.

<table>
<thead>
<tr>
<th>Shot</th>
<th>$t$ [ms]</th>
<th>$\int n_e dl$ [m$^{-2}$]</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1111091458</td>
<td>450</td>
<td>$5.60 \times 10^{18}$</td>
<td>$1.97 \pm 0.281$</td>
</tr>
<tr>
<td>1111091504</td>
<td>450</td>
<td>$6.20 \times 10^{18}$</td>
<td>$2.62 \pm 0.336$</td>
</tr>
</tbody>
</table>

A calibration factor $f$ can be defined as the ratio of the line integrated density from the inter-
ferometer to the line integrated density calculated from Thomson data. Uncertainty is incorporated
using a Monte Carlo approach. The test density value used in the calculation is set to the measured
density plus a normally distributed number multiplied by the uncertainty in the density measure-
ment. A set of 100 trials are run, and the standard deviations of the resulting test calibration
factors is used as the uncertainty. Results of the cross-calibration are summarized in Table 3.6. A
representative line integrated density signal is shown in Figure 3.22.

The weighted mean $\bar{f}$ of the individual calibration factors is taken as

$$\bar{f} = \frac{\sum_{i=1}^{N} f_i w_i}{\sum_{i=1}^{N} w_i}$$

where the weights $w_i = \sqrt{\int n_e dl}$ as the signal to noise ratio of the Thomson measurements
roughly scales as $\sqrt{N_s} \sim \sqrt{n_e}$. The result is $\bar{f} = 2.31 \pm 0.220$. Note that any misalignment of
the laser to the collection optics would result in a calibration factor greater than unity, if no other
factors were involved.
Figure 3.22: Line integrated density for shot 111091437. The complete discharge is not plotted because of ambiguity in removing fringe shifts during later times.
3.8 Data Processing

A raw image from the CCD is acquired using WinSpec/32 software and written to a data file. The 512 \times 512 pixel array from the raw image file is then written to the LTX MDSplus tree by an IDL procedure.

The determination of the electron temperature and density profiles is performed by another IDL procedure. This procedure first loads the raw data \( I_{ij} \) from MDSplus, where \( i \) and \( j \) represent the pixel location on the CCD. The master dark frame \( D_{ij} \) is subtracted, then divided by the flat field \( F_{ij} \) in order to correct for the variation in efficiency across the CCD. The result is the number of photoelectrons

\[
N_{pe,ij} = \frac{I_{ij} - D_{ij}}{F_{ij}}.
\]  

This has an associated uncertainty of

\[
\frac{\sigma^2_{N_{pe,ij}}}{N^2_{pe,ij}} = \frac{\sigma^2_{I_{ij}}}{(I_{ij} - D_{ij})^2} + \frac{\sigma^2_{F_{ij}}}{F^2_{ij}}
\]  

(3.34)

where \( \sigma_x \) represents the standard uncertainty of some quantity \( x \). As scattered photons are randomly emitted and collected at a fixed mean rate, their statistics follow a Poisson distribution. The variance of a Poisson distribution is equal to the mean, so

\[
\sigma^2_{I_{ij}} = I_{ij}.
\]  

(3.35)

The uncertainty of the master dark frame is taken from the standard deviation of the individual dark frames used to create the master. Since a large number of frames are used, the uncertainty is quite low. The uncertainty in the flat field is determined from precision light source calibrations.

The 512 \times 512 pixel array is converted to wavelengths (which also corrects image curvature), and then the wavelengths are binned and separated into 11 channels. Bin sizes are typically 1 nm so
that each bin will correspond to several pixels on a given channel. For channels viewing the plasma core, only data from 630 nm to 740 nm is binned, with bands from 646 nm to 660 nm excluded for the H-α notch filter, 669 nm to 674 nm excluded for the peak of the Li I line at 670 nm, and 685 nm to 702 nm excluded for the ruby light notch filter. For channels viewing the plasma edge, the excluded region for the ruby light notch filter is 689 nm to 701 nm. The number of counts in one bin are averaged as

\[ y_{\text{bin}} = \frac{1}{N_{\text{bin}}} \sum_{\text{bin}} N_{\text{pe,ij}} \]  

such that if pixel \(ij\) has an associated wavelength \(\lambda_{ij}\) within the wavelength bin \(y_{\text{bin}}\), \(N_{\text{pe,ij}}\) is included in the average. \(N_{\text{bin}}\) is the number of pixels included in a given bin. The uncertainty for this operation is

\[ \sigma^2_{y_{\text{bin}}} = \frac{1}{N^2_{\text{bin}}} \sum_{\text{bin}} \sigma^2_{N_{\text{pe,ij}}}. \]  

Finally, a Levenberg-Marquardt least-squares fitting program fits the spectral data from each spatial channel to a Gaussian-like function for Thomson scattered light plus an impurity line from the Li I 670.78 nm doublet convolved with the spectrometer instrumental function. Since the separation of the Li I doublet is far below the instrumental limits of the spectrometer, it is treated as a single source. The form of the fitting function is

\[ y_{\text{bin}} = \frac{1}{a} \int_{\lambda' - a/2}^{\lambda' + a/2} \left( \frac{p_0}{\sin \left( \frac{\theta}{2} \right)} \exp \left( -\frac{\left(\lambda_{\text{bin}} - \lambda_{\text{ruby}}\right)^2}{8\lambda^2_{\text{ruby}} p_1 \sin^2 \left( \frac{\theta}{2} \right)} \right) \right) + \]

\[ p_2 \exp \left( -\frac{\left(\lambda_{\text{bin}} - \lambda_{\text{Li}}\right)^2}{2p_3^2} \right) \]  

d\(\lambda + p_4\)

where the instrumental function width is \(a = 7.98\) nm, equivalent to the width of 19 pixels. This routine takes into account the uncertainties \(\sigma_{y_{\text{bin}}}\) to produce fitted parameters and their associated uncertainties. The fitting parameter \(p_1\) is simply the electron temperature

\[ T_e = p_1. \]
The parameter \( p_0 \) is directly proportional to the electron density, such that

\[
n_e = \frac{p_0 \lambda_{\text{ruby}} \Delta A}{N_i r_0^2 L} \sqrt{\frac{8\pi p_1}{m_e c^2}}.
\]

Note that the flat field correction already contains absolute density calibration factors and uncertainties. The parameters \( p_2 \) and \( p_3 \) are the amplitude and standard deviation, respectively, of the lithium line, and are not used other than to remove the impurity line’s contribution to the signal. Parameter \( p_4 \) represents constant offset of the signal from zero and is generally quite small.

The uncertainty in \( n_e \) due to measured or fit quantities is

\[
\frac{\sigma_{n_e}^2}{n_e^2} = \frac{\sigma_{p_0}^2}{p_0^2} + \frac{\sigma_{N_i}^2}{N_i^2} + \frac{\sigma_L^2}{L^2} + \frac{1}{2} \frac{\sigma_{p_1}^2}{p_1^2}.
\]

The standard 1-sigma errors in each fitting parameter are used for error bars. Typical values are 10% of \( T_e \) and 30% of \( n_e \).

The first good measurements of \( T_e \) and \( n_e \) were taken on December 1, 2010, and indicated \( T_e \) in the range of 50 eV to 100 eV. Values for \( n_e \) were uncalibrated. Sample fitting for a later shot, 1209141738, is shown in Figure 3.23, and \( T_e \) and \( n_e \) profiles for this shot are shown in Figure 3.24.
Figure 3.23: Data fitting from shot 1209141738. Corrected data for each channel is shown in green, with vertical error bars represent the standard uncertainty. The best fit for each channel is shown in blue, with separate contributions from Thomson scattered light and the lithium impurity line.
Figure 3.24: The results of data fitting from shot 1209141738. Vertical error bars represent the standard uncertainty and horizontal error bars represent the width of the viewing region. The 40.8 cm channel is not shown due to the poor quality of the fit.
Chapter 4

Results

4.1 TRANSP

TRANSP is a one-dimensional transport analysis code that is designed to analyze transport of plasmas using experimental data as inputs [110]. As implemented in TRANSP, the electron power balance equation for an Ohmically heated plasma is

$$
\frac{3}{2} \frac{\partial}{\partial t} n_e T_e + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{5}{2} r n_e T_e V_e \right) + \sum_k V_k \frac{\partial}{\partial r} n_k T_i - \frac{1}{r} \frac{\partial}{\partial r} \left( r n_e \chi_e \frac{\partial T_e}{\partial r} \right) = p_{\text{OH}} - q_{\text{ie}} - p_{\text{ioniz}} - p_{\text{rad}}
$$

where $V_e$ is the radial electron velocity, $k$ is the ion species index, $p_{\text{OH}}$ is the Ohmic heating power per unit volume, $q_{\text{ie}}$ is the ion-electron coupling, $p_{\text{ioniz}}$ is the power loss by ionization per unit volume, and $p_{\text{rad}}$ is the radiation power per unit volume (note that the ion terms here are due to convective power loss). The electron conductive heat flux is $q_{\text{e,cond}} = -n_e \chi_e \partial T_e / \partial r$. To determine the electron thermal diffusivity $\chi_e$, measurements or calculations of the terms in Equation 4.1 are necessary. Some of these terms are typically known experimentally on LTX, such as $T_e$ and $n_e$ profiles from the Thomson scattering diagnostic.
However, there are other terms that are either unavailable or difficult to experimentally measure. Interpretive modeling can be used to allow analysis to proceed. In general, interpretive modeling uses experimental datasets as inputs along with assumptions about the system in question. Appropriate models are selected and applied to the experimental data, which then allow determination of unknown quantities. For this particular analysis, TRANSP serves as the interpretive modeling tool that facilitates determination of $\chi_e$. TRANSP analysis requires several inputs such as a magnetic equilibrium, experimental plasma current, toroidal field strength, surface voltage $V_{\text{surf}}$, radiation power profiles, and density and temperature profiles. Other data, such as ion temperature and density profiles, neutral beam heating levels, or radio-frequency heating levels, can also be used as inputs, as they are available.

All calculations in TRANSP are reduced to one radial dimension. TRANSP calculates the plasma electrical conductivity $\sigma$, typically using a neoclassical formulation. TRANSP then solves the poloidal magnetic field diffusion equation (PMDE)

$$\frac{\partial B_P}{\partial t} = \frac{\partial}{\partial r} \left( \frac{1}{r \mu_0 \sigma} \frac{\partial}{\partial r} (r B_P) \right). \quad (4.2)$$

This allows calculation of ohmic heating profiles. The particle conservation equation and energy balance equation are applied to the data, and the ion power balance equation is solved. Electron thermal diffusivities are determined from the electron power balance equation. These provide the missing elements necessary to determine local transport coefficients. Better values of $\chi_e$ should result as more or better experimental data are available as inputs. Details of experimental data selection and preparation, assumptions used, and resulting local transport coefficients will be discussed in this chapter.


### 4.1.1 TRANSP Settings

To perform TRANSP analysis, experimental data must be properly imported into the code. For LTX, inputs to TRANSP are all in UFILE format. UFILES from experimental measurements of $I_p$, $V_{surf}$, and $RB_T$ are created using IDL procedures. UFILEs for the magnetic equilibria are created from EQDSK format files, which are the same type as the output of LRDFIT. These EQDSK files are converted into TRANSP UFILEs by a program called scrunch2. Thomson scattering measurements from a shot series are written to a UFILE as well.\footnote{Additional information on UFILEs is at \url{http://w3.pppl.gov/~pshare/help/ufiles.htm}}

The TRANSP namelist is an input file that specifies UFILE inputs and allows selection of various types of calculations. TRANSP is instructed to solve the one-dimensional poloidal magnetic field diffusion equation using electrical conductivities calculated neoclassically using a formulation by Sauter et al. \cite{111}. TRANSP allows many ways to solve the PMDE. In the current case, the computation attempts to match $I_p$ and $V_{surf}$ and predicts the $q$ profile and $Z_{eff}$. $Z_{eff}$ derived from the PMDE is referred to as $Z_{eff,md}$. The plasma composition $Z_{eff,p}$ is typically set to 1.2 for TRANSP analysis. This assumption is based on CDX-U results for lithium discharges (discharges without lithium were found to have $Z_{eff} = 2.4$) \cite{43}. A sensitivity analysis of the assumed $Z_{eff}$ is discussed in Section 4.3. As an example, a comparison of the two $Z_{eff}$ values for a TRANSP analysis further discussed in Section 4.2 are shown in Figure 4.1. $Z_{eff,md}$ and $Z_{eff,p}$ do not match at all times; however at the time of interest late in to the discharge, the match is good. As discussed later, the early data is part of the initialization of the ion temperature. The main ion species is hydrogen, the dominant impurity is set to be carbon ($A = 12, Z = 6$), and all particles are given the same density profile shape. 40 radial zones are used in TRANSP calculations.

Due to the lack of a neutral beam, localized ion temperature profile measurements are unavailable from the CHERS diagnostic. TRANSP allows calculation of $T_i$ using internal models. For this analysis, neoclassical improved Chang-Hinton \cite{112} calculations are used to calculate $T_i$. The
Figure 4.1: A comparison of the plasma composition $Z_{\text{eff},p}$ and the PMDE axial $Z_{\text{eff},\text{md}}$ for the 1111081819 shot series base case. Note that values prior to 449 ms are part of the equilibration time, and only values after 449 ms should be considered relevant.
Chang-Hinton formulations are valid in the lower aspect ratios found in spherical tokamaks, and other spherical tokamaks, such as START and NSTX, have observed ion thermal diffusivities \( \chi_i \) to be close to neoclassical levels \([113, 114]\). As will be further discussed later, chord-integrated passive CHERS measurements are consistent with TRANSP \( T_i \) calculations. An important step in calculating \( T_i \) profiles is to allow some simulation time before the times of interest (when Thomson profiles are acquired) for the ion temperature to evolve from the initialization level to physically meaningful values through ion power balance calculations by TRANSP. To accomplish this, the \( T_e \) and \( n_e \) data from Thomson scattering at 400 ms (typically 40 ms before the discharge starts) are set to 0.50 times the values of the earliest valid Thomson data. The \( T_e \) and \( n_e \) profiles are linearly interpolated by TRANSP from the 400 ms data to the time of the first profile, and the earliest available reconstruction is used. The pseudo-equilibration time variable (which is the experimental time before the TRANSP run begins in earnest, when the plasma profiles are allowed to initialize) is set to 0.5 ms, whereas typically 100 ms is used for NSTX TRANSP runs (which is much longer than any LTX discharge to date). An example of the \( T_i \) initialization and evolution is shown in Figure 4.2. Note how the initial \( T_i \) levels are unrealistically high, and take several milliseconds to equilibrate (at about 446 ms). This agrees with a simple estimate of the energy equilibration rate

\[
\bar{\nu}^{\bar{e}} = 3.2 \times 10^{-9} \text{ cm}^3 \text{s}^{-1} \text{eV}^{3/2} n_e Z^2 \lambda \mu^{-1} T_e^{-3/2}
\]

which produces an energy equilibration time of \( 1/\bar{\nu}^{\bar{e}} \approx 5 \text{ ms} \) during the initialization stage. Here \( \mu \) is the ratio of the ion mass to the proton mass and \( \lambda \) is the Coulomb logarithm. Outputs prior to valid Thomson data are not considered useful because they are not based on experimental data, but are merely part of the ion temperature initialization. A minimum \( T_i = 5 \text{ eV} \) is enforced in order to prevent problems calculating the ion power balance. If \( T_i \) drops below this limit, TRANSP adds additional “bogus” heating power to maintain the minimum \( T_i \).
Figure 4.2: $T_i$ initialization and evolution in TRANSP for the 1111081819 shot series. (a) Temporal evolution of axial $T_e$ and $T_i$. The run is set to start at 442 ms, with a 0.5 ms pseudo-equilibration time, as marked by dotted lines. Later times are when Thomson data is specified. (b) Spatial profiles of $T_e$ and $T_i$ at 442 ms (solid lines) and 449 ms (dashed lines).

It is worth noting that the type of TRANSP calculations performed here are relatively basic and depend heavily on the Thomson scattering profiles. TRANSP can accept many more experimental inputs such as ion temperature and density profiles, bulk velocities, radiation power profiles, neutral beam heating power, impurity levels, etc. Inclusion of more inputs should increase confidence in TRANSP results. More complex simulations could be performed as better diagnostic measurements and knowledge of LTX plasmas become available. Since there are few time steps for these calculations, LTX TRANSP runs can be performed on a single processor in about one minute.

Note that unlike the case for other tokamaks, TRANSP run numbers are not the same as LTX shot numbers. TRANSP run numbers can only have six digits, whereas the date- and time-based LTX shot numbers have 10 digits. Instead, a mapping of LTX shot numbers to TRANSP run numbers is used, such that the TRANSP run number is the number of LTX shots since February 27, 2009 with the first TRANSP run number set to be 100001. Note that a valid LTX shot in this case is merely any MDSplus shot number with data, which does not necessarily represent shots with plasma formation. As such, there are many coil or laser test shots included in the list. The
mapping for the shots is stored in a file for look-up and can be appended as new LTX discharges are created.

4.1.2 Radiation Power Profiles

In order to produce radiation power profiles for the $p_{\text{rad}}$ term in Equation 4.1, bolometric data is typically inverted. The basis of this algorithm is that an array of bolometer radiance measurements $L_{\text{bolo}}$ can be written as the product of a sightline length matrix $L_{\text{sightline}}$ and a $p_{\text{rad}}$ profile as

$$L_{\text{bolo}} = L_{\text{sightline}} p_{\text{rad}}.$$  \hspace{1cm} (4.4)

If $L_{\text{sightline}}$ is invertible to $L_{\text{sightline}}^{-1}$, then the $p_{\text{rad}}$ profile is

$$p_{\text{rad}} = L_{\text{sightline}}^{-1} L_{\text{bolo}}.$$ \hspace{1cm} (4.5)

However, to produce good inversions, the bolometer sightlines must extend to be tangent to the plasma edge region. LTX geometry (particularly the shells) prevents edge views, and inversions are not possible unless the plasma has a small minor radius. As such, there are significant contributions from radiation in the edge that cannot be resolved.

Inversions have been attempted following an algorithm described by Granstedt [84], which is itself an adaptation of a more general algorithm by R. Bell (personal communication, R. Bell, 5 September, 2013). Succinctly, this algorithm uses bolometer sightline and equilibrium geometry to divide the plasma into flux surface zones within which $p_{\text{rad}}$ is taken to be constant. Sightline boundaries are defined as the midpoints between adjacent sightlines (see Figure 4.3), with the outermost boundaries taken to be the LCFS. The minimum $\psi$ value along each sightline boundary is the point at which the sightline boundary is tangent to a flux surface. The value of minimum $\psi$ for each sightline boundary $\psi_{zb}$ is poloidally mapped using the equilibrium to determine the inter-
section points of each sightline and sightline boundary. The total length of the sightline between zone boundaries on both inboard and outboard sides is used to form the length matrix. Inversions are done separately for sightlines above and below the magnetic axis. As an example of the algorithm, Figure 4.3 shows the LRDFIT reconstruction for shot 1209141619 at 458 ms and bolometer sightline geometry. Notice the large distance between the LCFS and the next intersection point for each sightline, which exhibits the problems resolving edge radiation levels. Additionally, the bolometer is not adequately calibrated, which further complicates interpretation of its signals. If edge views were available, and the bolometer better calibrated, a better characterization of the edge contribution would be possible. To this end, additional edge-viewing bolometer channels could be added, which, in addition to existing core views, would allow inversions.

Since inversions are not possible with the existing bolometer array, estimates of the radiation power levels are used. If the impurity ion is assumed to be carbon \((Z = 6)\), the emission rates \(L_Z\) can be estimated using the results of a collisional-radiative model giving the emission rates for carbon as a function of \(T_e\) and \(n_e\) \[^{[115]}\]. While emission rates for carbon are only given for electron densities as low as \(10^{18} \text{ m}^{-3}\), there is not much variation in the emission rate for densities in that range, and \(L_Z\) is much more strongly a function of \(T_e\). Since \(T_e\) and \(n_e\) are known from Thomson scattering, the corresponding \(L_Z\) is determined for each spatial and temporal point. The radiation power profile \(p_{\text{rad}} = L_Z n_e n_C\) is then calculated, where \(n_C\) is the carbon density. \(n_C\) is assumed to be proportional to \(n_e\). If \(Z_{\text{eff}}\) and \(n_e\) are known, and the impurity is assumed to be a single species, then the density of that species can be determined by solving the system of equations for the definition of \(Z_{\text{eff}}\)

\[
Z_{\text{eff}} = \sum_i Z_i^2 n_i = \frac{Z_1^2 n_1 + Z_2^2 n_2}{n_e} \quad (4.6)
\]

and the quasineutrality condition

\[
n_e = \sum_i Z_i n_i = Z_1 n_1 + Z_2 n_2 \quad (4.7)
\]
Figure 4.3: Bolometer inversion geometry. The bolometer sightlines are in blue and sightline boundaries are in green. The flux surfaces for the inversion above and below the magnetic axis are shown in black. The limiter is shown in red.
where \( n_1 \) and \( n_2 \) are the densities of the respective ion species, and \( Z_1 \) and \( Z_2 \) are the atomic numbers of the respective ion species. The solution is

\[
\begin{align*}
n_1 &= \frac{n_e (Z_2 - Z_{\text{eff}})}{Z_1 (Z_2 - Z_1)} \\
n_2 &= \frac{n_e (Z_{\text{eff}} - Z_1)}{Z_2 (Z_2 - Z_1)}.
\end{align*}
\]

(4.8)

(4.9)

For example, choosing ion species 1 as hydrogen, ion species 2 as carbon, and \( Z_{\text{eff}} = 1.2 \) yields \( n_H = 0.96n_e \) and \( n_C = 0.0067n_e \).

### 4.1.3 Thomson Data Selection and Preparation

Since only one Thomson profile is produced per shot on LTX, shots with the same coil and fuel programming are repeated while the Thomson firing time is varied. Assuming that these discharges are reproducible, the Thomson scattering measurements are used to create a time evolution of the \( T_e \) and \( n_e \) profiles. Only shot series with good time-resolution (\( \leq 1 \) ms) and absolutely-calibrated densities are considered.

Due to difficulties with laser power supplies, capacitor banks, flashlamps, a failure of the CCD, and cases with densities too low to produce sufficient signal for reasonable fits, these shot series are few. All shot series are for cases with fresh lithium evaporation directly prior to the run, with plasmas operating within room-temperature shells (meaning the lithium is solid). No Thomson scattering measurements of bare stainless steel wall plasmas were possible. Those discharges are short duration (\( \sim 5 \) ms) with low plasma currents (\( \leq 15 \) kA). Measurements were also attempted in hot shell discharges, but densities seemed to be too low for measurements.

Selected Thomson profiles are loaded from the MDSplus tree. Bad fits are identified and removed from the analysis. Because of instrumental vignetting, the data at \( R = 0.408 \) m channel is not used. Other fits may be removed if the relative uncertainty is too high or clear outliers exist.
As $\chi_e$ calculations are dependent on spatial derivatives of $T_e$, each individual measurement profile is smoothed and interpolated with a cubic spline function using an algorithm that incorporates experimental uncertainty into the calculation. The strength of the smoothing is given by a smoothing parameter $S$, the level of which is noted for each analysis \[116\]. Smoothing reduces the effects of single measurement points that can reverse the sign of derivatives and produce negative $\chi_e$. The smoothed and interpolated profiles are then combined into a composite profile. Examples of the smoothing are shown in Figures 4.4 and 4.5.

A Monte Carlo analysis is used to incorporate uncertainty in temperature measurements. As each radial measurement point is independent from the others, values of $T_e$ are independently adjusted by a normally-distributed random number $x_{\text{normal}}$ (with a standard deviation of one) multiplied by the uncertainty to produce a test value

$$T_{e,\text{test}} = T_e + x_{\text{normal}} \sigma_{T_e}$$

(4.10)

for each measurement location. The test temperatures are smoothed in the same manner as the measured temperatures. This analysis allows $dT_e/dr$ to vary as well as $T_e$. Typically, 10 Monte Carlo profiles are generated for each composite temperature profile.

The minimum $n_e$ is set to 0, and the minimum $T_e$ is set to 5 eV, since TRANSP can have difficulties with ion power balance calculations for $T_e$ less than 5 eV. While $T_e$ measurements have never been this low, this step serves as a check on the Monte Carlo calculations and smoothing algorithm. Values lower than the minimum are set to the minimum.

In all cases densities are scaled using the interferometer correction described in Section 3.7.5. Measured densities for the two outermost radial points can sometimes be unrealistically high due to stray laser light. Profiles with higher densities in the edge than the closest measured valid density are adjusted down to match that level.
Figure 4.4: Fitted and smoothed $T_e$ profiles for the 1111081819 shot series.
Figure 4.5: Fitted and smoothed $n_e$ profiles for the 1111081819 shot series.
As mentioned previously, a profile with 0.50 times $T_e$ and $n_e$ values of the earliest Thomson profile is added at 400 ms to allow the TRANSP-computed $T_i$ to reach physically meaningful values. Profiles from shots at different times are made into a composite profile and written to a UFILE. Separate UFILEs are written for each Monte Carlo iteration.

### 4.2 Relatively Heavy Full Shell Lithium Evaporation Results

Experiments on November 8, 2011 took place directly following a one hour lithium crucible evaporation. The vessel had been cleaned recently from the first lithium run campaign, so the lithium inventory during operation is reasonably well known. The two lithium crucibles were filled with 7.2 g (north side) and 7.9 g (south side) on October 5, 2011. Since the two evaporators are spaced $180^\circ$ toroidally with each evaporator centered between the shell toroidal gaps, the north and south evaporators predominantly deposit lithium on the north and south shell pairs, respectively. See Appendix C for further records of the crucible fills. The first evaporation into the clean vessel was on November 7, 2011 (111107), and the November 8, 2011 (111108) evaporation was only the second evaporation of the run campaign. Later evaporations on November 9, 2011 (111109) and November 28, 2011 (111128) used the remaining lithium in the crucibles.

Equation 2.8 provides an estimate of evaporated lithium for the four evaporations from the crucible loads. An example of the calculation is shown in Figure 4.6. Results for the other evaporations are displayed in Table 4.1. Note that there are two thermocouples in each of the two crucibles, which allows for up to two measurements of the evaporated lithium mass per crucible. The north number 1 (N1) thermocouple was not in good thermal contact with the lithium for the 111108 and 111109 evaporations and so cannot be used. Note that this method over-predicts the total evaporated lithium, as the total evaporated mass calculated is larger than the fill amount. As a correction, the evaporated amounts can be normalized to the known fill masses. This produces a factor of $7.2/12.200 = 0.59$ for the N2 thermocouple, and factors of 0.51 and 0.53 for the two
south thermocouples. Corrected evaporated masses are displayed in Table 4.2. Summing the contributions from the north and south crucibles predicts from 4.2 g to 4.3 g deposition on November 8, 2011. Adding the deposition from the previous day produces a total lithium inventory in the vessel from 8.7 g to 8.9 g. Assuming that deposition was uniform, the thickness of the lithium $d$ can be estimated as

$$d = \frac{m_{\text{Li}}}{\rho_{\text{Li}} A_{\text{shell}}}$$

(4.11)

where $m_{\text{Li}}$ is the mass of the lithium, $\rho_{\text{Li}} = 0.537$ g/cm$^3$ is the lithium mass density, and $A_{\text{shell}} = 3.71$ m$^2$ is the total plasma-facing surface area of the shells, which gives $\rho_{\text{Li}} A_{\text{shell}} = 1.98 \times 10^6$ g/m. This results in 1 g of lithium deposition producing a lithium thickness of $5.05 \times 10^{-7}$ m. Thus the total evaporated lithium mass of 8.7 g to 8.9 g produced a lithium thickness of $4.4 \times 10^{-6}$ m to $4.5 \times 10^{-6}$ m. Note that while the deposition is fairly uniform, there are some spatial variations, as evidenced in photographs of the shells after a lithium run campaign (Figure 2.6) and by DEGAS 2 calculations of the deposition [70]. Even if the some PFCs are not as well coated, this type of evaporation has resulted in higher plasma currents and durations over bare stainless steel wall discharges.

Another method to estimate the evaporated mass is to examine the plateau times at the freezing point of lithium during cool-down, which are assumed to be proportional to the lithium mass remaining in the crucible. Plateau times are shown in Table 4.3. Since there was no lithium left in the crucibles on November 28, 2011, there was no plateau was observed during cool-down for that evaporation. Note that the plateau time is indicative of the amount of lithium remaining after an evaporation, and so can not predict the amount evaporated without good data on the initial amount of lithium before the evaporation. Using the corrected masses from the thermocouple data, the amount of lithium remaining in the crucible can be compared to the plateau time, as shown in Figure 4.7. The plateau time is quite linear to the calculated remaining lithium mass, suggesting that both methods are good ways to estimate lithium deposition. Note that the south
crucible seems to have a different cooling rate than the north. The plateau time method could be used independently to calculate the evaporated lithium if a freshly loaded crucible is heated to just above the melting point of lithium, but not high enough for appreciable evaporation, then allowed to cool, which would provide a calibration factor for the plateau time to the lithium remaining for each crucible fill.

<table>
<thead>
<tr>
<th>Date [YYMMDD]</th>
<th>$m_{N1}$ [g]</th>
<th>$m_{N2}$ [g]</th>
<th>$m_{S1}$ [g]</th>
<th>$m_{S2}$ [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>111107</td>
<td>4.290</td>
<td>4.164</td>
<td>3.906</td>
<td>3.994</td>
</tr>
<tr>
<td>111108</td>
<td>-</td>
<td>3.345</td>
<td>4.366</td>
<td>4.276</td>
</tr>
<tr>
<td>111109</td>
<td>-</td>
<td>2.775</td>
<td>4.204</td>
<td>4.128</td>
</tr>
<tr>
<td>111128</td>
<td>2.624</td>
<td>1.916</td>
<td>2.913</td>
<td>2.554</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>12.200</td>
<td>15.389</td>
<td>14.952</td>
</tr>
</tbody>
</table>

Table 4.1: Crucible evaporation estimates using temperature-based calculations for two thermocouples in each of the north and south crucibles.
### Table 4.2: Corrected crucible evaporation estimates using temperature-based calculations normalized to the fill masses for one thermocouple in the north crucible and two in the south crucible.

<table>
<thead>
<tr>
<th>Date [YYMMDD]</th>
<th>$m_{N2}$ [g]</th>
<th>$m_{S1}$ [g]</th>
<th>$m_{S2}$ [g]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.5</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>111108</td>
<td>2.0</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td>111109</td>
<td>1.6</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>111128</td>
<td>1.1</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.2</strong></td>
<td><strong>7.9</strong></td>
<td><strong>7.9</strong></td>
</tr>
</tbody>
</table>

Table 4.3: Crucible freezing plateau times for two thermocouples each in the north and south crucibles.

<table>
<thead>
<tr>
<th>Date [YYMMDD]</th>
<th>$t_{N1}$ [minute]</th>
<th>$t_{N2}$ [minute]</th>
<th>$t_{S1}$ [minute]</th>
<th>$t_{S2}$ [minute]</th>
</tr>
</thead>
<tbody>
<tr>
<td>111107</td>
<td>17.83</td>
<td>15.50</td>
<td>13.33</td>
<td>12.00</td>
</tr>
<tr>
<td>111108</td>
<td>-</td>
<td>9.33</td>
<td>8.00</td>
<td>8.00</td>
</tr>
<tr>
<td>111109</td>
<td>-</td>
<td>3.83</td>
<td>4.00</td>
<td>2.67</td>
</tr>
<tr>
<td>111128</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 4.7: A comparison of lithium mass remaining in the crucible with the plateau time during cool-down for the 111107, 111108, 111109, and 111128 evaporations. Labels indicate either north or south crucible and thermocouple number.
A series of 14 shots with the same field coil and fuel programming was repeated while the firing time of the Thomson scattering laser was varied. Plasma current, loop voltage, and fueling for these shot series is shown in Figure 4.8. The base LTX shot number for the shot series is 1111081819, which maps to TRANSP run number 103574. The MCI was at cryogenic (86 K) temperatures with backing pressure of 100 psia, and the LFSP had a backing pressure of 22 psia. There was an additional 2.6 ms pre-fueling LFSP pulse starting at 410 ms. The plasma species is hydrogen.

Despite intermittent problems with low laser energies for some shots, this shot series is perhaps the most complete Thomson scattering data set, as profiles are available from 449.0 ms to 451.5 ms at 0.5 ms intervals (The laser oscillator was later rebuilt, which ended problems with low laser energies). No interferometer data is available for this shot series, but the electron density as measured by Thomson scattering is scaled using the factor determined in Section 3.7.5. Fitted and smoothed $T_e$ and $n_e$ profiles are shown in Figures 4.4 and 4.5. The smoothing parameter is selected to be $S = N - \sqrt{N}$, where $N$ is the number of measurement points per profile. This is intended to reduce over-fitting of experimental measurements and make input $T_e$ profiles at later times reasonable. Note that at later times the temperature profiles appear to be hollow. This has been seen on other LTX discharges and was also the case for measurements on CDX-U [103]. LTX shot numbers for Thomson profiles used for the TRANSP analysis are summarized in Table 4.4.

<table>
<thead>
<tr>
<th>Shot</th>
<th>$t_{TS}$ [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1111081819</td>
<td>449.00</td>
</tr>
<tr>
<td>1111081826</td>
<td>449.50</td>
</tr>
<tr>
<td>1111081834</td>
<td>450.00</td>
</tr>
<tr>
<td>1111081840</td>
<td>450.50</td>
</tr>
<tr>
<td>1111081854</td>
<td>451.00</td>
</tr>
<tr>
<td>1111081859</td>
<td>451.50</td>
</tr>
</tbody>
</table>

Table 4.4: LTX shot numbers for Thomson profiles used for TRANSP run 103574.
Figure 4.8: Shot 1111081819 plasma current, loop voltage, and fueling. There was an additional 2.6 ms pre-fueling LFSP pulse starting at 410 ms. Vertical purple lines indicate the times of Thomson data collection.
As LRDFIT reconstructions for these plasmas are not available, a model equilibrium is used instead. This model equilibrium is based on LRDFIT reconstructions of discharges with identical coil programming as the 1111081819 shot series, and was developed as the result of significant effort as part of the analysis of recycling rate measurements by Granstedt [84]. The plasma is centered well below the midplane ($Z_0 = -4.6$ cm), in agreement with spectroscopic and fast camera estimates of plasma position. A comparison of the poloidal field coil currents for the reconstructed shot and shot 1111081819 is shown in Figure 4.9. Parameters for the equilibrium are $R_0 = 0.388$ m, $Z_0 = -0.046$ m, $a = 0.24$ m, $\kappa = 1.3$, and $\delta = 0.4$. The model equilibrium is re-created using the Cubic Hermite Element Axisymmetric Static MHD Equilibrium Solver (CHEASE) [117, 118]. The code can be used to create equilibria by solving the Grad-Shafranov equation for given shaping parameters, pressure profiles, and current profiles. CHEASE can output EQDSK format files, which are the same type as the output of LRDFIT and hence can be processed with scrunch2 to generate UFILEs for additional TRANSP analyses. The current profile is somewhat of a free parameter. For this case, the current profile is set to be fairly flat as a starting point. Note that TRANSP later determines its own current profile when solving the PMDE. The total current is set to match experimental measurements at each time point. The pressure profile is assumed to be inverse parabolic, with the maximum pressure set to 200 Pa. Note that the pressure from the equilibria is not actually used in TRANSP, but merely results in a slightly different flux surface shape. Using a fixed pressure instead of pressures from experimental measurements is intended to reduce sensitivity to experimental measurements, which intrinsically carry uncertainty. Note that in the CHEASE representation of the model equilibrium, $\delta$ is set to 0.28 so that the plasma does not extend beyond the shells. The shaping parameters are not varied with time, but are assumed to be constant (the model equilibrium was developed for plasmas at 447 ms). The model equilibrium is displayed in Figure 4.10.

As a base case, TRANSP is run with smoothed Thomson data, but with no estimate of the radiation power profile. The result of this run places an upper limit on $\chi_e$ and also allows evalu-
Figure 4.9: A comparison of coil currents for shots 1111081819 and 1112061424. Currents for 1111081819 are in color, and currents for 1112061424 are in black. Note the similarity in the current traces. Discrepancies appearing after 460 ms are after the discharge disrupts.
Figure 4.10: The model equilibrium as implemented with CHEASE for analysis of the 1111081819 shot series. Normalized flux contours in intervals of 0.1 are in black and the limiter used in the reconstruction is in red. The magnetic axis is denoted by a cross.
ation of assumptions used in the run. One such comparison is between calculated and measured $T_i$. While no neutral beam has been installed on LTX, ion temperature measurements from passive charge exchange as measured by the emission of the 516.689 nm lithium line are still possible [89]. Since light is collected from the entire line of sight of the CHERS viewing optics, and is not localized, interpretation of the locations of $T_i$ measurements is unclear. Passive CHERS measurements (D. Boyle, personal communication, December 17, 2013) are compared to values predicted by TRANSP in Figure 4.11. CHERS midplane viewing chords are plotted as a function of radius of tangency for the toroidal array. With the exception of the data point at 0.52 m, predicted TRANSP $T_i$ are in good agreement with measured passive CHERS $T_i$ levels. Since TRANSP calculates $T_i$ using neoclassical formulas, the agreement suggests that the assumption that ions behave neoclassically in these plasmas is reasonable. The current CHERS data lacks fits in the edge, which is typically necessary for Abel inversions. Even assuming a reasonable level of CHERS signals nearer to the edge produces extremely large error bars in an attempted inversion, indicating this data is not invertible (R. Bell, personal communication, February 4, 2014).

A set of 10 Monte Carlo runs is used to incorporate uncertainty in $T_e$ measurements into the $\chi_e$ calculation. Resulting $\chi_e$ profiles for the Monte Carlo analysis of the no-radiation case with the model equilibrium are shown in Figure 4.12. Note that measurements in the core and edge tend to produce either unrealistically high or negative $\chi_e$ as $dT_e/dr$ is difficult to measure in those regions, so mid-$r/a$ ranges are displayed. Later times have poorly-determined derivatives and result in negative $\chi_e$ values for most Monte Carlo trials. Note that $\chi_i$ is nearly equal to neoclassical predictions, which is to be expected as $T_i$ is calculated using neoclassical formulas. Neoclassical ion thermal diffusivity $\chi_{i,\text{neo}}$ is plotted as well, but is occasionally obscured by $\chi_i$ on a plot of this scale. The smoothest $\chi_e$ is at 449.5 ms, and is displayed alone in Figure 4.13. Calculated $W_{\text{kin}}$ and $\tau_E$ are shown in Figure 4.14. The plasma stored energy increases throughout the shot as the density is raised due to gas injection. Uncertainties displayed are propagated from $n_e$ uncertainties.
Figure 4.11: A comparison of the Thomson $T_e$, CHERS chord-integrated $T_i$, and $T_i$ from TRANSP at times near 450 ms for the 1111081819 shot series. Note that CHERS data is collected over a 2 ms duration centered at 449.951 ms.
Figure 4.12: Thermal diffusivity results for the no-radiation power profile case for the 1111081819 shot series. $\chi_0$ is in green, $\chi_i$ is in red, and $\chi_{L,\text{nom}}$ is in blue. The standard uncertainty in the mean is displayed using the colored bands. For $\chi_i$, the width of the line is larger than the uncertainty.
Figure 4.13: Thermal diffusivity results for the no-radiation power profile case for the 1111081819 shot series at 449.5 ms. $\chi_e$ is in green, $\chi_i$ is in red, and $\chi_{i,\text{neo}}$ is in blue. The standard uncertainty in the mean is displayed using the colored bands. For $\chi_i$, the width of the line is larger than the uncertainty.

Figure 4.14: (a) $W_{\text{kin}}$ and (b) $\tau_E$ from TRANSP for the 1111081819 shot series. Uncertainties in TRANSP results are calculated using runs with high and low uncertainties in $n_e$. 

The base run is repeated using $p_{\text{rad}}$ profiles calculated using the method described in Section 4.1.2. Carbon is assumed to be the only impurity species, and $p_{\text{rad}}$ assuming $Z_{\text{eff}} = 1.2$ and $Z_{\text{eff}} = 2.4$ are produced. The calculated radiation power profiles are shown in Figure 4.15. Note that the rise in density at later times causes an increase in the calculated $p_{\text{rad}}$. Modifications to $\chi_e$ due to calculated radiation power profiles are shown in Figure 4.16. The calculated level of radiation results in very small changes. Assuming $Z_{\text{eff}} = 1.2$ results in a drop in $\chi_e$ of less than 0.1 %. Using $Z_{\text{eff}} = 2.4$, taken to be somewhat of an upper limit as it was the CDX-U no-lithium value, results in a drop of about 0.65 %.

In order to better assess how radiation power levels affect transport levels, a series of runs is performed using several levels of flat $p_{\text{rad}}$ both spatially and temporally. Results are displayed in Figure 4.16. With $p_{\text{rad}}$ below $10^4$ W/m$^3$, the drop in $\chi_e$ is no more than 5 %. As $p_{\text{rad}}$ increases up to $5 \times 10^4$ W/m$^3$, $\chi_e$ begins to change significantly. When $p_{\text{rad}}$ reaches $2 \times 10^5$ W/m$^3$, $\chi_e$ becomes negative at mid-$r/a$. Requiring that $\chi_e > 0$ places a limit on $p_{\text{rad}}$ of around $2 \times 10^5$ W/m$^3$. This produces a large value of total radiation: the plasma volume is 0.544 m$^3$ at 449.5 ms, so a flat $p_{\text{rad}} = 2 \times 10^5$ W/m$^3$ would result in a total 108.8 kW of radiation power. For reference, at 449.5 ms the total Ohmic heating power is 153.8 kW. Since the change in $\chi_e$ is so small, $\chi_e$ calculated with no radiation is believed to be quite close to the actual value, with the exception of the edge region, where $p_{\text{rad}}$ could be more appreciable.

To assess the sensitivity of $\chi_e$ on $n_e$, runs with density shifted low or high by the uncertainty are performed. For this case, a Monte Carlo approach is not used, as much of the uncertainty in density is due to factors that affect all measurement channels, such as the laser energy or interferometer density correction. Densities are smoothed using the same approach as described previously. Results are shown in Figure 4.17. Lower $n_e$ results in higher $\chi_e$. As there is somewhat large uncertainty in the density, there is large variation of $\chi_e$. The low $n_e$ case (which has a mean $n_e$ 0.64 times the base) results in $\chi_e$ with a mean value 1.81 times the base case. The high $n_e$ case (which has a mean $n_e$ 1.36 times the base) results in $\chi_e$ with a mean value 0.58 times the base case.
Figure 4.15: Calculated radiation power profiles assuming carbon as the impurity species for $Z_{\text{eff}} = 1.2$ and $Z_{\text{eff}} = 2.4$ for the 1111081819 shot series.
Chapter 4. Results

Figure 4.16: $\chi_e$ results normalized to the no-radiation case $\chi_{e,\text{base}}$ for the 1111081819 shot series at 449.5 ms for (a) calculated radiation power profiles assuming $Z_{\text{eff}} = 1.2$ and $Z_{\text{eff}} = 2.4$, and (b) several levels of flat $p_{\text{rad}}$ profiles.

Figure 4.17: (a) $n_e$ used for base, low, and high uncertainties and (b) $\chi_e$ normalized to the base case $\chi_{e,\text{base}}$ at 449.5 ms for the 1111081819 shot series for high and low uncertainties.
Figure 4.18: The ratio of $\chi_e$ for the model equilibrium with $Z_0 = -2.3$ cm and $Z_0 = -4.6$ cm as a function of (a) $R$ and (b) $\sqrt{\Phi/\Phi_{lim}}$ for the 1111081819 shot series at 449.5 ms.

To assess the sensitivity on vertical position, the model equilibrium is shifted halfway to the midplane such that $Z_0 = -0.023$ m. A comparison between $\chi_e$ results for two vertical positions is shown in Figure 4.18. In both cases, the calculated $p_{OH}$ is the same, so the only difference is due to the mapping of the Thomson measurement points to flux surfaces. A more centered equilibrium results in midplane measurement points being mapped more to the center of the plasma, but changes in $\chi_e$ are only about 0.01 %.

### 4.3 Relatively Light Partial Shell Lithium Evaporation Results

Another shot series was performed on September 14, 2012. These discharges were created following a lithium evaporation from the north side crucible only, although the 5 mTorr neutral helium fill would have resulted in minimal lithium deposition on the southern side of the vessel as well. Following the previously discussed method, thermocouple data for the lithium temperature is used to produce an estimate of 93.7 mg of evaporated lithium. This is the raw value and is not corrected for total fill volume. The temperatures never exceeded 500 °C, as shown in Figure 4.19, but the thermocouple temperatures can be inaccurate if they are not in good thermal contact with
the lithium. It is possible that the thermocouple lost good contact at about 125 minutes into the evaporation, in which case the estimated deposition levels could be low. There was an 8.7 minute plateau of the temperature curve in the cool-down phase, indicating that some lithium remained in the crucible.

The most recent evaporation was on August 30, 2012, 15 days prior. At that time the north crucible thermocouples were in poor contact with the lithium, indicating unrealistically high temperatures over 700 °C at times, which produce unrealistically high estimates of evaporated lithium. The August 30, 2012 evaporation did not display a temperature plateau, most likely because of poor thermocouple contact to lithium, which makes it difficult to characterize the change in lithium mass in the crucible for the later September 14, 2012 evaporation. The south side evaporator temperatures produce an estimate of 288 mg evaporated for the August 30, 2012 evaporation.

Total lithium inventory can be estimated by examining fill records. The north evaporator was reloaded with 8.0 g of lithium on July 29, 2012, and had only the two evaporations on August 30, 2012 and September, 14, 2012. The south evaporator was last reloaded on July 2, 2012 and had been emptied by August 30, 2012. By summing the total lithium loaded for each evaporator since the vessel was cleaned, the total lithium inventory of LTX at the time of the experiment can be estimated, assuming the evaporators were fully emptied for each fill. The north evaporator deposited a minimum of 48.8 g and a maximum of 56.8 g, depending on how much of the most recent crucible loading was evaporated. The south evaporator deposited a total of 41.55 g, giving a total lithium inventory of 90.35 g to 98.35 g. Note that much of the introduced lithium had been in LTX for months, and much of the lithium may have been passivated.

One way to assess the level of lithium passivation is to examine the effect of lithium deposition on peak plasma currents. Plasmas were created on September 13, 2012, when the most recent lithium evaporation had been 14 days prior, and there was no additional deposition. The last shot of the September 13, 2012 run day had the same field coil and gas pulse programming as the first shot of the September 14, 2012 run day (but not shots later in the day, which are analyzed
in \textsc{transp}). This allows for a fairly direct comparison of plasma currents, which is shown in Figure 4.20. Note that the peak current for the shot with the one-side evaporation is 18\% higher than the peak current for the 14 day passivated lithium run with little change in plasma duration (30 ms versus 28 ms). This demonstrates that even though the evaporation was not as large as the November 8, 2011 evaporation, and was asymmetric, the lithium deposition had some benefit for plasma performance. Additionally, considering that plasmas with fully passivated lithium exhibit peak plasma currents similar to the bare stainless steel wall cases ($\leq 15$ kA), the lithium should not be considered fully passivated on September 13, 2012. This could be due to the relatively large lithium inventory in LTX coupled with efforts to eliminate vacuum vessel leaks.

A series of 15 shots with the same coil current and fuel programming was repeated, and the Thomson laser firing time was varied. Fueling for the discharge was from a series of SGI pulses with a backing pressure of 22 psia. $T_e$ and $n_e$ profiles are available at four points in time near
Figure 4.20: A comparison of $I_p$ signals for the same shot programming for 14 day passivated lithium (1209131646) and the one-side evaporation (1209141413).
the peak plasma current, with multiple measurements for some time points. The base LTX shot number for the series is 1209141619, which maps to TRANSP run number 105989. The plasma current, loop voltage, and fueling pulses for shot 1209141619 are shown in Figure 4.21. This shot series has similar peak currents to the November 8, 2011 shot series, but lower loop voltages. This is because in the latter portion of 2012, the Ohmic capacitor bank was being run with different pulse width modulation programming and also had been reconfigured with an additional coil in series with the output to increase the overall inductance of the circuit, thereby lengthening the time during which \( V_{\text{loop}} > 0 \), which resulted in longer discharges (the 1111081819 discharge was \( \sim 14 \) ms long, while the 1209141619 discharge was \( \sim 27 \) ms long). Note that the longer fueling pulse from 454 ms to 457 ms enabled good Thomson measurements by increasing the plasma density. The plasma species is hydrogen.

At 457 ms and 458 ms, several Thomson profiles are available, and only one Thomson profile is available at 456 ms and 459 ms. Shots with the most similar \( I_p \) traces are selected, as shown in Figure 4.22. LTX shot numbers for Thomson profiles used for the TRANSP run are summarized in Table 4.5. Fitted and smoothed \( T_e \) and \( n_e \) profiles are shown in Figures 4.23 and 4.24. The smoothing parameter is chosen to be \( S = N - \sqrt{2N} \), where \( N \) is the number of measurement points per profile. This is a slightly lower level of smoothing than the previously discussed shot series, mainly because the raw profiles were a bit smoother initially. No interferometer data is available for this shot series, but the electron density as measured by Thomson scattering is scaled using the factor determined in Section 3.7.5. As time progresses, \( n_e \) increases due to the SGI fueling pulse. There are slight delays in the valve response to the fueling pulse, which explains the delayed rise in plasma density. The spatial position of peak \( T_e \) moves inward over time.

Good LRDFIT reconstructions of shot 1209141619 are available at 457 ms, 458 ms, and 459 ms. These reconstructions were constrained by flux loop signals only. Flux surfaces for the reconstructions are shown in Figure 4.25. Note that the reconstructed plasma is centered slightly below midplane, and almost fills the shell volume. Better centering of these plasmas in comparison
Figure 4.21: Shot 1209141619 plasma current, loop voltage, and fueling. The noise spike between 456 ms and 457 ms is due to the Thomson laser firing, and the noise spike between 471 ms to 472 ms is due to the disruption that terminates the discharge. There was an additional 2.1 ms pre-fueling SGI fueling pulse starting at 410.1 ms. Vertical purple lines indicate the times of Thomson data collection.
CHAPTER 4. RESULTS

Figure 4.22: Plasma currents for the 1209141619 shot series. Noise spikes are due to the Thomson laser capacitor banks and Pockels cell firing. Shots which have the most similar plasma currents are selected: 1209141634, 1209141629, 12091416722, and 1209141738.

<table>
<thead>
<tr>
<th>Shot</th>
<th>$t_{TS}$ [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1209141634</td>
<td>456.00</td>
</tr>
<tr>
<td>1209141629</td>
<td>457.00</td>
</tr>
<tr>
<td>12091416722</td>
<td>458.00</td>
</tr>
<tr>
<td>1209141738</td>
<td>459.00</td>
</tr>
</tbody>
</table>

Table 4.5: LTX shot numbers for Thomson profiles used for TRANSP run 105989.
Figure 4.23: Fitted and smoothed $T_e$ profiles for the 1209141619 shot series.
Figure 4.24: Fitted and smoothed $n_e$ profiles for the 1209141619 shot series.
to the 11111081819 plasmas can be attributed to configuring the orange poloidal field coils to be separately powered, allowing easier adjustment of plasmas vertical position. Assuming that the reconstruction is representative of the actual plasma position, this means that the Thomson scattering data for the shot series covers the entire minor radius. Experimental $I_p$, $V_{\text{loop}}$, and $R B_T$ values are taken from shot 1209141619.

As a base case, TRANSP is run using LRDFIT reconstructions with smoothed Thomson data, but with no estimate of the radiation power profile. Passive CHERS $T_i$ measurements (D. Boyle, personal communication, October 30, 2013) are again compared to values predicted by TRANSP in Figure 4.26. For this case, an inversion of the chord-integrated CHERS measurements was possible (R. Bell, personal communication, February 4, 2014). A spline fit to the chord-integrated $T_i$ is used in the inversion. However, as good measurements do not extend to the plasma edge, the inversion is highly uncertain, and is included only for comparison. As in the previously analyzed shot series, agreement between the measured and calculated $T_i$ is quite good.

Additionally, the total stored energy and energy confinement time as calculated by TRANSP are compared to independent calculations using the compensated diamagnetic loop in Figure 4.27.
Figure 4.26: A comparison of the Thomson $T_e$, CHERS chord-integrated $T_i$, and $T_i$ from TRANSP at 458 ms and 459 ms for the 1209141619 shot series. Note that CHERS data is collected over a 2 ms duration centered at 458.752 ms.
Figure 4.27: (a) $W_{\text{kin}}$ and (b) $\tau_E$ from TRANSP in green and the compensated diamagnetic loop in black for the 1209141619 shot series. Uncertainty in TRANSP results are calculated using runs with high and low uncertainties in $n_e$.

Here the circular plasma limit is used for diamagnetic loop calculations. Both $W_{\text{kin}}$ and $\tau_E$ exhibit good agreement with diamagnetic loop data. This, coupled with the good agreement of $T_i$ values, suggests that the assumptions used in TRANSP analysis are reasonable.

Again, a set of 10 Monte Carlo runs are used to incorporate uncertainty in $T_e$ measurements into the no-radiation case $\chi_e$ calculation. Values of $\chi$ from the analysis are shown in Figure 4.28.

As in the previous shot series, the ion transport levels are near neoclassical, with electron transport levels above ion levels, rising strongly from the core to the edge. Note that at 457 ms, the variation in the gradient resulting from the relatively large uncertainty of the temperature measurement at 0.517 m produces large uncertainty in $\chi_e$. However, better Thomson measurements at later times result in lower levels of relative uncertainty in $\chi_e$. In the 459 ms case, the level of transport near the edge is difficult to constrain. A closer plot of $\chi_e$ at 458 ms is displayed in Figure 4.29. With no value for $p_{\text{rad}}$, these runs represent an upper limit on $\chi_e$.

The base run is repeated using a calculated $p_{\text{rad}}$ profile, assuming carbon as the only impurity species for both $Z_{\text{eff}} = 1.2$ and $Z_{\text{eff}} = 2.4$ and Thomson data as inputs. The calculated $p_{\text{rad}}$ profiles are shown in Figure 4.30. The predicted level of $p_{\text{rad}}$ is low enough as to not significantly affect the
Figure 4.28: Thermal diffusivity results for the no-radiation power profile case for the 1209141619 shot series. $\chi_e$ is in green, $\chi_i$ is in red, and $\chi_{l,\text{neo}}$ is in blue. The standard uncertainty in the mean is displayed using the colored bands. For $\chi_i$, the width of the line is larger than the uncertainty.
Figure 4.29: Thermal diffusivity results for the no-radiation power profile case for the 1209141619 shot series at 458 ms. $\chi_e$ is in green, $\chi_i$ is in red, and $\chi_{i,\text{neo}}$ is in blue. The standard uncertainty in the mean is displayed using the colored bands. For $\chi_i$, the width of the line is larger than the uncertainty.
level of electron transport. A comparison of the no-radiation case with calculated radiation cases is shown in Figure 4.31. Even assuming $Z_{\text{eff}} = 2.4$, $\chi_e$ only drops less than 1%. The calculated $p_{\text{rad}}$ levels are much less than the Ohmic heating profiles $p_{\text{OH}}$, shown in Figure 4.32. The radiation power term in the electron power balance equation is then only a small correction in the calculation of $\chi_e$ and should affect the results much.

To further assess how radiation power levels affect transport levels, a series of runs (without Monte Carlo analysis) is performed using flat $p_{\text{rad}}$ both spatially and temporally. Results of the scan are shown in Figure 4.33. For levels below $10^4$ W/m$^3$, $\chi_e$ changes of no more than 10% are produced. For higher levels, the calculated level of transport begins to drop sharply. At $7.5 \times 10^4$ W/m$^3$, $\chi_e$ is still positive, but at $10^5$ W/m$^3$, $\chi_e$ becomes negative in the edge. The change in the shape of $\chi_e/\chi_e,\text{base}$ from the previous analysis is mainly due to a change in the shape of the calculated $p_{\text{OH}}$ profile.

As noted previously, the TRANSP input impurity $Z_{\text{eff}}$ is assumed to be 1.2 in accordance with the CDX-U measurement for lithium-walled plasmas. A parameter scan of $Z_{\text{eff}}$ is performed to assess the change in $\chi_e$. Figure 4.34 shows the results of the scan. Electron thermal diffusivities increase with $Z_{\text{eff}}$. For $Z_{\text{eff}} = 2.4$, the no-lithium level from CDX-U, $\chi_e$ is about 20% higher in the core and 6% higher in the edge. A similar scan varying the assumed impurity species is also performed. Oxygen (mass number $A = 16$, atomic number $Z = 8$) and lithium ($A = 7$, $Z = 3$) are assumed, and $Z_{\text{eff}}$ is set to either 1.2 or 2.4. Results are shown in Figure 4.35. For $Z_{\text{eff}} = 1.2$, changes are small, regardless of the impurity species. Larger $Z_{\text{eff}}$ results in higher $\chi_e$, particularly in the lithium case, where the core value is 32% higher.

To assess sensitivity on the reconstructed equilibrium, a CHEASE equilibrium is created with $R_0$, $Z_0$, $a$, $\kappa$, and $\delta$ taken from the LRDFIT reconstruction at each time ($\delta$ is taken as the mean of the upper and lower triangularity to create a vertically symmetric equilibrium). The electron thermal diffusivity profile at 458 ms calculated for the LRDFIT and CHEASE equilibria is shown in Figure 4.36. When plotted as a function of $R$, the two calculated $\chi_e$ profiles show discrepancies.
Figure 4.30: Calculated radiation power profiles assuming carbon as the impurity species for 
$Z_{\text{eff}} = 1.2$ and $Z_{\text{eff}} = 2.4$ for the 1209141619 shot series.
Figure 4.31: \( \chi_e \) results for calculated radiation power profiles for the 1209141619 shot series assuming \( Z_{\text{eff}} = 1.2 \) and \( Z_{\text{eff}} = 2.4 \), normalized to the no-radiation case \( \chi_{e,\text{base}} \) at 458 ms.
Figure 4.32: Ohmic heating profile calculated by TRANSP for the 1209141619 shot series at 458 ms.
Figure 4.33: $\chi_e$ normalized to the no-radiation case $\chi_{e,\text{base}}$ at 458 ms for several levels of flat $p_{\text{rad}}$ profiles for the 1209141619 shot series.
Figure 4.34: $\chi_e$ normalized to the base case $\chi_{e,\text{base}}$ at 458 ms for several levels of $Z_{\text{eff}}$ for the 1209141619 shot series.
Figure 4.35: $\chi_e$ normalized to the no-radiation case $\chi_{e,\text{base}}$ at 458 ms for alternate assumed impurity species for the 1209141619 shot series.
Figure 4.36: A comparison of $\chi_e$ calculated using the LRDFIT reconstruction and an ideal CHEASE equilibrium based off the reconstructed parameters as a function of (a) $R$ and (b) $\sqrt{\Phi/\Phi_{\text{lim}}}$ at 458 ms for the 1209141619 shot series.

However, much of the difference is due to flux surface mapping, as is evident in plots as a function of the TRANSP $x = \sqrt{\Phi/\Phi_{\text{lim}}}$ variable. While the geometrical center of these LRDFIT and CHEASE equilibria are the same, they have different Shafranov shifts, which change where the plasma axis is located. This affects calculations such as the Ohmic heating profile, which slightly changes the resulting $\chi_e$. This mainly affects how $\chi_e$ is mapped in the core but not much at mid-$r/a$.

Sensitivity analysis of $n_e$ uncertainties is performed in the same manner as previously described. The $n_e$ profiles for the base, high, and low cases is shown in Figure 4.37 as are the changes in $\chi_e$. The relative uncertainty in $n_e$ is a bit higher in this shot series than the first, resulting in slightly more change in $\chi_e$. The low $n_e$ case (which has a mean $n_e$ 0.59 times the base) results in $\chi_e$ with a mean value 2.17 times of the base case. The high $n_e$ case (which has a mean $n_e$ 1.38 times the base) results in $\chi_e$ with a mean value 0.52 times the base case.
Figure 4.37: (a) $n_e$ used for base, low, and high uncertainties and (b) $\chi_e$ normalized to the base case $\chi_{e,\text{base}}$ at 458 ms for high and low uncertainties for the 1209141619 shot series.

### 4.4 Conclusions

This study is the first to perform TRANSP simulations of LTX plasmas. TRANSP allowed determination of quantities unavailable through experimental measurements, and facilitated interpretive modeling of LTX discharges. Techniques identified here were used to produce TRANSP analysis that led to the first determination of $\chi_e$ in LTX or CDX-U based on measurements of plasmas with low-recycling lithium wall coatings. While experimental radiation pressure profile measurements were unavailable, estimates were used to constrain the change in transport based on sensitivity studies using model data. Agreement between passive CHERS chord-integrated $T_i$ measurements and TRANSP neoclassical $T_i$ calculations suggests that ions in LTX may behave neoclassically. Additionally, compensated diamagnetic loop $\tau_E$ and $W_{\text{kin}}$ measurements agree with corresponding TRANSP calculations and suggest that assumptions used in TRANSP analysis are reasonable.

The electron thermal diffusivity of two shot series with different $V_{\text{loop}}$ programming, fueling, and lithium deposition was calculated using TRANSP. A comparison of the $\chi_e$ results for the two shot series is shown in Figure 4.38. For this comparison, the no-radiation Monte Carlo cases are used, and the comparison is made in flux coordinates, since the two plasmas had different locations...
and sizes. Note that TRANSP analysis has difficulty calculating $\chi_e$ near the core as $dT_e/dr$ is not well-defined, and values beyond $\sqrt{\Phi/\Phi_{\text{lim}}} = 0.85$ are probably not realistic due to difficulties measuring the electron temperature gradient in the edge. $\chi_e$ near $\sqrt{\Phi/\Phi_{\text{lim}}} = 0.6$ is higher for the 1111081819 series, but is similar at $\sqrt{\Phi/\Phi_{\text{lim}}} = 0.3$ and $\sqrt{\Phi/\Phi_{\text{lim}}} = 0.45$. A similar comparison of the mean $\chi_e$ as a function of time for several values of $\sqrt{\Phi/\Phi_{\text{lim}}}$ is shown in Figure 4.39. Note that the 1111081819 data has lower transport toward the core at earlier times, which rises at later times. Transport at $\sqrt{\Phi/\Phi_{\text{lim}}}$ of 0.4 and 0.5 is generally lower for 1111081819. Results at $\sqrt{\Phi/\Phi_{\text{lim}}}$ of 0.6 and 0.7 vary for the 1111081819 shot series quite a bit, but are at about the same level as the 1209141619 shot series. For $\sqrt{\Phi/\Phi_{\text{lim}}}$ of 0.8, $\chi_e$ seems lower for the 1209141619 series.

As previously shown, global confinement times are calculated to be about 0.4 ms for the 1111081819 series at 449.5 ms, and 1.1 ms for the 1209141619 series at 458.0 ms. Note that the 1111081819 series has a current peak around $t = 450.0$ ms, which has $\tau_E$ of about 0.4 ms. $W_{\text{kin}}$ is near 60 J in those cases. The current peak for 1209141619 is at about 456.5 ms. $\tau_E$ at 457.0 ms is about 0.8 ms, and the stored energy is about 45 J. As is discussed in more detail later, the Ohmic heating power is about a factor of 2.4 larger in the 1111081819 case.

The run day with relatively heavy full shell lithium evaporation (November 8, 2011) had between 4.2 g and 4.3 g of fresh lithium deposition on top of what had been deposited the previous day, for a total lithium inventory of 8.7 g to 8.9 g. In contrast, the run day with relatively light partial shell lithium evaporation (September 14, 2012) had an evaporation on only one side of the vessel, with much less lithium deposition (estimated to be less than 100 mg if thermocouple readings were correct). The total lithium inventory in LTX for the run was between 90.35 g and 98.35 g. Much of the lithium had been in the vessel for months and the most recent evaporation took place 15 days earlier, but passivation of the lithium was only partial after that time span.

Another important difference between the run days is the $V_{\text{surf}}$ level. As mentioned previously, in the latter portion of 2012, the Ohmic power supply was reconfigured such that the output was in
Figure 4.38: A comparison of $\chi_e$ for the 1111081819 shot series at 449.5 ms and the 1209141619 shot series at 458.0 ms. Lines represent mean values and high and low uncertainties in the mean from previously-shown Monte Carlo analysis of measured $T_e$ uncertainties.

Figure 4.39: A comparison of mean $\chi_e$ for the 1111081819 shot series and the 1209141619 shot series for the base case (a) without and (b) with Monte Carlo analysis. Data displayed is $\chi_e$ as a function of time for several $\sqrt{\Phi/\Phi_{lim}}$ for both shot series.
series with an additional inductive coil. This facilitated longer pulse durations as the coil current ramp was slowed, lowering $V_{\text{surf}}$ and also the rate at which the Ohmic power supply’s energy was depleted, facilitating longer pulse durations. For the times analyzed of the 1111081819 shot series (449.0 ms to 451.5 ms), $V_{\text{surf}}$ ranged from 3.01 V to 2.25 V (decreasing in time). For comparison, the 1209141619 shot series (from 457.0 ms to 459.0 ms) had $V_{\text{surf}}$ from 1.45 V to 1.15 V (decreasing in time as well). Plasma currents were a bit higher on the 1111081819 shot series: 52.3 kA rising to 54.4 kA then dropping to 52.9 kA, whereas the 1209141619 shot series had $I_P$ dropping from 46.0 kA to 41.8 kA. The overall plasma conductance $G_P = I_P/V_{\text{surf}}$ can be calculated. For shot 1111081819, $G_P$ was initially $17.4 \times 10^3 \Omega^{-1}$ and rose to $23.5 \times 10^3 \Omega^{-1}$. Shot 1209141619 had higher $G_P$ at the analyzed times: initially $31.7 \times 10^3 \Omega^{-1}$ rising to $36.5 \times 10^3 \Omega^{-1}$. Another effect of higher $V_{\text{surf}}$ for the 1111081819 shot was higher Ohmic heating levels: for 1111081819 at 449.5 ms, $P_{\text{OH}} = 154$ kW, whereas for 1209141619 at 458.0 ms, $P_{\text{OH}} = 66.2$ kW.

Coil currents for the two shot series analyzed here are shown in Figure 4.40. The relatively light partial shell lithium evaporation run day (1209141619) had better-developed PF coil programming, which resulted in more vertically centered plasmas than the relatively heavy full shell lithium evaporation run day (1111081819). This was partially due to a reconfiguration of power supply and coil connections such that the top and bottom orange poloidal field coils were independently controlled. This allowed the plasma position to be examined shot-to-shot using fast camera images and adjusted accordingly until the plasma was sufficiently vertically centered. The TF levels were identical, but PF coil currents were all different. Note that changing the manner in which the Ohmic bank was operated required redeveloping shot programming to allow breakdown. The green coil currents are particularly necessary to cancel eddy currents in the vessel generated by the Ohmic solenoid, and the yellow coils are used to create a vertical field null. The yellow coils were not used on the 1111081819 shot series, which was able to create a vertical field null using a combination of other coils. The internal coils have faster response than other PF coils used to create the main vertical field, such as the red and blue, and were used to quickly ramp up the vertical field after
breakdown for the 1111081819 shot series. The 1111081819 shot series had larger currents in both
the red and blue coil sets. Note that plasmas for the 1111081819 shot series were more inboard
than the 1209141619 shot series ($R_0 = 0.388$ m for 1111081819 from the model equilibrium, and
$R_0 = 0.424$ m for 1209141619 at 458.0 ms from the LRDFIT reconstruction). Note also that the
1111081819 shot series had stronger fueling from the cryogenic MCI with a backing pressure of
100 psia, whereas the 1209141619 shot series had SGI fueling with a backing pressure of 22 psia.

The two analyzed discharges have similar $\chi_e$ levels. The similarity could indicate that lithium
conditions were not significantly different between the two run days, despite a difference in the
level of freshly evaporated lithium. The September 13, 2012 run exhibited a lack of complete
lithium passivation despite a 14 day period since the most recent lithium evaporation. This suggests
that total lithium inventory and passivation levels should also be considered in addition to fresh
lithium deposition levels. Additionally, there are geometrical differences between the plasmas that
could affect confinement. The 1209141619 series had a higher elongation ($\kappa \approx 1.55$) than the
1111081819 series ($\kappa \approx 1.30$). Higher elongation has been shown to increase confinement in
Ohmic L-mode plasmas [119]. However, the difference in plasma currents and loop voltage levels
at the time of analysis prevents direct comparisons. Further studies could elucidate the effects of
lithium PFC conditions on confinement and transport.

Comparisons of LTX results can be made to electron thermal diffusivity measurements from
other spherical tokamaks. Analysis of Small Tight Aspect Ratio Tokamak (START) plasmas found
$\chi_e$ to be $20 \text{ m}^2/\text{s} - 30 \text{ m}^2/\text{s}$ in the core. $\chi_i$ ranged from about $5 \text{ m}^2/\text{s}$ to $13 \text{ m}^2/\text{s}$, in good agreement
with neoclassical calculations using Chang-Hinton formulas [113].

Measurements of $\chi_e$ in CDX-U were performed using perturbation techniques. Perturbation
experiments using gas fueling pulses found $\chi_e$ to range from $2.2 \text{ m}^2/\text{s}$ to $2.6 \text{ m}^2/\text{s}$ from $r/a = 0.33$
to $r/a = 0.36$. Results using sawteeth resulted in core $\chi_e$ values ranging from $0.8 \text{ m}^2/\text{s}$ to $2.2 \text{ m}^2/\text{s}$.
These values were estimated to be from 5 to 10 times neoclassical values [103]. Note that the
Figure 4.40: A comparison of PF and TF currents for the 1111081819 (top) and 1209141619 (bottom) shot series.
perturbative technique is less sensitive to values such as the Ohmic power and radiation power profiles. The plasmas analyzed on CDX-U did not have lithium-coated PFCs.

In NSTX, TRANSPP analysis of plasmas with neutral beam injection found an upper limit of $\chi_e$ as low as 6 m$^2$/s (as radiation power profiles were unavailable). Heating with a high-harmonic fast-wave system produced values of 8 m$^2$/s in the core, which increased up to near 100 m$^2$/s in the edge [120]. A later study by Kaye et al. used TRANSPP analysis of NSTX discharges to find $\chi_e$ up to $\sim$ 50 m$^2$/s near $r/a = 0.25$ for high $B_T$ discharges, which lowered to $\sim$ 7 m$^2$/s for low $B_T$ discharges. $\chi_e$ past $r/a = 0.5$ was much lower and decreased with $B_T$ due to $T_e$ flattening. The study also found that ion transport in NSTX was often near neoclassical levels [114]. A recent study revealed that $\chi_e$ depended on dimensionless collisionality. Collisionality could be lowered by increasing overall between-shot lithium deposition, which then broadened the $T_e$ profile and reduced $\chi_e$. At $\sqrt{\Phi/\Phi_{lim}} = 0.7$, $\chi_e$ decreased from 20 m$^2$/s to 0.7 m$^2$/s with increasing between-shot lithium deposition, while $\chi_i$ increased [121].

To facilitate broader comparisons of $\chi_e$ to other experimental results, various calculations of the neoclassical electron thermal conductivity $\chi_{e,\text{neo}}$ are shown in Figure 4.41. The formulations of Angioni and Sauter [122] are valid over arbitrary collisionality and aspect ratio and are probably the most accurate comparison. For consistency, TRANSPP calculations of the trapped particle fractions $f_t$, dimensionless electron collisionality $\nu_e^*$, and magnetic averages $\langle B^2 \rangle$ and $\langle B^{-2} \rangle$ are used to evaluate these formulations. Additional comparisons are made to formulations used by the BALDUR code [123], Merezhkin et al. [124], and the banana regime coefficient given by Wesson [8]. As can be seen in Figure 4.41, $\chi_{e,\text{neo}}$ calculations can vary significantly among models, but $\chi_e$ is generally much higher than the neoclassical value. A comparison of the two series results normalized to the $\chi_{e,\text{neo}}$ value using the Angioni and Sauter formulation is shown in Figures 4.42 and 4.43. Clearly, electron transport is anomalous for both shot series.
A model for anomalous transport driven by the electron temperature gradient (ETG) \[125\] predicts
\[
\chi_e = 0.1 \frac{c^2 \tilde{s} v_e}{\omega_{pe}^2 q R} \eta_e (1 + \eta_e)
\]
where \(\tilde{s} = (r/q)(dq/dr)\), \(\omega_{pe}\) is the electron plasma frequency, \(v_e\) is the electron thermal velocity, and \(\eta_e = (d(\ln T_e)/dr)/(d(\ln n_e)/dr)\). TRANSP runs include a calculation of this model \(\chi_e\), which allows for comparisons to the analyzed \(\chi_e\) as shown in Figure 4.44. The predicted transport levels are mainly dependent on \(\eta_e\) as shown in Figure 4.45. For both analyzed plasmas, the ETG model transport levels are lower than the analyzed \(\chi_e\), except toward the edge. A second comparison is made to the LAG model for Ohmic L-mode plasmas that includes displacement of trapped particles by banana widths \[126, 127\]. The LAG model electron thermal diffusivity is
\[
\chi_e = 0.33 v_i \left( \frac{T_e}{T_i} \right)^{3/2} \left( \frac{\rho_i R_{\max}}{R_0 \epsilon} \right)^2 \frac{q}{\kappa R_0 f^4}
\]
where \(v_i\) is the ion thermal velocity, \(\rho_i\) is the ion gyroradius, and \(R_{\max}\) is the outermost major radius of each flux surface. Plasmas on START had electron transport in good agreement with predictions by the LAG model \[113\]. The LAG model predicts transport on the 1111081819 series reasonably well close to the core, but not at larger radii. The 1209141619 series has LAG \(\chi_e\) lower than analyzed \(\chi_e\) levels. Note that CDX-U transport levels did not agree with LAG model predictions \[103\].
Figure 4.41: Comparisons of $\chi_e$ to $\chi_{e,neo}$ and $\chi_{i,neo}$ for the (a) 1111081819 series at 449.5 ms and the (b) 1209141619 series at 458 ms.

Figure 4.42: A comparison of $\chi_e$ for the 1111081819 shot series at 449.5 ms and the 1209141619 shot series at 458.0 ms normalized to $\chi_{e,neo}$. Lines represent mean values and high and low uncertainties in the mean from previously shown Monte Carlo analysis of measured $T_e$ uncertainties.
Figure 4.43: A comparison of $\chi_e$ for the 1111081819 shot series and the 1209141619 shot series for the base case (a) without and (b) with Monte Carlo analysis, normalized to $\chi_e$. Data is displayed as a function of time for several $\sqrt{\Phi/\Phi_{\text{lim}}}$ for both shot series.

Figure 4.44: Comparisons of $\chi_e$ to model predictions for the (a) 1111081819 series at 449.5 ms and the (b) 1209141619 series at 458 ms.
Figure 4.45: Comparisons of (a) $T_e$ and (b) $\eta_e$ for the 1111081819 series at 449.5 ms and the 1209141619 series at 458 ms.
Chapter 5

Conclusions and Future Work

A Thomson scattering diagnostic was developed and used to measure $T_e$ and $n_e$ profiles of hydrogen plasmas in a spherical tokamak with solid lithium PFC coatings on PFCs conformal to the design LCFS. Measurements of lithium PFC plasmas showed peak $T_e$ values can reach the 150 eV range with peak $n_e$ values up to $1.5 \times 10^{19}$ m$^{-3}$.

TRANSP simulations of LTX plasmas were performed using composite Thomson profiles of repeated plasma discharges. Lacking localized $T_i$ measurements, techniques were developed to allow calculation of $T_i$. Ions were treated neoclassically, and simulations produced $T_i$ in line with passive CHERS measurements. The resulting $\chi_i$ was close to neoclassical predictions, as was seen in START and NSTX. This result suggests ions in LTX behave neoclassically. Good agreement was also found between independent compensated diamagnetic loop $\tau_E$ and $W_{\text{kin}}$ measurements and TRANSP results. This result validates the technique of using magnetic analysis to measure confinement times, which found enhanced confinement on CDX-U plasmas in the low-recycling regime [44].

These simulations were used to measure $\chi_e$ in the range of 7 m$^2$/s at $\sqrt{\Phi/\Phi_{\text{lim}}} = 0.3$ which rose to near 100 m$^2$/s at $\sqrt{\Phi/\Phi_{\text{lim}}} = 0.7$ for plasmas with between 4.2 g and 4.3 g of fresh lithium deposition. A plasma with less ($\leq 100$ mg) fresh lithium deposition, but a larger overall lithium
inventory, better-controlled PF waveforms, lower $V_{\text{loop}}$ levels resulted in $\chi_e$ in the range of 20 m$^2$/s at $\sqrt{\Phi}/\Phi_{\text{lim}} = 0.3$, and 80 m$^2$/s to 90 m$^2$/s at $\sqrt{\Phi}/\Phi_{\text{lim}} = 0.7$. The electron thermal diffusivities are anomalous, with $\chi_e/\chi_e,\text{neo}$ reaching as high as $\sim 300$.

Note that measurements by Granstedt [84] found that the core recycling coefficient $R_{\text{core}}$ was 0.554 to 0.820 for fresh lithium and 0.599 to 0.762 for partially passivated lithium for plasmas very similar to the November 8, 2011 discharges. The plate recycling coefficient $R_{\text{plate}}$ was 0.779 to 0.94 for fresh lithium and 0.599 to 0.762 for partially passivated lithium. The effective particle confinement time, $\tau_p^*$ is lower for fresh lithium than partially passivated lithium (0.97 ms to 1.65 ms versus 1.12 ms to 2.44 ms).

Electron temperature and density gradient measurements could be further constrained with the addition of more spatial channels to the Thomson diagnostic. The existing viewing optics fiber groove allows 25 possible viewing locations, of which only 11 are imaged in the spectrometer. An additional spectrometer and CCD in a similar setup to the existing system would expand the spatial resolution of the system.

Currently in progress is the installation and commissioning of an edge Thomson diagnostic. The system will use the same ruby laser beam line as the core Thomson system, but with separate collection optics on an angled view on the beam entrance flange. Measurement points will be grouped at approximately $R = 65$ cm with 5 mm spatial resolution. An $f = 35$ cm lens will focus light onto 1 mm diameter (900 $\mu$m cladding, 800 $\mu$m core) fibers. The light will then be imaged into five polychromators designed by General Atomics. As summarized in Table 5.1, four spectral filters will sample the scattered light spectra. Light will then be imaged into avalanche

<table>
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<tr>
<th>Central Wavelength [nm]</th>
<th>Transmission FWHM [nm]</th>
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<tr>
<td>699.8 ± 0.6</td>
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<td>707.8 ± 0.9</td>
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<tr>
<td>734.3 ± 1.5</td>
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Table 5.1: Filter set used in LTX edge Thomson polychromators.
photodiodes coupled to transimpedance amplifiers. Data will be acquired in four Costruzioni Apparrecchiature Elettroniche Nucleari S.p.A. (CAEN) V1720 digitizers operating at 250 MS/s. This allows light collection before, during, and after a laser pulse, which enables simple background light subtraction.

This system offers several advantages over the core Thomson spectrometer and CCD system. It is much more sensitive to light, and can thus measure at lower densities as found in the plasma edge. Each channel will use a single polychromator with a set of filters and amplifiers, and thus will be modular and expandable. Fibers from the current viewing optics can be imaged in the polychromators, providing comparisons of measurements between the two systems.

LTX has a larger set of diagnostics than when the data used for this analysis was acquired. A fixed midplane interferometer, reflectometer, and an enhanced magnetics diagnostic set have been recently added. A planned neutral beam will allow active CHERS measurements of ion temperatures. Experiments similar to those discussed here could be repeated to yield more confident results. If possible, a bolometer array should be developed that can view from the plasma core to the edge in order to produce radiation power profiles.

The need for reliable magnetic reconstructions remains. Without them, it is difficult to perform many types of analysis. To aid this, an enhanced Mirnov coil set has been added to LTX. Concurrently, there are efforts to perform three-dimensional reconstructions, which may be necessary given intrinsic asymmetries in the shell configuration.

Another challenge is determining coil programming and operation of the Ohmic power supply that will allow longer plasma current flat-top times. Recently the Ohmic power supply was reconfigured so that all IGBTs fire simultaneously, which reduces the risk of transient voltages becoming too high and damaging hardware, thereby allowing more aggressive pulse width modulation. Longer flat-top times could facilitate magnetic reconstructions as eddy currents are allowed to decay.
LTX has the capability for feedback control of poloidal field currents. While it will take effort to configure the digitizer to operate in a feedback mode, this could result in well-centered and more reproducible plasmas. Additionally, there is work to be done to develop fueling techniques that keep the density roughly constant in the presence of lithium-coated PFCs with strong wall pumping. The recently-added high field side puffer could be useful for this purpose.

There is a large remaining parameter space to study on LTX. To date, only hydrogen plasmas have been produced; deuterium could be used as to vary ion mass for confinement studies. Furthermore, an upcoming TF upgrade will allow a wider range of toroidal fields in LTX. This will allow a wider range of parameters that should affect local transport and global confinement.

Finally, further studies of lithium PFC wall conditions will continue with a focus on plasmas with a liquid lithium reservoir stirred by an electron beam between discharges. This will eliminate slow passivation of the lithium in the time between deposition and plasma formation, which in this work has been on the scale of a few hours. Studies similar to those on NSTX, in which the lithium deposition between shots was varied, could be easily performed. A liquid lithium reservoir will produce conditions more similar to a possible liquid lithium wall reactor, which may someday become a reality.
Appendix A

Thomson Scattering

Following Sheffield [128], assume an incident planar monochromatic wave with an electric field

$$ E_i = E_{i0} \cos (k_i \cdot r - \omega_i t) \tag{A.1} $$

where $k_i$ is the incident wavevector propagating in the $\hat{i}$ direction, $r$ is the spatial position, and $\omega_i$ is the incident angular frequency. The magnetic field of the incident wave is

$$ B_i = \frac{1}{c} \hat{i} \times E_i. \tag{A.2} $$

The electric field resulting from the scattering of the incident wave on a particle of charge $q$ and mass $m$ is given by

$$ E_s = \frac{q}{4\pi \epsilon_0} \left[ \frac{(\hat{s} - \frac{\hat{v}}{c}) \left( 1 - \frac{v^2}{c^2} \right)}{(1 - \frac{\hat{s} \cdot \hat{v}}{c})^3 R'^2} \right]_{\text{ret}} + \frac{q}{4\pi \epsilon_0 c} \left[ \hat{s} \times \left( (\hat{s} - \frac{\hat{v}}{c}) \times \frac{1}{c} \frac{d\hat{v}}{dt'} \right) \right]_{\text{ret}} \tag{A.3} $$
where $R'$ is the distance from the observer to the charge at time $t'$, $\hat{s}$ is the direction of scattering, and ret denotes evaluation at the retarded time [129]. The retarded time is defined as

$$t' = t - \frac{R'}{c}$$  \hspace{1cm} (A.4)

which is approximately equal to

$$t' \approx t - \frac{|R - \hat{s} \cdot r(0)|}{c}$$  \hspace{1cm} (A.5)

where $R$ is the distance to the object at time $t$. In the nonrelativistic limit ($v \ll c$), Equation [A.3] reduces to

$$E_s = \frac{q}{4\pi\varepsilon_0 c^2 R} \hat{s} \times \left( \hat{s} \times \frac{dv}{dt} \right).$$  \hspace{1cm} (A.6)

With a force balance of

$$m \frac{dv}{dt} = qE_i$$  \hspace{1cm} (A.7)

Equation [A.6] becomes

$$E_s = \frac{q^2}{4\pi\varepsilon_0 mc^2 R} \hat{s} \times (\hat{s} \times E_i).$$  \hspace{1cm} (A.8)
Substituting in the form of the incident field from Equation A.1, the scattered electric field is then

\[ E_s = \frac{q^2}{4\pi\varepsilon_0 mc^2 R} \hat{s} \times (\hat{s} \times E_i(0)) \cos (k_i \cdot \mathbf{r}(t') - \omega_i t'). \]  

(A.9)

The Doppler shifted angular frequency is \( \omega_s = \omega_i + k \cdot \mathbf{v} \) with \( k = k_s - k_i \) where \( k_s \) is the scattered light vector and \( k_i \) is the incident light vector. Ignoring external fields, a particle undergoing motion has a position at the retarded time of approximately

\[ \mathbf{r}(t') = \mathbf{r}(0) + \mathbf{v} t'. \]  

(A.10)

Combining Equation A.10 and Equation A.5 gives

\[ t' = t - \frac{R}{c} + \frac{\hat{s} \mathbf{r}(0)}{c} \left( 1 - \frac{\hat{s} \mathbf{v}}{c} \right). \]  

(A.11)

The argument of the cosine in Equation A.9 can be simplified as

\[ k_i \cdot \mathbf{r}(t') - \omega_i t' = k_i \cdot \mathbf{r}(0) + \frac{(k_i \cdot \mathbf{v} - \omega_i) \left( t - \frac{R}{c} + \frac{\hat{s} \mathbf{r}(0)}{c} \right)}{1 - \frac{\hat{s} \mathbf{v}}{c}} = k_i \cdot \mathbf{r}(0) + \frac{\omega_i t \frac{\hat{s} \mathbf{v}}{c} - \omega_i \frac{\hat{s} \mathbf{r}(0)}{c} - k_i \frac{\hat{s} \mathbf{v}}{c} \cdot \mathbf{r}(0) - \omega_i R - \frac{\omega_i \hat{s} \cdot \mathbf{r}(0)}{c}}{1 - \frac{\hat{s} \mathbf{v}}{c}} = k_i \cdot \mathbf{r}(0) + \frac{k_i \mathbf{R} \left( 1 - \frac{\hat{s} \mathbf{v}}{c} \right) - \omega_i t \left( 1 - \frac{\hat{s} \mathbf{v}}{c} \right) - k_i \frac{\hat{s} \cdot \mathbf{r}(0) \left( 1 - \frac{\hat{s} \mathbf{v}}{c} \right)}{1 - \frac{\hat{s} \mathbf{v}}{c}}}{1 - \frac{\hat{s} \mathbf{v}}{c}} = k_i \mathbf{R} - \omega_i \frac{\hat{s} \cdot \mathbf{v}}{c} t - k_i \frac{\hat{s} \cdot \mathbf{r}(0)}{1 - \frac{\hat{s} \mathbf{v}}{c}} \cdot \mathbf{r}(0) + k_i \cdot \mathbf{r}(0) = k_s R - \omega_s t - (k_s - k_i) \cdot \mathbf{r}(0) = k_s R - \omega_s t - \mathbf{k} \cdot \mathbf{r}(0) \]  

(A.12)
where
\[ k_s = k_i \frac{1 - \frac{i \nu}{c}}{1 - \hat{s} \cdot \nu/c} \quad \text{(A.13)} \]
and
\[ \omega_s = \omega_i \frac{1 - \frac{i \nu}{c}}{1 - \hat{s} \cdot \nu/c} \quad \text{(A.14)} \]
resulting in the form
\[ E_s = \frac{q^2}{4 \pi \epsilon_0 mc^2 R} \hat{s} \times (\hat{s} \times E_{i0}) \cos (k_s R - \omega_s t - \mathbf{k} \cdot \mathbf{r}(0)). \quad \text{(A.15)} \]

The Poynting vector is
\[ \mathbf{S}_s = \epsilon_0 c E_s \times \mathbf{B}_s. \quad \text{(A.16)} \]

Since \( B_s = E_s/c \), and \( \mathbf{B}_s \) is perpendicular to \( E_s \) this reduces to
\[ S_s = \epsilon_0 c E_s^2. \quad \text{(A.17)} \]

The scattered power is proportional to the surface area multiplied by magnitude of the Poynting vector,
\[ P_s = R^2 S_s. \quad \text{(A.18)} \]

Combining Equations \[\text{A.15}\] \[\text{A.17}\] and \[\text{A.18}\] the scattered power in some solid angle \( d\Omega \) is
\[ P_s d\Omega = \epsilon_0 c E_{i0}^2 \left( \frac{q^2}{4 \pi \epsilon_0 mc^2} \right)^2 \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 \cos^2 \left( k_s R - \omega_s t - \mathbf{k} \cdot \mathbf{r}(0) \right) d\Omega. \quad \text{(A.19)} \]

As \( q^2/4\pi\epsilon_0 mc^2 \) is much larger for an electron than an ion, most of the scattered light will come from electrons. Ignoring the ions, this term is then replaced by the classical electron radius \( r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2} \), where \( e \) is the electron charge and \( m_e \) is the electron mass. Time-averaging the equation for scattered power gives
\langle P_s \rangle \, d\Omega = \frac{\epsilon_0 c E_i^2 r_e^2}{2} \left( \hat{s} \times \left( \hat{s} \times \hat{E}_i \right) \right)^2 \, d\Omega \quad (A.20)

as \langle \cos^2 x \rangle = 1/2. In terms of the incident power

\langle P_i \rangle = \frac{\epsilon_0 c E_{i0} r_e^2}{2} \quad (A.21)

Equation [A.19] becomes

\langle P_s \rangle \, d\Omega = \frac{\langle P_i \rangle r_e^2}{R^2} \left( \hat{s} \times \left( \hat{s} \times \hat{E}_i \right) \right)^2 \, d\Omega. \quad (A.22)

Generalizing for scattering off \( N_e \) electrons with some velocity distribution function \( f(v) \), the scattered power in some angular frequency range \( d\omega_s \) is

\langle P_s \rangle \, d\omega_s \, d\Omega = \frac{N_e \langle P_i \rangle r_e^2}{R^2} \left( \hat{s} \times \left( \hat{s} \times \hat{E}_i \right) \right)^2 \, d\omega_s \, d\Omega \times

\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(v) \delta(\omega_s - \omega_i - k \cdot v) \, dv_k \, dv_{k\perp} \, dv_{kT} \quad (A.23)

The velocity component \( v_k \) is in the same direction as \( k \), \( v_{k\perp} \) is perpendicular to \( k \) in the plane of \( \hat{s} \) and \( \hat{i} \), and \( v_{kT} \) is transverse to the plane of \( \hat{s} \) and \( \hat{i} \). The delta function accounts for the Doppler shift. By aligning the coordinate system properly, the integral simplifies the power to

\langle P_s \rangle \, d\omega_s \, d\Omega = \frac{N_e \langle P_i \rangle r_e^2}{R^2} \left( \hat{s} \times \left( \hat{s} \times \hat{E}_i \right) \right)^2 \frac{1}{k} \frac{1}{k} \int_{-\infty}^{+\infty} f \left( \frac{\omega_s - \omega_i}{k} \right) \, d\omega_s \, d\Omega. \quad (A.24)

Assuming a Maxwellian velocity distribution

\[ f(v) = \left( \frac{m_e}{2\pi T_e} \right)^{\frac{3}{2}} \exp \left( -\frac{m_e \left( v_k^2 + v_{k\perp}^2 + v_{kT}^2 \right)}{2T_e} \right) \] \quad (A.25)
the scattered power is

\[ \langle P_s \rangle \ d\omega_s \ d\Omega = \frac{N_e \langle P \rangle}{R^2} \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 \frac{1}{k} \sqrt{\frac{m_e}{2\pi T_e}} \exp \left( -\frac{m_e (\omega_s - \omega_i)^2}{2T_e k^2} \right) \ d\omega_s \ d\Omega. \quad (A.26) \]

By the law of cosines,

\[ k^2 = k_s^2 + k_i^2 - 2k_s k_i \cos \theta. \quad (A.27) \]

Assuming that \( v \ll c \) such that Equation A.13 reduces to \( k_s \approx k_i \), the magnitude of \( k \) can be approximated to

\[ |k| \approx |k_i| \sqrt{2 - 2 \cos \theta} \approx 2 |k_i| \sin (\theta/2) \quad (A.28) \]

which gives

\[ \langle P_s \rangle \ d\omega_s \ d\Omega \approx \frac{N_e \langle P \rangle}{R^2} \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 \frac{1}{2 |k_i| \sin (\theta/2)} \times \]

\[ \sqrt{\frac{m_e}{2\pi T_e}} \exp \left( -\frac{m_e c^2 (k_i - k_s)^2}{8T_e k_i^2 \sin^2 (\theta/2)} \right) \ d\omega_s \ d\Omega. \quad (A.29) \]

Casting the equation in terms of wavelength further uses the approximation that \( k_s \approx k_i \) such that

\[ \left( \frac{\omega_s - \omega_i}{k} \right)^2 = \frac{c^2}{4 \sin^2 (\theta/2)} \left( \frac{k_s - k_i}{k_i} \right)^2 \]

\[ = \frac{c^2}{4 \sin^2 (\theta/2)} \left( \frac{\lambda_s - \lambda_i}{\lambda_i} \right)^2 \]

\[ \approx \frac{c^2}{4 \sin^2 (\theta/2)} \left( \frac{\lambda_s - \lambda_i}{\lambda_i} \right)^2 \quad (A.30) \]
which finally gives a scattered power from $\lambda_s$ to $\lambda_s + d\lambda_s$ of

$$\langle P_s \rangle d\lambda_s d\Omega \approx \frac{N_e \langle P_i \rangle r_e^2}{R^2} \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 \frac{c}{2\lambda_i \sin (\theta/2)} \times \sqrt{\frac{m_e}{2\pi T_e}} \exp \left( -\frac{m_e c^2 (\lambda_s - \lambda_i)^2}{8T_e \lambda_i^2 \sin^2 (\theta/2)} \right) d\Omega d\lambda_s. \quad (A.31)$$

Converting power to the number of scattered photons $N_s$ collected over a solid angle $\Delta \Omega$ in a wavelength band $\Delta \lambda$, and also writing $N_e/R^2 = n_e L$ where $L$ is now the length of the scattered region imaged by collection optics gives

$$N_s = \frac{N_i n_e r_e^2 L \Delta \Omega \Delta \lambda}{\lambda_i \sin (\theta/2)} \sqrt{\frac{m_e c^2}{8\pi T_e}} \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 \exp \left( -\frac{(\lambda - \lambda_i)^2 m_e c^2}{8T_e \lambda_i^2 \sin^2 (\theta/2)} \right) \quad (A.32)$$

where $N_i$ is the number of incident photons and the subscript $\lambda_s$ has been dropped. In terms of photoelectrons in a detector where $N_{pe} = G\eta T N_s$ where $G$ is the gain of the detector, $\eta$ is the detector’s quantum efficiency, and $T$ is the transmission of the optical path, the number of scattered photons is

$$N_{pe} = \frac{N_i G \eta T n_e r_e^2 L \Delta \Omega \Delta \lambda}{\lambda_i \sin (\theta/2)} \sqrt{\frac{m_e c^2}{8\pi T_e}} \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 \exp \left( -\frac{(\lambda - \lambda_i)^2 m_e c^2}{8T_e \lambda_i^2 \sin^2 (\theta/2)} \right). \quad (A.33)$$

Some authors define $\delta = \sin(\theta/2) \sqrt{8T_e / m_e c^2}$ \[94\] which reduces the above equation to a more compact form of

$$N_{pe} = \frac{N_i G \eta T n_e r_e^2 L \Delta \Omega \Delta \lambda}{\lambda_i \delta \sqrt{\pi}} \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 \exp \left( -\frac{(\lambda - \lambda_i)^2 m_e c^2}{\lambda_i^2 \delta^2} \right). \quad (A.34)$$

The differential cross section is defined as

$$\frac{d\sigma}{d\Omega} = \frac{P_s A}{P_i d\Omega}. \quad (A.35)$$
Substituting the scattered power from Equation \ref{eq:A.26}, the differential cross section for a single particle is

\[
\frac{d\sigma}{d\omega_s} = r_e^2 \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 \frac{1}{k} \sqrt{\frac{m_e}{2\pi T_e}} \exp \left( - \frac{m_e (\omega_s - \omega_i)^2}{2T_e k^2} \right) d\omega_s. \tag{A.36}
\]

Integrating over frequency gives

\[
\frac{d\sigma}{d\Omega} = r_e^2 \left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2. \tag{A.37}
\]

Converting unit vectors to angles yields

\[
\left( \hat{s} \times (\hat{s} \times \hat{E}_i) \right)^2 = 1 - \left| \hat{s} \cdot \hat{E}_i \right|^2
= 1 - \sin^2 \theta \cos^2 \phi \tag{A.38}
\]

where $\theta$ is the angle between the incident and scattered light and $\phi$ is the angle between the incident polarized electric field and the scattering angle as projected into the plane of the electric field \cite{130}. The differential cross section is thus

\[
\frac{d\sigma}{d\Omega} = r_e^2 \left( 1 - \sin^2 \theta \cos^2 \phi \right). \tag{A.39}
\]

Integrating over $d\Omega = \sin \theta \, d\theta \, d\phi$ gives the total Thomson scattering cross section as

\[
\sigma = \int \frac{d\sigma}{d\Omega} \, d\Omega
= \int_0^{2\pi} \int_0^\pi r_e^2 \left( 1 - \sin^2 \theta \cos^2 \phi \right) \sin \theta \, d\theta \, d\phi
= r_e^2 \int_0^{2\pi} \left( 2 - \frac{4}{3} \cos^2 \phi \right) \, d\phi
= \frac{8\pi}{3} r_e^2.
\tag{A.40}
\]
Appendix B

Drawings
Figure B.1: Thomson scattering entrance flange. The beam enters through the 4 5/8 inch conflat port at the center of the flange. The port on the left is for the edge Thomson viewing optics, and the two ports on the right are for spectroscopic views of a lower shell limiter.
Figure B.2: Thomson scattering exit flange. The beam exits through the 4 5/8 inch conflat port at the center of the flange. The port on the left is for the auxiliary pumping system, and the port on the right is currently unused.
Figure B.3: Flight tube assembly.
Figure B.4: Spectrometer fiber holder.
Figure B.5: Spectrometer entrance slit.
Figure B.6: Baffle 1. Flight tube baffles are numbered by the order in which they are encountered by the laser.

Material: 316 Stainless Steel
All dimensions in inches
Tolerances: ±0.005 in, ±1°

Reflective polished finish
Drill and lap for 4.40 screws every 120°
Figure B.7: Baffle 2. Flight tube baffles are numbered by the order in which they are encountered by the laser.
Figure B.8: Baffle 3. Flight tube baffles are numbered by the order in which they are encountered by the laser.

Material: 316 Stainless Steel
All dimensions in inches
Tolerances: ±0.005 in, ±1°

Reflective polished finish

Drill and tap for 4-40 screws every 120°
Figure B.9: Baffle 4. Flight tube baffles are numbered by the order in which they are encountered by the laser.

Material: 316 Stainless Steel
All dimensions in inches
Tolerances: ±0.005 in, ±1°
Appendix C

Lithium Fill Records
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<td>–</td>
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Table C.1: Record of lithium fills in the evaporator and filler systems.
Bibliography


