Effects of RF power on SOL density profiles and RF coupling on the Alcator C-Mod tokamak

by

Cornwall Lau

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

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Abstract

A 100-146GHz swept-frequency X-mode reflectometer constructed and installed at three poloidal locations adjacent to the lower hybrid (LH) launcher and one location adjacent to the new field aligned ion cyclotron range of frequencies (ICRF) antenna has been used to measure the scrape-off-layer (SOL) density profiles under a wide range of plasma parameters in order to study plasma-antenna coupling and non-linear RF-SOL interactions on Alcator C-Mod.

After validating the reflectometer density profiles with other density profile diagnostics in easily diagnosed and well understood plasma conditions, detailed reflectometer density profile measurements in plasmas with application of ICRF, LH and ICRF+LH power will be shown in order to understand the physical mechanisms for RF-induced density profile modifications. Results indicate that both ICRF and LH power create significant poloidal density profile asymmetries that are correlated with video camera emissivity measurements. These results will be shown to depend on various plasma parameters such as launched $n_{||}$ of the LH waves, ICRF antenna location, and toroidal magnetic field direction.

Both LH and ICRF power have been experimentally observed to modify the poloidal flow in the SOL. These flows are reminiscent of LH and ICRF induced convective cells that have been discussed in the literature. A 2-D diffusive-convective model has been applied to quantify the effects of these RF-induced ExB drifts on the SOL density profiles. For the LH case, the simulation reproduces the experimental trends at all three reflectometer poloidal locations adjacent to the LH launcher and indicates that LH-induced ExB drifts is the dominant physical mechanism producing the experimentally measured density profile modifications. Understanding this RF-induced transport helps elucidate these nonlinear RF-SOL mechanisms.

One consequence of these density profile modifications is a change in LH coupling
efficiency. A 2-D slab LH coupling model has also been used to quantify the effects of the density profile modifications on LH coupling. It will be shown that LH coupling is extremely sensitive to the edge density profile and to poloidal asymmetries in the density profiles. The inclusion of LH and ICRF-induced ExB drift effects on the observed density profile asymmetries is necessary to understand the experimentally measured LH coupling results during LH only and LH+ICRF operations.

Thesis Supervisor: Yijun Lin
Title: Research Scientist

Thesis Supervisor: Earl S. Marmar
Title: Senior Research Scientist
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I would also like to thank Dr. Greg Hanson and Dr. John Wilgen of Oak Ridge National Laboratory for their substantial expertise and contributions to this reflectometry diagnostic. I specifically learnt most of my millimeter-wave expertise from Dr. Greg Hanson through our many discussions on millimeter-wave technology and waveguide development. The development of this millimeter-wave reflectometer would not have been accomplished without their great help.

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who have substantially helped in this project: Dr. Syuinchi Shiraiwa and Dr. Orso Meneghini for discussion on LH coupling, Dr. Brian Labombard for discussions on Langmuir probes, Dr. Jerry Hughes and Dr. Yunxing Ma for discussion on Thomson scattering, Dr. Jim Terry for discussions on GPI measurements, Rui Vieira for leading the design of the reflectometer supports, Rick Leccacorvi for designing the LH waveguides, Henry Savelli for designing the ICRF waveguides, Bill Beck for introducing me to COMSOL and for brazing of the reflectometer horns, and Atma Kanojia for constantly helping me move the LH launcher to the appropriate radial location. I would also like to thank all the many other engineers, technicians, and machinists who have helped build or installed parts of this reflectometer project.

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Chapter 1

Introduction

1.1 Nuclear Fusion

As the human population increases and oil, coal, natural gas and other energy resources grow more scarce, there is an growing demand for a clean, renewable, and reliable energy source. Nuclear fusion could be one such energy solution. The fusing of light isotopes, such as D-D, D-T, and D-He\textsuperscript{3}, are exothermic reactions so there is a net energy gain if energy production from these reactions can overcome potential energy losses. If energy can be produced without external power input, then the fusion reaction has reached “ignition”. In 1955, Lawson \cite{Lawson} quantified the conditions necessary for this ignition state. From the nuclear cross sections, the D-T reaction can reach ignition at \( T \sim 10-20 \text{ keV} \) if \( nT\tau_E \geq 10^{21} \text{ keVs/m}^3 \) where \( n \) is the density, \( T \) is the temperature, and \( \tau_E = \frac{W}{P_{\text{loss}}} \) is the energy confinement time, which is defined as the energy content, \( W \), divided by the power loss, \( P_{\text{loss}} \). Other reactions such as D-He\textsuperscript{3} can also be used, but they require higher ignition temperatures. Ignition, breakeven (energy production = energy loss or \( Q_{DT} = 1 \)) or reactor conditions, however, has still not been achieved in present day devices with any nuclear reaction. Figure \ref{fig:triple_product} shows the triple product for past, present, and planned magnetic confinement fusion devices. Understanding how \( nT\tau_E \) varies with controllable parameters in
Figure 1-1: The fusion triple product is shown for various fusion-relevant experiments that have been built around the world. The projected triple product for ITER and future fusion power plants are also shown by the dashed blue lines [2].

present day devices and how $nT\tau_E$ scales to future fusion reactors is one of the main goals of nuclear fusion research.

### 1.2 Plasma Physics

Plasmas are often referred to as a sea of charged electrons and ions that have collective behavior. Plasma physics is important to nuclear fusion applications since it is the medium that most easily satisfies Lawson’s criterion. Concepts such as particle drifts, waves, fluid models, kinetic theory, and wave-particle interactions are critical to understanding the physics of achieving nuclear fusion. Most of these topics are beyond the scope of this thesis, but they can be found in textbooks such as references [1,3].
Only the background material necessary to this thesis will be presented here. The theory of cold plasma waves will be discussed in chapter 2. Particle drifts and debye sheath theory will be briefly discussed in the next sections.

1.2.1 Single Particle Motion

For a charged particle in combined electric, \( \vec{E} \), and magnetic, \( \vec{B} \) field, Newton’s laws of motion can be written as
\[
\frac{d\vec{u}}{dt} = q(\vec{E} + \vec{u} \times \vec{B}). \tag{1.1}
\]
If the electric field and magnetic field are independent of space and time, then the velocity can be split into components perpendicular and parallel to the magnetic field so that
\[
m \frac{du_{\parallel}(t)}{dt} = qE_{\parallel}, \quad m \frac{d\vec{u}_\perp(t)}{dt} = q\vec{E}_\perp + q\vec{u}_\perp(t) \times \vec{B}. \tag{1.2}
\]
If \( \vec{u}_\perp(t) \) is also independent of time, then
\[
\vec{u}_\perp = \frac{\vec{E}_\perp \times \vec{B}_\perp}{B^2}. \tag{1.3}
\]
This velocity is known as the ExB drift. It is independent of the particle species and always perpendicular to the magnetic field. The parallel drift velocity is proportional to \( E_{\parallel} \), and the resulting motion of charged particles is a gyration around magnetic field lines with a gyroradius \( \sim \vec{u}_\perp/\omega_c \) where \( \omega_c = qB/m \) is the cyclotron frequency. In magnetically confined plasmas, the gyroradius is usually small relative to the magnetic field gradient scale length so charged particle trajectories approximately follow the magnetic field line trajectories.

There are other particle drifts perpendicular to the magnetic field, such as the grad-B, curvature, and polarization drifts, that exist due to spatial and temporal variations of \( \vec{E}_\perp \) and/or \( \vec{B}_\perp \). The drift direction of these drifts depend on the particle species.

20
1.2.2 Debye Sheaths

Since electrons are much faster than ions, a positive plasma potential develops near material surfaces to maintain ambipolarity. The ions are accelerated and the electrons decelerated near material surfaces. This can be quantified by using the Boltzmann relation, Poisson’s equation, ion energy equation and ion momentum conservation equation to solve for four unknowns: plasma potential, ion density, electron density, and ion velocity \[3\]. For a one dimensional slab geometry with \( T_e = T_i \), it can be shown that the plasma potential \( \sim 3T_e \) for deuterium, ions enter the sheath at the sound speed, \( (T_e/m)^{1/2} \), and the characteristic length scale is the Debye length \( \sim (T_e/n_e)^{1/2} \). This fundamental concept is important for plasma-material interactions and some plasma diagnostics.

1.3 Tokamak

There are a number of different concepts that have been proposed to achieve nuclear fusion. The tokamak (figure 1-2) is the most developed magnetic confinement fusion concept and has produced the highest triple product to date.

In a tokamak, the plasma is toroidally shaped and is confined by magnetic fields with the goal of achieving high density, temperature, and energy confinement time. The magnetic field is used to reduce the outflow of particles and energy to the edge of the tokamak. This is achieved by wrapping the magnetic field lines together into two dimensional magnetic flux surfaces so that charged particles flow rapidly along the flux surfaces and diffuse slowly across flux surfaces. In principle, wrapping the field lines together into one-dimensional flux lines will also reduce cross field drifts, but slight misalignments of these flux tubes creates an unstable configuration that is prone to cross-field drifts.

To achieve equilibrium and stable magnetic flux surfaces, toroidal, poloidal and
vertical magnetic fields are required. The toroidal and vertical magnetic fields are created by field coils. The poloidal field is created by the toroidal plasma current, which can be generated by a central solenoid inside the central column. A solenoid is inherently not steady state, so future devices will require a non-inductive toroidal current drive for steady state tokamak operation. It is also important to consider that the plasma must eventually interact with a material surface. While it is desirable to maintain hot temperatures in the core plasma, it is desirable to maintain cold temperatures on the surface of the tokamak to reduce melting, impurity generation, and other deleterious plasma-surface interactions. This region, called the scrape-off-layer (SOL), has open magnetic field lines that intersect the material boundaries. To reduce plasma surface interactions, it was speculated that if the plasma surface interactions are dominated by field lines distant from the main plasmas, the interactions between the core plasma and boundary will be reduced. This is the basis for divertor configurations where magnetic field lines is diverted to another region in the SOL.

A typical magnetic geometry of a diverted tokamak is shown in figure 1-3. Since the tokamak is toroidally symmetric, the magnetic geometry can be shown in the radial and poloidal plane. The cyan lines represent the closed magnetic flux surfaces of the plasma. The red line is the last closed flux surface (LCFS) or separatrix that separates the core plasma from the SOL. The SOL is denoted by yellow lines. Both ends of the field lines in the SOL intersect material surfaces. A substantial fraction of these field lines are diverted to the divertor that is located at the bottom of the picture.

1.4 Alcator C-Mod Tokamak

One such tokamak is Alcator C-Mod [6], a compact, high field, high density, and diverted tokamak located at the MIT Plasma Science and Fusion Center. The ranges of plasma parameters possible on Alcator C-Mod are shown in table 1.1.
Figure 1-2: Schematic of a typical tokamak [5]. The central solenoid transformer, toroidal and vertical field coils are shown. The twisted field lines of the plasma are also shown.

<table>
<thead>
<tr>
<th>$R_0$</th>
<th>0.67 m</th>
</tr>
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<tr>
<td>$a$</td>
<td>0.22 m</td>
</tr>
<tr>
<td>$B_T$</td>
<td>2.8 T</td>
</tr>
<tr>
<td>$I_p$</td>
<td>3.2 MA</td>
</tr>
<tr>
<td>$n_e$</td>
<td>$2 \times 10^{20} m^{-3}$</td>
</tr>
<tr>
<td>$t_{pulse}$</td>
<td>1-3s</td>
</tr>
<tr>
<td>Net $P_{ICRF}$</td>
<td>6MW</td>
</tr>
<tr>
<td>Net $P_{LH}$</td>
<td>1.2MW</td>
</tr>
</tbody>
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Table 1.1: Table of typical plasma parameters on Alcator C-Mod.
Figure 1-3: Magnetic geometry of a typical diverted tokamak shown in the poloidal plane cross-section. Cyan lines represent the closed magnetic flux surfaces, red line represent the LCFS, and yellow lines represent magnetic field lines the SOL region.
A top view of the machine is shown in figure 1-4. Key heating and diagnostic systems used for this thesis are shown here. The locations of these systems and diagnostics are also shown in a toroidally unfolded cross-section view of the outer wall of the tokamak in figure 1-5.

To raise the plasma temperatures to greater than 1keV, heating and current drive systems are required. Alcator C-Mod is equipped with non-auxiliary heating (ion cyclotron range of frequencies heating or ICRH) and current drive (lower hybrid current drive or LHCD) systems in addition to ohmic (OH) heating and current drive. Although there is a diagnostic neutral beam, there is no dedicated neutral beam and current drive system. A full description of heating and current drive mechanisms is discussed in reference [1]. Details on RF heating and current drive can be found in
Figure 1-5: Unfolded cross section map of the outer wall of Alcator C-Mod. Locations for the ICRF antennas, LH launcher, X-mode reflectometer, GPI diagnostic, surface science station ($S^3$) emissive probes, Thomson scattering, and scanning probes are shown.
A brief summary of the physics and systems on Alcator C-Mod is outlined below.

1.4.1 Ohmic Heating

Since the plasma is a very good electrical conductor, it can be heated by an electric current. The toroidal current generated by the central solenoid is already necessary to create the poloidal magnetic field, and it also can be used to heat the plasma. There are, however, two issues with ohmic heating. The plasma resistivity scales with $T_e^{-3/2}$, so as the temperature increases, ohmic heating becomes much less effective. Above a temperature of $\sim 1$ keV in most tokamaks, additional non-inductive heating is usually required. Ohmic heating is also inherently not steady state, so steady state heating and current drive are needed to sustain high temperatures in a future magnetic confinement fusion power plant.

1.4.2 Ion Cyclotron Range of frequencies Heating

On Alcator C-Mod, ICRH is the dominant auxiliary heating tool. ICRH relies on plasma particle-wave interaction: the left elliptically polarized ion cyclotron range of frequencies (ICRF) fast wave will transfer some or all of its wave energy to particles through a resonant process at the ion cyclotron frequency. In standard minority heating scenarios, the fast wave will transfer its energy to the minority ions through cyclotron damping. Collisions between resonant minority ions and majority electrons and ions will transfer energy to the bulk particles. Under ideal plasma conditions, this absorption mechanism can be extremely efficient, often with more than 90% of the ICRF wave energy transferred to the bulk plasma.

There are three ICRF antennas located at D, E, and J port (figure 1-6) on Alcator C-Mod. D and E are 2 two strap ICRF antennas fed at 80 and 80.5 MHz and J is a 4 strap ICRF antenna that can range from 40-80 MHz. In the 2011-2012 campaign, the
J port ICRF antenna has been rotated approximately $10^\circ$, so that the current straps are aligned perpendicular to the total magnetic field. On Alcator C-Mod, the standard heating scenario is hydrogen minority heating in deuterium majority plasmas. At high temperatures of approximately $\geq 2$ keV, second harmonic majority heating ion absorption of D can also contribute to the ion heating. Other less commonly used heating scenarios on Alcator C-Mod are mode conversion heating at high hydrogen fractions, and mode conversion heating with $^3He$ as the second ion species. The 4 strap ICRF antenna can also be used for flow drive or current drive, especially when operated in current drive phasing in a mode conversion damping scenario. In total, 8 MW of ICRF source power and up to 6 MW net ICRF power (forward power - reflected power) have been coupled into Alcator C-Mod plasmas. A more complete description of the Alcator C-Mod ICRF systems can be found in references [9] and [10].
1.4.3 Lower Hybrid Current Drive

Lower hybrid current drive (LHCD) is the main auxiliary current drive and current profile control tool on Alcator C-Mod. The lower hybrid (LH) launched slow wave can Landau damp on resonant electrons, creating a tail in the electron distribution function and thus current drive. If the waves are driven in a specific toroidal direction and at a specified index of refraction parallel to the magnetic field, $n_{||}$, current drive at a localized radial location can be achieved. The launched $n_{||}$ is controlled by the phasing between each column of the waveguide.

On Alcator C-Mod, a LH launcher located at C-port is shown in the photograph.
The LH launcher launches waves at 4.6 GHz through 16 columns and 4 rows of waveguides. The peaked $n_{||}$ launched at the waveguide mouth can be controlled from 1.5 to 3.1. In total, up to 1.2 MW of net LH power has been injected on Alcator C-Mod. A full description of the LH system can be found in references [9] and [11].

1.4.4 RF-SOL interactions

The goal of heating and current drive is to couple the ICRF and/or LH power into the core and/or edge of the plasma where the plasma is well confined. Since the SOL plasma is not confined by closed flux surfaces, the confinement losses are (intentionally) large, concentrating plasma-material interactions to the divertor; it is highly undesirable to have ICRF/SOL or LH/SOL interactions. Unfortunately, such interactions do exist.

ICRF and LH operations are very sensitive to the SOL density profile. In particular, the ICRF fast wave and LH slow wave are evanescent below certain plasma densities, so the waves need to tunnel through an evanescent layer to propagate into the plasma. This problem is known as the antenna-plasma coupling problem. To improve antenna-plasma coupling, ICRF antennas and LH launchers often need to be located in regions of high density plasmas, that are located closer to the LCFS, to reduce the evanescent layer length. This, however, makes the antennas more susceptible to increased heat flux and possible risk of damage to the antenna or launcher. There is therefore a tradeoff, and optimization between increased coupling and increased risk of damaged antennas or launchers is required.

There are also other RF-SOL interactions that are less well understood. On Alcator C-Mod, observations indicate that LHCD has a density limit where the current drive efficiency drops significantly before the classical accessibility limits are reached [12]. LH-induced SOL absorption is suspected to be a possible cause. In many experiments, ICRF power is associated with a significant core impurity contamination.
ICRF-induced SOL plasma potentials are believed to cause the increased core impurity concentration through either increased sputtering and/or increased SOL transport [13][14]. A better understanding of how ICRF and LH power affect the SOL and how the SOL affects ICRH and LHCD operations, is necessary to improve the effectiveness of both ICRF and LH operations. In particular, as it will be shown later in this thesis, these RF-SOL interactions can modify the SOL density profiles, and therefore antenna-plasma coupling. This suggests that the problems of RF-SOL interactions and antenna-plasma coupling are interconnected. These RF-SOL interactions will be further discussed in section 2.2.

Investigation of these issues forms the basis of this thesis. A SOL reflectometer diagnostic is used to measure detailed SOL density profile modifications resulting from the application of ICRF and/or LH power. These observations, along with measurements from other diagnostics, provide significant details on the physical mechanisms that drive RF-SOL interactions and affect antenna-plasma coupling. In particular, the three LH-SOL reflectometer horns have provided the first measurements of density profiles and density profile asymmetries in front of a LH launcher in a tokamak, leading to new insights into the above mentioned physical mechanisms and their effects on LH coupling.

1.4.5 Diagnostics

There are many diagnostics on Alcator C-Mod [15], so only the diagnostics most relevant to this thesis will be listed here. The SOL reflectometer [16] is a focus of this thesis and will be discussed in detail in chapter 3. Thomson scattering [17], scanning probes [15] and fixed Langmuir probes [15] are used to measure the density and temperature in the core, edge, and SOL. Some of the Langmuir probes are specially designed to measure other parameters such as plasma potential [18]. Directional couplers [9], located on all ICRF antennas and LH launchers, are used to measure the forward and reflected power within the transmission lines of each system. Gas puff
imaging diagnostics [19] are used to measure radial profiles of poloidal velocity in the
SOL. The location of all these diagnostics is denoted in figures 1-4 and 1-5. This
section will briefly discuss some of these diagnostics.

There is a large set of Langmuir probes located around the Alcator C-Mod ma-
chine. The most relevant to these studies are discussed here. There are six stationary
Langmuir probes that are attached to the LH launcher to measure the density and
temperature at 3 poloidal and 2 radial locations. These Langmuir probes are mainly
used to measure the density in front of the LH launcher. They are also used to con-
strain the reflectometer density profile measurements, as discussed in section 3.4.5).
There are two reciprocating Langmuir probes than can measure SOL profiles. The
A-port probe scans horizontally and is located about 11 cm above the midplane and
\( \sim 65^\circ \) away toroidally from the LH-SOL reflectometer. The F-port probe scans ver-
tically and is located on the diveror shelf, about \( \sim 110^\circ \) away toroidally from the
LH-SOL reflectometer. There are also probes located on the Surface Science Station
\((S^3)\). The probes on \( S^3 \) are fixed during a discharge, but can be moved radially be-
tween discharges. The probes on \( S^3 \) [18], and at A-port and F-port can be used to
measure the plasma potential, electron density, electron temperature, and ion tem-
perature profiles using either double probes, ion sensitive probes, emissive probes,
and/or retarded field analyzers (RFA). Due to the limited space, only a few of these
probes can be used during each run day, so only a subset of these possible plasma
parameters can be measured for a given discharge. Between run days, the probes
can be switched out, allowing for measurement of different plasma parameters on a
subsequent run day. It should be noted that there are also ion sensitive and emissive
probes located near the AB limiter, to measure the plasma potential [18].

Directional couplers are located behind the ICRF antennas and LH launcher. For
this thesis, the directional couplers for the LH system are most relevant so they
are discussed here. There are 16 directional couplers, one for each of the 16 4-way
splitters, that are used to measure the averaged forward and reflected power over the
4 rows of each 4-way splitter. The deviation of the reflection coefficients are within
1-2% during an in-vessel calibration but up to 5-20% during plasma discharges. The increased variation during plasma discharges is believed to be due to SOL density fluctuations. In this thesis, the averaged reflection coefficient measured by the 16 waveguide directional couplers is used to represent the LH coupling efficiency of the entire $4 \times 16$ waveguide grill. This averaging process also reduces the effects of cross coupling between waveguide columns. The reflection coefficient shown is adjusted for the measured waveguide attenuation during an in-vessel calibration, so as to indicate only the antenna-plasma coupling losses.

Alcator C-Mod has core and edge Thomson scattering systems [17] located at G-port. Photons in the vertically aligned laser beam scatter off the plasma electrons and are detected by polychromators at the appropriate scattering locations. This is used to measure the density and temperature profile at the core and edge of the plasma. The Thomson scattering system on Alcator C-Mod consists of 16 core collection fibers and 20 edge collection fibers.

Gas puff imaging (GPI) is a diagnostic that is located at the A-B limiter [15]. It consists of a camera that covers a 4 cm x 4 cm (radial and vertical) region in the edge and SOL. The diagnostic uses neutral gas to enhance and localize radiation to study the dynamics of emission fluctuations. In particular, for this thesis, the fast time resolution of the camera images is used to measure the radial structure of the poloidal phase velocity [20]. In OH plasmas, this phase velocity is shown to be equivalent to the ExB drift velocity measured by Langmuir probes. It is assumed that this phase velocity is also equivalent to the ExB drift velocity during ICRF and/or LH operations.

For all of the diagnostics that are located above or below the midplane, an equilibrium magnetic field fitting code, EFIT [21], is used to map these locations to the midplane of the tokamak, and to compare measurements among different diagnostics. Further details will be discussed in chapter [3].
1.5 Thesis Outline

The thesis is outlined as follows. Chapter 2 discusses the cold theory of electromagnetic waves in plasmas, especially in the context of reflectometry and RF-SOL interactions. A summary of the relevant RF-SOL interactions is also presented. Chapter 3 discusses reflectometry and the SOL reflectometer system on Alcator C-Mod. Since the SOL reflectometer is a newly constructed diagnostic, the engineering design and implementation will be discussed in detail.

Chapter 4 presents detailed SOL density profile measurements from the SOL reflectometer for a wide range of plasma parameters and operational regimes, including line averaged density ($\bar{n}_e$), current ($I_p$), majority atomic species, L-mode, H-mode, outer gap, LH launcher location, and localized gas puffing. Comparison with other density diagnostics in often-studied and easily diagnosed plasma conditions will be shown to increase confidence in the validity of the reflectometer measurement. Density profile measurements during less commonly measured plasma conditions, such as with localized gas puffing, will then be shown. Localized gas puffing is shown to increase the density only along magnetic field lines that are magnetically connected to the nozzles.

Chapter 5 will examine the effects of LH power on the SOL flows and density profiles. LH power is shown to cause substantial poloidal density profile asymmetries. These LH-induced density profile modifications depend on plasma parameters such as toroidal field ($B_t$) direction, inner gap, $\bar{n}_e$ as well as launched $n_{\parallel}$ of the LH launched waves. The experimental observations suggest that LH-induced SOL absorption drives ExB drifts, and the resulting convective transport drives poloidal density asymmetries. A diffusive-convective model is presented to quantify the effects of LH-induced ExB drifts and convective transport on the density profile. The model is shown to reproduce the experimental trends. The measured density profile asymmetries have also been used as inputs into a LH coupling simulation to simulate the LH reflection coefficients. The results show that the LH-induced ExB drifts can
reduce LH coupling efficiency and that it is necessary to measure the density profile in front of, and not between waveguide mouths, to accurately understand LH coupling. These results suggest the importance of including these poloidal density profile asymmetries to understand and model LH coupling, LH-induced SOL absorption, and LH-resultant heat fluxes.

Chapter 6 discusses the effects of ICRF power on the SOL flows and SOL density profiles. The same diagnostics and simulation tools shown in chapter 5 are used to quantify the effects of ICRF-induced ExB drifts on the observed ICRF-induced density profile modifications. ICRF power is also shown experimentally to create poloidal flows and density profile modifications. These density profile modifications are necessary to understand the effects of ICRF power on LH coupling. Results of a dedicated experiment to understand the differences of the measured LH reflection coefficients between LH only, and LH+ICRF cases show that simultaneous operation of ICRF antenna adjacent to the LH launcher leads to degradation of the LH coupling efficiency. Operation with a ICRF antenna located 144° away from the LH launcher causes only minimal effects on LH coupling. Magnetic field line mapping and ICRF-induced convective transport is shown to be critical in understanding these results.

Chapter 7 summarizes the presented work and discusses topics for follow-on investigations.
Chapter 2

ICRF, LH, and ECRF waves in tokamak plasmas

The theory of cold electromagnetic waves in plasmas has been widely developed and used in numerous heating, current drive, and diagnostic applications in tokamaks. This chapter presents this theory for both homogeneous and inhomogeneous plasmas. Most of the discussion will focus on electron cyclotron range of frequency (ECRF) waves, which have direct applications for reflectometry diagnostics. Similar techniques can be extended to understand ICRF and LH waves, which have applications for heating and current drive. Since this thesis does not actually focus on the propagation and absorption of plasma waves in the core of a tokamak, the use of hot electromagnetic waves theory is not used here. The cold theory is generally sufficient to understand RF-SOL interactions and reflectometry. A discussion of the interactions between RF waves and SOL is also presented at the end of this chapter.
2.1 Cold Electromagnetic Waves in Plasmas

2.1.1 Cold Electromagnetic Waves in Homogeneous Plasmas

This derivation of the propagation of cold electromagnetic waves in homogeneous plasmas can be found in references [7], [8], or [23]. Derivation begins with Ampere’s law and Faraday’s law:

\[
\begin{align*}
\nabla \times \mathbf{B} &= \mu_0 \mathbf{J} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}, \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}.
\end{align*}
\]

By using Ohm’s law (\(\mathbf{J} = \sigma \cdot \mathbf{E}\)) and Fourier analysis in both the spatial and temporal domains (\(\nabla \rightarrow i \mathbf{k}\) and \(\frac{\partial}{\partial t} \rightarrow -i\omega\)), these equations can be rearranged to

\[
\left\{ \frac{\epsilon}{\omega^2} + \frac{c^2}{\omega^2} (k k - k^2 \mathbf{I}) \right\} \cdot \mathbf{E} = 0,
\]

where \(\epsilon = \frac{i}{\omega\epsilon_0} \sigma + \mathbf{I}\) is the dielectric tensor. This is a general equation that applies to dielectrics, plasmas, and other materials. Plasma physics is only contained in the conductivity tensor, \(\sigma\). To calculate the plasma conductivity tensor, the cold plasma equation of motion (equation 1.1) for a single particle is used. Since plasmas have both freely flowing ions and electrons, electrons and all ion species need to be considered.

To simplify the derivation of equation 1.1, it is standard convention to choose \(\mathbf{B}\) to be along the z-axis and \(\mathbf{k}\) to be in the x-z plane with \(\theta\) being the angle between \(\mathbf{k}\) and \(\mathbf{z}\). Using this coordinate system, the velocity vector can be written as

\[
\begin{align*}
\mathbf{u}_x &= \frac{q_s (i \omega E_x - \omega_{cs} E_y)}{m_s (\omega^2 - \omega_{cs}^2)}, \\
\mathbf{u}_y &= \frac{q_s (i \omega E_y + \omega_{cs} E_x)}{m_s (\omega^2 - \omega_{cs}^2)}, \\
\mathbf{u}_z &= \frac{iq_s E_z}{\omega m_s},
\end{align*}
\]

37
where $\omega_{cs} = \frac{qB_s}{m_s}$ is the cyclotron frequency, $q$ is the charge, and $s$ is the subscript that denotes the species of the particle. This analysis is linear and can be repeated for both electrons and ions. Using the fact that the dielectric tensor is additive in each of its components, $\mathcal{N} = \frac{\mathbf{k}}{\omega}$, $\mathbf{J} = \sum_s q_s n_s \mathbf{u}_s = \mathbf{\bar{\sigma}} \cdot \mathbf{E}$, equation 2.4, and equation 2.6, equation 2.3 can be rewritten as:

$$\begin{pmatrix}
S - N^2 \cos^2 \theta & -iD & N^2 \cos \theta \sin \theta \\
iD & S - N^2 & 0 \\
N^2 \cos \theta \sin \theta & 0 & P - N^2 \sin^2 \theta
\end{pmatrix}
\begin{pmatrix}
E_x \\
E_y \\
E_z
\end{pmatrix} = 0,$$

where

$$S = \frac{1}{2}(R + L), \quad D = \frac{1}{2}(R - L), \quad P = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2},$$

$$R = 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega + \omega_{cs})}, \quad L = 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega - \omega_{cs})}.$$  

(2.7) and (2.8)

$\mathcal{N}$ is a vector with the magnitude of the index of refraction, $N$, and direction of propagation of $\mathbf{k}$. $\omega_{ps}$ is the plasma frequency for species $s$. A non-trivial cold plasma dispersion relation can be found when the determinant of this $3 \times 3$ matrix is 0. This equation can be rearranged and written in many forms; one such form is:

$$\tan^2 \theta = \frac{-P(N^2 - R)(N^2 - L)}{(SN^2 - RL)(N^2 - P)}.$$ 

(2.10)

$N = 0$ is called a cutoff and $N = \infty$ is called a resonance. It can be shown that a reflection occurs at a cutoff while absorption occurs at a resonance. For cases with both resonances and cutoffs, reflection, absorption and/or mode conversion can all occur. In section 2.1.4, the derivation of these cases will be shown. For reflectometry applications, cutoffs are the necessary reflecting surfaces. Resonances are undesirable since wave energy does not reflect and thus does not couple to the receiving reflectometer horn. On the other hand, ICRH and LHCD applications require resonances to transfer wave energy to particle energy. Cutoffs are undesirable since they partially reflect the wave energy back into the antenna/launcher.
2.1.2 Electron cyclotron range of frequencies waves

For ECRF waves, \( \omega \sim \omega_{ce} \sim 170 \text{ GHz}, \omega_{ci} \sim 40 \text{ MHz}, \) and \( \omega_{pi} \sim 3 \text{ GHz} \) for deuterium ions in the core of Alcator C-Mod. \( \omega_{ce} \gg \omega_{ci} \) and \( \omega_{ce} \gg \omega_{pi} \) so the response of ions in the cold plasma dispersion relations can be ignored. For waves propagating perpendicular to the magnetic field (\( \theta = \pi/2 \)), there are two solutions to equation 2.10 that are known as O-Mode \( (N^2 = P \text{ and } E_\perp = 0) \) and X-mode \( (N^2 = RL/S \text{ and } E_z = 0) \). For \( N = 0 \), the X-mode cutoffs occur when \( R = 0 \) (X-mode R-cutoff), \( L = 0 \) (X-mode L-cutoff) and the O-mode cutoff occurs at \( P = 0 \). The X-mode resonance occurs at \( S = 0 \). A resonance can be found when \( \omega^2 = \omega_U^2 = \omega_{ce}^2 + \omega_{pe}^2 \). This is known as the upper hybrid resonance. With the inclusion of ions, the X-mode also has a resonance called the lower hybrid resonance. With the inclusion of hot plasma effects, there are also resonances called cyclotron resonances. These cyclotron resonances can be important for the accessibility of O-mode in high density plasmas. Other resonances can be important for reflectometer applications when the density \( \sim 10^{16} \text{ m}^{-3} \) or when the temperature \( \geq 5 \text{ keV} \) for relativistic corrections to be important. For most other scenarios, the cold plasma treatment shown here generally suffices.

The range of frequencies from 30-200 GHz on Alcator C-Mod is highly desirable for reflectometry. The X and O-mode have natural cutoffs, so a reflecting surface exists. Resonances for the X and O-mode can often be avoided. In tokamak plasmas, the X and O-mode are easy to launch and receive since it is easy to design the direction of propagation of the transmitting and receiving waves to be perpendicular to the magnetic field \( (i.e \theta = \pi/2) \) as well as the polarization to be parallel (O-mode) or perpendicular (X-mode) to the magnetic field. The X and O-mode are therefore the standard modes of operation for reflectometers in tokamaks. Reflectometry applications with X and O-mode will be further discussed in section 3.1.2.
2.1.3 Ion cyclotron and lower hybrid range of frequencies

The analysis carried out for ECRF waves can be carried out for ICRF ($\omega \sim \omega_{ci}$) and LH ($\omega^2 \sim \omega_{ci}^2 + \omega_{pe}^2/(1 + \omega_{pe}^2/\omega_{ce}^2)$) waves with the inclusion of the ion terms. Since the analysis is very similar, only the results will be shown here. The two branches of waves relevant to ICRH and LHCD are called the fast and slow waves. The dispersion relation for the ICRF fast wave is

$$N^2_\perp = \frac{(N^2_\parallel - R)(N^2_\parallel - L)}{S - N^2_\parallel}.$$  \hspace{1cm} (2.11)

For the LH slow wave, the dispersion relation can be written as

$$N^2_\perp \sim \frac{(S - N^2_\parallel)(P + S) - D^2}{2S} - \frac{\sqrt{[(S - n^2_\parallel)(P + S) + D^2]^2 - 4PS[(n^2_\parallel - S)^2 - D^2]}}{2S}.$$ \hspace{1cm} (2.12)

The above dispersion relations are often written as a function of $n_\parallel$ since $k_\parallel = \omega n_\parallel/c \sim k_\phi \approx n_\phi/R$, a quantity that is conserved under the toroidal symmetry assumption in a tokamak. $n_\parallel$ does not equal $n_\phi$ experimentally in tokamaks, however, as $n_\parallel$ at the core of the plasma can significantly upshift from the launched $n_\parallel$ at the LH launcher as the wave propagates into the core of the tokamak due to the existence of the poloidal magnetic field.

The ICRF fast wave is an electromagnetic wave that is launched from the ICRF antennas on Alcator C-Mod. The fast wave is usually used since $E_\parallel$ is relatively small compared to that of the electrostatic slow wave, which often suffers from impurity contamination because of the substantial $E_\parallel$ \[1\]. In standard minority hydrogen heating in deuterium plasmas, the fast wave is absorbed at the minority hydrogen cyclotron frequency resonance in the core of the plasma.

The electrostatic slow wave is used for LHCD. For LHCD purposes, the radial location of the driven current depends on $n_\parallel$, so $n_\parallel$ needs to be controlled and fixed for LHCD to be a tool to not only drive current but control the current profile. The toroidal component of the wave is matched to the dispersion relation of the slow wave.
by a phased array of waveguides. The phasing of the waveguides sets the launched $n_{||}$. The slow wave is absorbed by electron Landau damping. $n_{||}$ can upshift during propagation through the plasma, however, as discussed above, so it is also important to build models to simulate the $n_{||}$ spectrum at different spatial locations in the tokamak.

Both the ICRF fast wave and the LH slow wave have cutoffs in the periphery of the plasma at relatively low density that reflect the launched power and reduce the net power to the plasma. This will be discussed in section 2.2.1.

2.1.4 Cold Electromagnetic Waves in Inhomogeneous Plasmas

Since tokamak plasmas do not have homogeneous plasma parameters, it is necessary to consider cases when the plasmas have substantial spatial variations. This analysis can be found in many textbooks. The treatment here follows those in reference [23].

The WKB technique can be used to understand wave propagation in inhomogeneous plasmas if the wavelength is short compared to the characteristic scale length of the variation in the plasma parameters. It should be noted that this approximation of WKB theory is violated at or near cutoffs. In this case, it is necessary to consider singular turning point theory. Since the principle of reflectometry is based on cutoffs, the use of singular turning points will also be used here. The equations that are needed are the same as for the homogeneous case: Faraday’s law, Ampere’s law, and Newton’s equation of motion. For inhomogeneous plasmas, though, the Fourier analysis can only be done in the time domain and not in the spatial domain. If this is done, then the resulting equation becomes:

$$\left[ \nabla \times (\nabla \times E) - \frac{\omega^2}{c^2} \right] \cdot E = 0.$$  \hspace{1cm} (2.13)

For ECRF waves, the O-mode and X-mode are the eigenvalues of this dielectric
tensor, so this vector equation results in two independent scalar equations:

\[
\left[ \frac{d^2}{dx^2} + \frac{\omega^2}{c^2} P \right] E_z = 0 \quad (O - mode), \quad (2.14)
\]

\[
\left[ \frac{d^2}{dx^2} + \frac{\omega^2}{c^2} \left( S + \frac{D^2}{S} \right) \right] E_y = 0 \quad (X - mode). \quad (2.15)
\]

If the inhomogeneity is only in the radial direction, both equations can be written in a Helmholtz equation form:

\[
\frac{d^2 E}{dr^2} + k^2(r) E = 0. \quad (2.16)
\]

Far away from resonances and cutoffs, and assuming that the wavelength is much smaller than any plasma scale length, WKB theory gives the standard solution for the phase from the transmitting antenna to the cutoff:

\[
\phi = \frac{\omega}{c} \int_{r_0}^{r_1} N(r)dr, \quad (2.17)
\]

where \(N\) is the index of refraction, \(r_0\) is the location of the cutoff and \(r_1\) is the location of the transmitting antenna. Since WKB theory does not apply for cutoffs and resonances, the standard technique of singular turning point theory is to consider a case where \(k^2(r) = k_0^2(r - r_0)^n\), where \(n\) is an arbitrary integer. For \(n > 0\), this gives a cutoff at \(r = r_0\). For \(n < 0\), this gives a resonance at \(r = r_0\). If \(n > 0\), equation \(2.16\) can be solved analytically and is given by a linear combination of ordinary Bessel functions \([23]\). This equation is a second order differential equation, so any solution requires two boundary conditions. Enforcing continuity at \(r = r_0\) gives one of the the necessary boundary conditions. For a wave launched at \(r \gg r_0\) that can propagate in vacuum, as is the case for reflectometer applications, the solution is required to be bounded for \(r > r_0\) and evanescent for \(r < r_0\). This gives the second necessary boundary condition.

For \(n = 1\), Budden first derived the solution using Airy equations \([24]\), which are a subset of the Bessel equations. By using the appropriate boundary conditions, analysis of the equations for regions both greater and less than \(r_0\) show that for a launched propagating wave at \(r \gg r_0\), no wave is transmitted to the region where \(r < r_0\) and there is perfect reflection at the cutoff, \(r = r_0\). The phase from the launched horn to
the receiving horn is
\[ \phi = 2\frac{\omega}{c} \int_{r_1}^{r_0} N dr - \frac{\pi}{2}. \]  \hspace{1cm} (2.18)

where \( N \) is the index of refraction. Due to the assumption that there is only 1 reflectometer horn that both launches and receives waves, the factor of 2 occurs since the wave travels the same launched and reflected paths. This equation forms the basis of reflectometer density profile measurements.

For \( n = -1 \), this analysis can be repeated. The solution is a sum of a Bessel and Neumann function. The resulting reflection coefficient at the resonance, \( r = r_0 \), is 0. By including hot plasma effects, it can be shown that the wave is perfectly absorbed at these resonances.

### 2.1.5 Budden Tunneling

It is highly desirable to avoid resonances and absorption in reflectometry, but this is sometimes unavoidable. The X-mode, for example, has a resonance at the upper hybrid frequency. The previous singular turning point theory only assumes either cutoffs or resonances, but cutoffs and resonances can often be close together in a tokamak plasma. For example, launching the X-mode from the low field side (LFS) passes through the R-cutoff first before arriving at the UH resonance. Budden showed that the Helmholtz like X-mode equation for this resonance-cutoff pair can be written as,

\[ \frac{d^2 E}{dr^2} + \left( \frac{v(r)}{r} + \frac{\omega^2}{c^2} \right) E = 0, \]  \hspace{1cm} (2.19)

where \( v(r) \) is 0 at the radial location of the R-cutoff and \( r = 0 \) at the UH resonance. This can be solved using singular turning point techniques with the boundary conditions discussed in section [2.1.4]. The reflection and transmission coefficients are:

\[ |R| = 1 - e^{-\pi \eta}, \]  \hspace{1cm} (2.20)

\[ |T| = e^{-\frac{1}{2} \pi \eta}, \]  \hspace{1cm} (2.21)
where $\eta = k|\delta|$, $|\delta|$ is the radial distance between the cutoff and resonance and $k$ is the wavenumber of the launched wave. Thus, if the resonance is far away from the cutoff ($|\eta| \gg 1$), the solution reduces to $|R| = 1$ and $|T| = 0$, which is the previously derived case of having only a cutoff.

A resonance-cutoff pair for the X-mode occurs at low densities. For Alcator C-Mod, figure 3-3 shows how the UH resonance and R-cutoff vary for typical densities and magnetic fields. At low densities, $|\delta| \sim 0$, so $|R| = 0$ and $|T| = 1$. Reflectometry diagnostics therefore receive low signal levels at low densities, so there exists a lower density limit that reflectometers can measure.

It should be noted that this derivation is not completely valid (note that $|R| + |T| < 1$), and that a hot plasma treatment is necessary for core propagation and absorption. In particular, more accurate treatments include processes like mode conversion that are needed to accurately understand this problem [7].

### 2.2 ICRF-SOL and LH-SOL interactions

Since ICRH and LHCD are important tools in tokamaks, substantial attention focuses on phenomena that reduce heating and current drive performance. Some topics, such as antenna-plasma coupling, are common to both RF frequency ranges. Other issues are distinct for a given range of frequency. ICRF heated plasmas in metallic wall tokamaks have long been associated with increased core impurity contamination and thus decreased plasma performance [25]. This is believed to be due to ICRF-induced sheath potentials in the SOL. For the LH range of frequencies, a density limit has been recently observed where the LHCD efficiency drops abruptly below the classical density limit [12]. LH-induced SOL absorption is believed to be a possible cause. These issues are still a topic of current research and will be discussed throughout this thesis.
Figure 2-1: ICRF and LH waves are evanescent in vacuum, so it is necessary to tunnel through an evanescent region before being absorbed in the plasma. Some of the propagating wave is therefore reflected.

### 2.2.1 ICRF and LH coupling

To study ICRF and LH coupling, the Budden tunneling theory of the ICRF fast wave and LH slow wave is often used. While tunneling from cutoffs to resonances is undesirable for reflectometry, it is desirable for heating and current drive applications. The launched ICRF fast and LH slow waves are evanescent in vacuum, so these waves need to tunnel through the evanescent region to the propagating region before they can be absorbed in the plasma. The waves are therefore partially reflected, and some of the transmitted power is loss. This process is illustrated schematically in figure 2-1.

Singular turning point theory can be again used to solve this problem for a cutoff with propagation from the evanescent side. Launching waves from the evanescent side \( r \ll r_0 \) entails a different boundary condition than launching waves from the propagating side, but the analysis is otherwise very similar. The result for the ICRF
The fast wave is:

$$|T| = e^{-2\eta}, \quad (2.22)$$

where $\eta = k|\xi|$ and $|\xi|$ is the radial distance from the antenna to the cutoff. This is an important result for ICRF coupling, showing that ICRF coupling is exponentially sensitive to the distance of the evanescent layer. It can also be shown numerically that LH coupling is also extremely sensitive to the width of this evanescent layer \[26\].

The solution from the above analysis uses connection formulas with Bessel function approximations for $r \to \infty$ and $r \to -\infty$. This assumes that the antenna is far away from the cutoff ($k|\xi| \gg 1$). This is not true practically or else $|T| = e^{-2k|\xi|} \ll 1$ and negligible ICRF power will tunnel to the propagating region and be absorbed in the plasma. For the practical situation of ICRF coupling where $k|\xi| \sim 0$ to 3, Bilato \[27\] used a similar analysis to analytically show that

$$|T| \approx e^{-1.1\eta}, \quad (2.23)$$

As pointed out in reference \[27\], this relationship may better fit the results observed in Tore Supra and JET. Multiple other authors \[28\][29][30] have either extended this WKB approach or used other analytical approaches to better understand ICRF and LH coupling. While the distance to the evanescent layer is important, the density gradient, especially in the propagating region, is also important in predicting the antenna coupling. A flatter density gradient in the propagating region of the ICRF fast wave or LH slow wave improves antenna-plasma coupling, while a steep density gradient in the propagating region degrades antenna-plasma coupling.

Due to the complicated geometry of ICRF antennas and LH launchers, an accurate prediction requires dedicated modeling. Sophisticated codes such as TOPICA \[31\], TOPLHA \[32\], and COMSOL \[33\] have used inputted experimental density profiles to predict antenna-plasma coupling. For the ICRF case, multiple authors \[34\][31][35] have shown good agreement between the experimentally measured and simulated ICRF reflection coefficients. For the LH case, the density is usually measured at one
fixed radial location, so there is a lack of experimentally measured density profiles. The evanescent layer and/or density gradient can be freely adjusted. Doing this can lead to reasonable agreement between experiment and theoretical predictions \cite{36,12}. A local and accurate density profile measurement can resolve these ambiguities.

2.2.2 ICRF-SOL interactions

ICRH has been successful in bulk plasmas heating, but one of the undesirable consequences of ICRH can be the increased core impurity contamination that has been observed in JET \cite{37}, Alcator C-Mod \cite{38}, ASDEX \cite{39}, AUG \cite{40}, TEXTOR \cite{41}, TFTR \cite{42}, Tore Supra \cite{43} and PLT \cite{44}. Since these experiments have different material surfaces, antenna design, and heating scenarios, the observations of the impurity characteristics generally differ among machines. In all these cases, though, the dominant underlying physical mechanism is believed to be ICRF sheath rectification that causes impurity contamination by increased impurity source, sputtering, and/or transport.

ICRF sheaths can increase the impurity source through increased physical sputtering. The sputtering yield as a function of sheath voltage is shown in figure 2-2 for typical ion mixtures that are found in Alcator C-Mod. It can be observed on this log-log graph that the sputtering yield strongly increases with increasing sheath potential, especially for potentials greater than 100 V. In ohmic plasmas, the standard Bohm sheath criterion (section 1.2.2) predicts that the DC sheath potential, $V_{sh} \sim 3T_e$, is usually on the order of a few tens of volts. During ICRF-heated discharges, $V_{sh}$ has been observed to be in excess of 100 V \cite{18}. RF-rectified sheaths terminate at material surfaces on open field lines, leading to an expected increase in sputtering. The mechanism for this RF sheath production lies in strong oscillating RF voltage. Under certain assumptions in the 1-D case that are mostly relevant to capacitive RF discharges, the DC sheath analysis for the Bohm-sheath criterion can be solved analytically \cite{46} by including an oscillating RF current in the standard DC sheath
The sputtering yield is shown as a function of sheath potential for three different possible ion ratios (different colored lines) found on Alcator C-Mod [45].

Equations. In tokamak plasmas, a combination of analytic theory and numerical simulations is often used [47][48]. One widely used model for ICRF sheaths in tokamaks is based on this equation:

\[ V_{sh} = C_{sh} \int E_{\parallel RF} dl, \]  

(2.24)

where \( C_{sh} \) is an arbitrary constant, \( E_{\parallel RF} \) is the oscillating parallel RF electric field and the integral is carried along a magnetic field line. In this model, the sheath potential is therefore constant along a field line, but can vary for different field lines. \( C_{sh} \) is predicted to be \( 1/\pi \) in the analytic theory presented in reference [46]. In reference [48], due to the complicated radial structure of the RF potentials, 2-D fluid simulations predict that \( C_{sh} \) is between .4 - .45. \( E_{\parallel RF} \) is usually found by detailed computer simulations of RF-antennas. The exact physics of \( E_{\parallel RF} \) is strongly dependent on the antenna geometry, but general principles are often cited to develop designs aimed at reducing \( \int E_{\parallel RF} dl \) in order to reduce \( V_{sh} \). Symmetry arguments, such as with dipole phasing (0-\( \pi \)) operation in a two-strap antenna, where the RF fields from each of the two strap cancels out when integrating over a magnetic field line, are often used.
to explain the better ICRF performance with dipole phasing compared to that of
monopole phasing \[25\]. $V_{sh}$ can still be high, however, for field lines that intersect the
corners of the antenna, where the field line only passes through one strap and not both
straps, and the cancellation over the magnetic field line does not occur. This occurs
because the ICRF antenna is often misaligned with respect to the magnetic field pitch
angle. Based on these simple symmetry arguments, a rotated 4-strap ICRF antenna,
aligned with the total magnetic field direction, has been designed and constructed to
reduce $V_{sh}$ \[49\] on Alcator C-Mod. Due to the currents on the Faraday screen and
the antenna box, the simulation model predicts that $V_{sh}$ should be reduced in dipole
phasing (0-$\pi$-$\pi$-0) and even more so in monopole phasing (0-0-0-0) relative to the
unrotated antenna.

It needs to be pointed out that $V_{sh}$ can have other contributions, especially from
possible ICRF-induced DC currents \[41\]. These effects have not been included in the
simulation model in reference \[49\], but may need to be included to understand RF
sheath rectification.

Another factor in reducing impurities is high single pass absorption. The com-
ponent of the fast wave is usually considered negligible, so the slow wave is believed
to drive RF sheaths \[25\]. If the core single pass absorption is low, the fast wave can
reflect many times off material surfaces, leading to increased SOL (collisional etc.)
losses and possibly causing an increased $E_{\parallel\text{RF}}$. The fast wave can also be mode con-
verted to the slow wave due to misalignments between the magnetic field and the
reflecting surfaces \[50\].

ICRF sheaths can also drive increased cross-field transport. Due to strong radial
and poloidal gradients in the sheath potentials across different magnetic field lines,
$\nabla V_{sh}$ can drive ExB convective eddies. An example of this is shown in figure \[2-3
\[51\] where radial and poloidal resolution floating potential measurements on Tore
Supra are shown. Radial resolution is achieved by a radial scanning Langmuir probe
and poloidal resolution is achieved by scanning the plasma current. Magnetic field
Figure 2-3: The floating potential as a function of radial and vertical distance is shown during ICRF discharges in Tore Supra [51]. The resulting ExB flows are shown by the arrows.
line mapping from the ICRF antenna to the Langmuir probe is then assumed to map out the poloidal variation. The sheath potential is shown to be high at the top and bottom of the antenna near the ICRF limiter \[20\] \[52\] \[51\]. This convection can therefore drive an ExB flow pattern that increases the plasma flux towards the antenna, and modifies the impurity screening, impurity transport, and core impurity contamination. To reduce these effects, one possible solution is to reduce $\nabla V_{sh}$. This can be done by reducing $V_{sh}$ everywhere in the SOL.

Experimentally, there have been many observations of ICRF sheaths. Most notably, dipole phasing created substantially less core impurity contamination than monopole phasing on JET and TFTR \[13\]. Density profile modifications consistent with ICRF sheaths were observed on TFTR \[13\] (figure 2-4), and vertical asymmetry in local heat flux, especially for magnetic field lines that connects with the corner of the antenna, were observed on Tore Supra \[53\]. Detailed SOL density, flows, potentials, and/or impurity concentration profiles are scarce on virtually all experiments, making the physical mechanisms of RF sheaths difficult to understand. They are also rarely made simultaneously. Measurement of the ICRF-induced SOL density profile

Figure 2-4: RF-induced density profile modifications in TFTR \[13\]. Solid line is experimental measurement from a reflectometer and dashed line is a model of RF-induced ExB convective transport.
modifications at multiple poloidal and toroidal locations and their relationship to ICRF-induced flows will give a more complete understanding of RF sheaths. These density modifications can also strongly affect LH coupling in simultaneous LH and ICRF operations. These issues will be discussed later in this thesis.

2.2.3 LH-SOL interactions

LHCD has been used to drive current and control the current drive profile in many tokamaks. One of the biggest difficulties for LHCD has been to drive current in high density discharges [23]. The classic density limit for lower hybrid waves is known as the accessibility criterion. This occurs when the slow wave mode converts to fast wave. For a fixed value of \( n_\parallel \),

\[
|n_\parallel| > \sqrt{1 - \frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2} + \frac{\omega_{pe}}{\omega_{ce}|}}.
\] (2.25)

This classical density limit does not fit the experimental observations at high densities on Alcator C-Mod [12], Alcator C [54], or FTU [55]. On Alcator C-Mod, it has been observed that as \( \bar{n}_e \) increases, the current drive efficiency rapidly decreases, for \( n_e \) well below the classical density limit. This is shown in figure 2-5. It is also shown that magnetic topology is an important parameter in this behavior. As the magnetic topology is changed from diverted to inner wall limited, the current drive efficiency rapidly improves for increasing \( \bar{n}_e \).

One possible mechanism to explain these results is non-linear parametric decay instabilities (PDI) [56]. PDI have been observed on all three experiments and occur at the edge of the plasma when the launched LH wave couples into lower-hybrid sidebands and ion-cyclotron quasi-modes [57] [56]. For a high enough density, the growth rate of the ion-cyclotron mode is larger than the cyclotron and Landau damping rate of the ion-cyclotron mode. In reference [57], it is shown that \( \omega^2 < 4\omega_{LH}^2 = 4\omega_{ci}^2 + 4\omega_{pi}^2/(1 + \omega_{pe}/\omega_{ce}) \) is a necessary condition for parametric decay instabilities. This can set the density limit for LH operations in tokamaks.
Figure 2-5: The hard x-ray count rates, a proxy for LHCD efficiency, measured by a hard x-ray camera are shown for different line averaged densities and magnetic geometries [12].
On Alcator C, a density limit at $\omega \sim 2\omega_{LH}$ was observed [54][56]. Measurements of the power spectrum indicated strong PDI activity, so PDI was concluded to cause the observed density limit. On FTU, it is believed that parametric decay broadens the $n_{||}$ through an increase in the density fluctuations [55]. This broadening, combined with quasi-linear absorption in the edge/SOL, may be limiting the current drive efficiency observed in the core.

On Alcator C-Mod, PDI is also observed. In reference [12], PDI were not considered to be the cause of the density limit, as they did not occur until $\omega/\omega_{LH} \sim 3.75$. The observed decrease in current drive efficiency from nonthermal ECE and hard x-rays occurred for densities much lower than this limit ($\omega/\omega_{LH} < 2$). These experiments, however, were only made at the outer midplane. More recent experiments have shown that PDI activity is much stronger in the inner wall and divertor shelf than on the outer wall of Alcator C-Mod during diverted discharges [58]. More research needs to be done to verify if PDI is the cause of the LHCD density limit on Alcator C-Mod.

Other mechanisms can also cause this LH density limit. Effect of collisional absorption on the lower hybrid wave propagation through both electron-ion and electron-neutral collisions was explored in reference [12]. They were determined to be a contributing factor in explaining the density limit. In reference [59], a full wave code was applied to study LH propagation and absorption. It was found that there was a strong $n_{||}$ upshift, especially for high density plasmas. This strong $n_{||}$ upshift can cause Landau damping to occur at the edge and in the SOL, and thus may also be a factor in explaining the reduced current drive efficiency in high density core plasmas.

Not only does the SOL affect LH propagation, but LH power also affects the SOL. Ponderomotive forces and electron impact ionization are two mechanisms that result during both ICRF and LH operations. The ponderomotive potential drives particles from regions of higher oscillating electric fields to regions of lower oscillating electric fields. This has been theorized to deplete the density local to the LH launcher and
Figure 2-6: Plasma flow measurements of a lower hybrid vortex are shown on a linear machine in the left picture [66]. The associated ion saturation current is shown on the right. These Langmuir probe measurements indicate that the LH-induced flows drive density profile asymmetries.

is speculated to reduce LH coupling on both Alcator C-Mod [60] and ASDEX [61]. Ionization can increase the density profile in the SOL. This is often intentionally done by localized gas puffing near the LH launcher to improve LH coupling [62]. Direct LH-induced ionization has also been proposed as an important mechanism in reference [62].

LH-induced SOL absorption can also occur when fast electrons, caused by high \( n_{||} \) modes (\( n_{||} > 45 \)), Landau damp in low temperature regions in the SOL. High \( n_{||} \) modes are excited and observed in multijunction lower hybrid experiments on Tore Supra [63] [64]. These can generate significant local heating and damage. On Alcator C-Mod, the launched power in the high \( n_{||} \) spectrum of the grill antenna is not as high as the launched power in the high \( n_{||} \) component of a multijunction, so this effect is not believed to be as strong on Alcator C-Mod as on Tore Supra [12]. The poloidal emissivity striation patterns observed on visible video cameras in Tore Supra, TdeV, and Asdex [65] have also been attributed to the high \( n_{||} \) mechanism.

Additional evidence for significant SOL absorption, as is suspected to be the case in high density Alcator C-Mod LHCD discharges, comes from other LH-induced SOL modifications that are observed. Strong SOL currents are observed on the probes in
the LH launcher. LH-induced ExB drifts and LH-induced density profile modifications have been observed on linear machines \[66\]. The ExB drifts are shown in figure 2-6. In this thesis, the measured ExB drifts and density profile modifications are reported for the first time in a tokamak with both plasma flow and density profile measurements. They are shown to have important implications for LH coupling.
Chapter 3

SOL Reflectometer on Alcator C-Mod

Reflectometry has been a widely used diagnostic to measure plasma density, density fluctuations, and rotation profiles with high temporal and spatial resolution [67]. These measurements have contributed to better understanding of many physical mechanisms, such as ELM dynamics [68][69], MHD modes [70], turbulence [71], RF coupling [72], and propagation of RF waves [73]. This thesis is devoted to density profile measurements, using reflectometry as the primary diagnostic technique. Density profile measurements rely on the fact that there exist natural cutoffs in plasmas, so that a transmitting antenna can launch a wave that is reflected from a cutoff layer and then detected by a receiving antenna (figure 3-1). This chapter first discusses important practical concepts relevant to any reflectometer in tokamaks, before detailing design, implementation, and analysis of the SOL reflectometer on Alcator C-Mod.
3.1 Reflectometry Principles in Tokamaks

Equation 2.18 is the basis for reflectometer measurements in tokamaks. There are however a variety of physical effects that can complicate reflectometer analysis, and impact the design choices of the SOL reflectometer. This is highlighted in detail in references [67] and [74]. A brief discussion of a few of these issues is given here.

3.1.1 Validity of Reflectometer Theory

Equation 2.18 is an idealized case derived from cold plasma wave theory and singular turning point theory assuming a density profile with only radial variation. Hot plasma effects and multidimensional effects are not included. 2-D and 3-D curvature effects are clearly not predicted by one dimensional theory. This is not an issue if the horns are perpendicular to the flux surface and the spot size of the beam is much
smaller than the poloidal radius of curvature of the plasma. If the horns are not perpendicular to the surface, ray tracing may be required to at least verify equation 2.18. Undesirable Bragg reflections can take place if the horns are far from perpendicular to the surface. While this effect makes the density profile measurement difficult, it has proven useful for Doppler reflectometry applications [71].

Magnetic shear can couple the X-mode and O-mode together. As long as the shear is slowly varying over space and the reflectometer horn is tilted to match the pitch of the magnetic field lines, the WKB process ensures that there should not be significant O-X or X-O mode conversion. This is therefore not an issue for large aspect ratio tokamaks. It can be an issue in spherical tokamaks where the magnetic shear varies rapidly with radius [67].

Relativistic effects can be important in the hot core of a tokamak. The hot plasma dispersion relations for X-mode R and L cutoffs and the O-mode cutoff have been derived in reference [8]. For hot temperatures $\geq 5\text{keV}$, such as on the core of ITER, relativistic corrections are necessary.

### 3.1.2 X mode vs. O-mode

Accessibility of the O-mode and X-mode is necessary to determine the desired polarization for the specific reflectometer application. O-mode and X-mode cutoffs and resonances for typical Alcator C-Mod density and magnetic field profiles are shown in figures 3-2 and 3-3. Since the density is highest in the center of the plasma, the O-mode and X-mode L-cutoff frequencies are not monotonic. The launched waves are reflected off the first cutoff surface encountered, so if the antenna is located on the low field side (LFS) of a tokamak, the use of the O-mode and X-mode L-cutoff for density profile measurements is radially limited to only the LFS of the tokamak. The O-mode cutoff may also be inaccessible if the reflectometer frequency is first absorbed at the electron cyclotron layer ($f_{ce}$ layer in figure 3-2). The X-mode R-cutoff launched from the LFS can measure the high field side (HFS) of the tokamak plasma, but this
Figure 3-2: Upper hybrid resonances and cutoffs for the O-mode and X-mode R and L cutoffs are shown by the black lines for typical plasma parameters in the core and edge of Alcator C-Mod. The red line shows a typical parabolic density profile in the core.

is not often done due to the additional expense of launching and receiving at higher frequencies. In present-day tokamaks, access on the LFS is usually much easier, so the reflectometer is usually used for density profile measurements on the LFS. The density is assumed to be constant on a flux surface and a magnetic equilibrium code is used to map the LFS results to the HFS.

Since the O-mode cutoff only depends on density and is usually at an inexpensive frequency range for electronics and transmission line components, the O-mode is frequently used for core and edge reflectometer measurements in present-day tokamaks. The X-mode L-cutoff is not often used since the frequencies necessary for density profile measurements require a large frequency bandwidth ratio. Many standard waveguide sizes or custom corrugated waveguides are usually needed to cover the density range.

The X-mode R-cutoff is rarely used in the core due to both relativistic effects
Figure 3-3: Resonances and cutoffs for the O-mode and X-mode (black line) are shown for typical plasma parameters in the SOL of Alcator C-Mod. Note that for a X-mode wave transmitted from the low field side (LFS), a cutoff-resonance pair occurs at the R-cutoff and UH resonance. The red line shows a typical SOL density profile using Langmuir probe and edge Thomson scattering data.
and expensive electronic components. The X-mode R-cutoff does have significant advantages at low densities, though. As shown in figure 3-3, the O-mode cutoff and X-mode L-cutoff frequency is zero when the density is zero. For densities less than $10^{18} \, m^{-3}$, this usually requires multiple transmission lines to cover the frequency bandwidth. On the other hand, the X-mode R-cutoff has a frequency bandwidth ratio less than 2 for densities up to $10^{19} \, m^{-3}$, so one standard waveguide band is sufficient to cover the density range.

The X-mode R-cutoff does have a physical lower density limit, though. Section 2.1.5 already noted that the transmitted power of the X-mode is 100% and the reflected power is 0 at zero density due to the tunneling of the X-mode R-cutoff to the UH resonance. For greater than 20% reflected power in most tokamaks, equation 2.20 requires that $n \geq 10^{16} - 10^{17} \, m^{-3}$. The lowest possible measured density therefore depends on the sensitivity of the electronics and the 3-D effects of this Budden tunneling, so it is very difficult to predict and is still a subject of present-day research [75]. The practical lower density limit of the X-mode R-cutoff is estimated to be approximately $10^{16} \, m^{-3}$ and is lower than the practical lower density limit for either the O-mode cutoff or the X-mode L-cutoff.

### 3.1.3 Effect of density fluctuations

Density fluctuations can complicate the analysis of reflectometer density profile measurements. Fluctuations often cause changes in the shape and location of the cutoff layer, that lead to phenomenon such as phase runaway [76] and complicate reflectometer density profile measurements. In the early 1990’s, techniques were developed to mitigate this effect and improve the density profile measurements. This will be discussed in the next section and later in the chapter. While density fluctuations complicate the density profile analysis, they do enable reflectometry to measure density fluctuations. This will be discussed in section 3.5.
3.1.4 Reflectometer Techniques

In the mid to late 1980’s, the earliest reflectometers used multiple fixed frequency or slow swept-frequency systems [74]. These techniques had significant difficulty measuring density profiles due to the effects of fluctuations. These systems, however, proved very effective in measuring density fluctuations. Present-day tokamaks still have fixed frequency reflectometers or slow swept reflectometers running in staircase mode to measure density fluctuations and/or plasma flows [72][71].

For profile measurements, a different setup is required. Different techniques that have been attempted are fast swept full phase reflectometry [78][79][80][81], differential phase or amplitude modulated reflectometry [82], and pulsed radar reflectometry [74].

Full phase reflectometry is the most often employed reflectometry density profile technique. The frequency is swept quickly so that the density fluctuations are effectively frozen over the frequency sweep time. This is crucial for avoiding the phase runaway phenomenon. Sweep times of approximately 10-50 $\mu$s are shown to be necessary on most tokamaks. It should be noted that this technique does not eliminate the effect of the fluctuations, but only “freezes” the fluctuations during a sweep. Thus, if the amplitude of the density fluctuations is large, as in the SOL of tokamaks, this technique may be less effective. Nevertheless, fast swept reflectometry has proven to be successful in many tokamaks, such as DIII-D [79], ASDEX Upgrade [81], Tore Supra [78], and JET [80]. This technique has also proven useful for density fluctuations studies [83].

Pulsed radar reflectometry, which measures the time of flight of the signal, and is commonly used for atmospheric measurements, has been attempted in tokamaks [74]. The biggest advantage of this technique is the time resolution: pulse times are approximately 1 ns. This technique is technologically challenging though, as it is difficult to separate out plasma effects from waveguide dispersion. Compared to
full phase frequency and two frequency systems, this technique has been much less developed in tokamaks.

Amplitude modulated or differential phase reflectometry measures the phase difference between two launched frequencies. If the difference between the radial location of the cutoff layers of two launched frequencies is less than the correlation length of the density fluctuations, the effect of the density fluctuations on the density profile measurement can be reduced. It should be noted that the choice of difference frequency is critical, as a small difference frequency yields a small phase difference, requiring sensitive and accurate detectors, and a large difference frequency results in the density fluctuation correlation length being greater than the distance between cutoff layers. Multiple difference frequencies may therefore be necessary to measure different density profiles. This technique does not require fast sweeping oscillators, so it was used extensively in the late 1980’s and early 1990’s before technology for fast sweeping reflectometry had been developed. Nowadays, the technical complexity and expense of launching multiple frequencies makes this technique less common than fast-swept full phase reflectometry. It is still used for correlation reflectometer measurements and for density profile measurements in the SOL [84], where reducing the large amplitude of the density fluctuations may be highly advantageous.

### 3.2 SOL reflectometer on Alcator C-Mod

To minimize the challenges of reflectometry measurements in tokamaks, the SOL reflectometer [85] on Alcator C-Mod is designed to be a differential and full phase swept X-mode reflectometer system, that can be swept from 100-146 GHz in times as fast as 10 μs. For typical $B_0 = 5.4$ T, the density range covered is from $5 \times 10^{16}$ to $6 \times 10^{19}$ m$^{-3}$. Because the relative density fluctuation amplitude can approach 100% in the SOL, both differential phase and full phase techniques have been employed on Alcator C-Mod.
The above criteria for the reflectometer were chosen from modelling of magnetic field profiles using EFIT, and density profiles from Langmuir probe and Thomson scattering measurements. This modeling indicated that the frequency range needed to be 100-146 GHz X-mode to cover the typical Alcator C-Mod SOL densities at $B_0 = 5$-5.4 T. As discussed in section 3.1.2, X-mode has advantages over O-mode at low densities, so the X-mode R-cutoff was chosen.

For the differential phase measurement, a 500 MHz frequency difference was chosen. Results in figure 3-1 showed that the expected cutoff layer separation is less than 1 mm, much less than the measured radial correlation lengths of 7-15 mm for the SOL fluctuations in reference [19]. This choice ensures that the differential phase technique will reduce the effects of density fluctuations on the density profile measurements. The choice of 500 MHz was also made so that the differential phase shift will be greater than 1/2 radian, balancing the demands for uniqueness of the phase data and accuracy of the phase detectors.

The modeling also made sure that all the concerns discussed in section 3.1.1 were addressed. The temperatures are less than 100 eV in the SOL, so relativistic effects are unimportant. The effect of curvature was examined with a ray tracing code [86], and was deemed unimportant as long as the reflectometer horns were tilted to match the curvature of the flux surface. The density measurement at low densities ($n \sim 10^{16}$ $m^{-3}$) does prove to be an issue, and this topic will be discussed in section 3.4.5.

There are three pairs of reflectometer horns that are located at the top, middle, and bottom locations adjacent to the C-port LH launcher (figure 1-7), and one pair of reflectometer horns at a port adjacent to the J-port ICRF antenna (figure 1-6). These 4 different locations will be referred as the top, middle, and bottom LH-SOL reflectometer and ICRF-SOL reflectometer in this chapter. Since the reflectometer system shares one set of electronics, only one reflectometer horn location can be used for each discharge. Waveguide switches are used between discharges to select a different location for the subsequent discharge. Multiple poloidal and toroidal locations
Figure 3-4: a) A typical density profile for an L-mode discharge is shown in black. The corresponding X-mode R-cutoff frequency is shown in red. b) The simulated reflectometer phase, c) differential phase, and d) cutoff layer separation at a 500 MHz difference frequency, respectively, are shown for reflectometer frequencies from 110-145 GHz.
were chosen, so as to measure possible toroidal and poloidal density profile asymmetries. This proved invaluable in understanding the physical mechanism for ICRF and LH-induced density profile modifications.

The rest of the chapter describe the design and implementation of the electronics, transmission line, and reflectometer horns before discussing the analysis of the SOL reflectometer density profile and density fluctuation measurements.

3.3 Hardware

3.3.1 Electronics

The schematic for the SOL reflectometer electronics is shown in figure 3-5.

As discussed in section 3.1.4, fast frequency swept reflectometers are necessary for density profile measurements. Since fast swept sources are not available at 100 GHz, frequency multiplication of fast swept sources at approximately 10 GHz are used. A high slew-rate voltage controlled oscillator (VCO) from 6.35 to 9.2 GHz is used to generate the low frequency probing signals. An Agilent arbitrary waveform generator is used to set the voltage that controls the frequency of the VCO. The waveform can be set arbitrarily, but generally a sawtooth (sweep over multiple frequencies), continuous (dwell over one frequency), or staircase (dwell over multiple frequencies) waveform is used. A custom-made voltage amplifier was used to convert the -5 to 5 V arbitrary waveform to the necessary 6 to 16 V needed as input into the 6.35-9.2 GHz VCO. The resulting 6.35 to 9.2 GHz output is then split into two signals. One of these signals is the input to the plasma arm. It goes through a frequency mixer, doubler, and another splitter. The two resulting split signals are each downconverted with fixed frequency mixers that are separated by a 62.5 MHz difference frequency. The signals are then ×8 multiplied to reach the desired 100.4 to 146.6 GHz and 99.9 to 146.1 GHz signals. The desired 500 MHz difference in the launched frequencies is maintained at
Figure 3-5: Schematic of the reflectometer electronics for the 2010-2011 campaign. An upgrade used for the 2011-2012 campaign will be shown in figure 3-20.
all times. The other signal from the VCO is used for the reference arm, which consists of a coaxial delay line of ∼ 30 m and a ×8 frequency multiplier to reach the 50.8-73.4 GHz. A coaxial delay line in the reference arm is used to compensate for the phase delay of the waveguides in the plasma arm in order to reduce the the measured beat frequency, $d\phi/dt$ below the digitization rate (10-40 MHz) of the digitizer.

The 100-146 GHz waves in the plasma arm are combined using a power combiner and are then sent through ∼ 15 m of waveguides before reaching the plasma, reflect from the cutoff layer, come back through ∼ 15 m of a different set of waveguides and are sent into the input of a second-harmonic mixer. The 50.8-73.4 GHz reference signal is the reference input of the second-harmonic mixer. The result is that the 100.4 to 146.6 GHz and 99.9 to 146.1 GHz plasma signals are downconverted into 1200 and 1700 MHz signals, respectively. Both the 1200 and 1700 MHz signals are band-pass filtered and amplified by phase limiting amplifiers. The 1700 MHz signal is then split into two signals. One signal is then sent into an I/Q detector to get the full phase measurement. The other 1700 MHz signal and the 1200 MHz signal are used as inputs into a mixer to obtain a 500 MHz signal that is then used as input to another I/Q detector to get the differential phase measurements. The signals at the I/Q detectors are then video amplified and sent to a fast digitizer. Phase accuracy is critical in the detection circuit, so all components were designed for phase accuracy and stability over a wide range of temperatures, amplitudes, and frequency variations.

In designing any swept frequency reflectometer system, it is necessary to consider the effects of spurious harmonics in the launched frequencies. Since the system is frequency-swept, the intermodulation of second and third harmonics often produces undesirable signal within the bandwidth of the reflectometer. For example, a combination of the second harmonic of the VCO at 6.35 GHz and the fundamental 3.05 GHz frequency source ($2 \times 6.35-3.05 = 9.65$ GHz) is in the 9.4-12.25 GHz bandwidth (6.6 + 3.05 GHz) of the desired mixer output (refer to bottom left of figure 3-5). If the amplitude of this spurious harmonic is large compared to the desired signal, this will affect the phase measurement. For all the frequency mixers and frequency multipliers,
a careful design is thus necessary to reduce the spurious harmonics. Substantial testing and optimization of the system is critical. Band-pass filters, isolators, attenuators and amplifiers at the appropriate locations are necessary to achieve acceptable performance. After extensive optimization, spectrum analyzer measurements indicated that the spurious harmonics of the launched signals were at least 20 dBc lower than the main signal for the entire 100-146 GHz bandwidth.

Another important consideration is signal power and dynamic range. Measurements without plasma indicate that there is sufficient signal level even if there is a 65 dB transmission line loss for 100-135 GHz and 55 dB transmission line loss for 135-145 GHz. The decrease in dynamic range at the higher frequency range is due to a decreased effectiveness at higher frequencies for both the ×8 multiplier chain and the WR-08 power combiner. With an expected total transmission line loss of around 45-50 dB on Alcator C-Mod, the electronics provide enough signal for accurate measurements.

Spurious effects due to stray magnetic field, RF interference, and temperature variations were also considered. Firstly, the reflectometer electronics box (figure 3-6) was chosen to be in the diagnostic lab rather than the cell due to the higher RF, power supply, and magnetic field noise sources close to the tokamak. The electronics box is a specially designed RF shielded box. Magnetically sensitive components such as WR-08 isolators were magnetically shielded with an iron pipe. Oscillator frequencies, especially sweeping oscillators such as the VCO, drift with temperature modifications, so fans were put in the electronics box to keep the temperature of the box reasonably constant. Measurements showed that the frequency drift of the 6.35-9.2 GHz VCO was 2-3 MHz over the day, which is a negligible result compared to the 6.35 to 9.2 GHz source frequency. The fixed frequency oscillators drifted much less, on the order of 5 ppm/°C. It turns out though that for differential phase operation, the temperature induced frequency drift of the fixed frequency oscillators can still cause substantial phase drifts. This phase drift will be discussed in section 3.4.3.
Figure 3-6: Picture of the SOL reflectometer electronics box and electronics inside the diagnostic laboratory.
3.3.2 Transmission Line

The schematic of the LH-SOL reflectometer transmission lines is shown in figure 3-7. The design of the ICRF-SOL reflectometer transmission line is very similar and is not shown. The main difference is that the length of WR-90 waveguides is reduced in the ICRF-SOL reflectometer transmission line.

The ICRF-SOL and LH-SOL reflectometer transmission lines consist mainly of standard WR-90, WR-22, and WR-08 rectangular waveguides. Most of the waveguide length was chosen to be operated in oversized WR-90 and WR-22 tallguide modes ($T_{E01}$) to reduce ohmic heating losses. Ohmic heating losses in a metallic waveguide depend on the surface resistivity of the metal, dimensions of the waveguide, and the frequency, mode number, and type of the propagating mode. The exact formulas can be found in Pozar [87]. For 100-146 GHz, the theoretical attenuation losses for copper...
WR-08 fundamental ($TE_{10}$), WR-22 tallguide ($TE_{01}$), and WR-90 tallguide ($TE_{01}$) are \(~ 4, 0.8, \text{ and } 0.1\) dB/m, respectively. Since the ohmic loss in WR-08 $TE_{10}$ mode is large, the use of WR-08 waveguide is minimized. The total theoretical transmission line losses are calculated to be less than 14 dB. Since experimental waveguide losses are usually up to 2 times greater than theoretical losses due to surface roughness and other factors, the estimated ohmic attenuated transmission line loss is less than 28 dB.

Due to the use of $TE_{01}$ mode in oversized waveguides, multiple modes besides the fundamental mode can propagate inside the waveguide. Mode conversion losses can therefore be substantial, especially in situations where resonant losses are important \[88\]. Theoretical estimates for the mode conversion losses of tapers, twists, hyperbolic secant radius of curvature bends, and miter bends are found in reference \[88\]. The mode conversion losses strongly depend on the ratio of the broad waveguide dimension (a) to wavelength ($\lambda$). If this ratio is small ($a/\lambda \lesssim 5$), h-plane bends can be designed with a large constant radius of curvature bend to give low mode conversion losses. E-plane bends require the design of a hyperbolic secant radius of curvature bend. If $a/\lambda \gtrsim 5$, miter bends often give comparable losses to other bends and require much less space. For this reflectometer system, therefore, WR-22 waveguides ($a/\lambda \sim 2 - 3$) used radius of curvature bends and WR-90 waveguides ($a/\lambda \sim 10$) used miter bends.

The lack of space inside and outside the Alcator C-Mod tokamak requires the use of many more bends, twists, and tapers than is usually desired. The round-trip transmission line for the LH-SOL reflectometer consists of ten WR-08 to WR-22 tapers, four WR-22 to WR-90 tapers, two WR-90 e-plane 90° miter bends, two WR-90 h-plane 90° miter bends, two 6 inch radius of curvature WR-22 h-plane bends, two 2 inch radius of curvature WR-22 h-plane bends, and two 2 inch 10° WR-22 twists. The 10° twist is used to match the angle of the reflectometer horn to the expected 10° magnetic pitch angle of a $B_0 = 5.4$T and $I_p = 1$MA discharge, so as to preferentially launch and receive X-mode polarization. For the top and bottom reflectometer horns of the LH-reflectometer transmission line and for the ICRF-SOL
reflectometer transmission line, WR-22 e-plane hyperbolic secant radius of curvature bends are used to match the reflectometer horns to the poloidal curvature of the plasma (refer to bottom left of figure 3-7). The complications in manufacturing the precise dimensions necessary for e-plane hyperbolic secant radius of curvature bends made their use less desirable.

Using the theoretical formulas in reference [87], the h-plane 90° miter bends were designed to have 4-8% mode conversion losses while e-plane 90° miter bends have 13-17% mode conversion losses. All the other parts were designed to have less than 2% mode conversion losses for 100-146 GHz. These mode conversion losses were verified numerically with the 3-D finite-element method (FEM) solver COMSOL [89]. A sample simulation of the electric field for a WR08-22 taper is shown in figure 3-8. COMSOL allows for the exact geometry to be modelled and for the boundary condition at the port boundaries to be any of the standard TE or TM rectangular waveguide modes. The material is chosen to be lossless, so that the ohmic losses do not contribute to the simulated losses. The S-parameters ($S_{21}$ gives the mode converted loss) at various frequencies can then be calculated. For the WR08-22 taper, $TE_{01}$ polarization was chosen as the input of the WR-22 waveguide and the $TE_{10}$ was chosen as the output polarization of the WR-08 waveguide. The result from this simulation is shown by the red line in figure 3-9. The theoretical mode conversion losses for the $TE_{01}$ to $TE_{21}$ and $TM_{21}$ mode are shown by the blue dashed line. These two modes are predicted to dominate the mode conversion losses [88]. The simulation and theory agree quite well.
Except for the WR-90 miter bends, simulation and theory for all of the above components agree reasonably \[90\]. The differences are probably because theoretical treatments for standard bends, tapers, and twists are calculated for each TE/TM mode and are valid for only slowly varying cross sections (i.e., mode conversion losses \( \ll 100\% \)). The analytic theory also only considers the modes with the highest mode conversion losses, so it can slightly underpredict the total mode conversion losses with the inclusion of all the modes. Simulation takes these effects into account. Since the miter bends have a substantial mode conversion loss, it is not too surprising that theory and simulation do not agree as well for these relatively higher mode conversion losses bends.

3.3.3 Vacuum Window/ DC Break

A 25 \( \mu \text{m} \) thickness mica disk, sandwiched between a o-ring and a standard conflat WR-08 flanges, was chosen as the vacuum window. A photograph of this assembly is shown in figure \[3-10\]. Since the reflectometer launches multiple frequencies, clever \( \lambda/4 \) tricks cannot be used to optimize the thickness of the window for a specific frequency.
The reflection coefficient for a very thin window can however be small over a wide range of frequencies and is given by the following equation [91]

\[ R^2 = (\epsilon - 1)^2 \left( \frac{\pi d}{\lambda} \right)^2, \]  

(3.1)

where \( \epsilon \) is the dielectric constant, \( d \) is the thickness of the window, and \( \lambda \) is the wavelength.

This equation only holds when \( d \ll \lambda \). For the reflectometer where \( d=25 \mu m \) and \( \lambda \sim 2 \) to 3 mm, this is easily satisfied. The transmission loss for a 25 \( \mu m \) thickness and \( \epsilon = 5 \) mica window is calculated to be less than .1dB over the entire 100-146GHz frequency range. The mica window must also be thick enough to maintain vacuum integrity. An estimate of tensile stress in a thin circular disk of thickness 25\( \mu m \) over 1 atmosphere vacuum pressure gradients with WR08-waveguide aperture dimensions indicated that the expected stress (\( \sim 4000 \) psi) was much less than the tensile strength (\( \sim 40000 \) psi) of mica. The use of WR-08 waveguides rather than the larger WR-22 and WR-90 waveguides for the window assembly allowed for the use of a thinner window and consequently lower transmission losses while still maintaining vacuum integrity. All the mica window assemblies subsequently passed vacuum integrity tests.
For the DC break, a 75 µm kapton slit, sandwiched between two standard WR-90 flanges and held together by insulating micarta flanges and nylon screws, is used to shield the electronic components from possibly strong DC currents travelling in the waveguide walls during a plasma discharge. A rectangular hole slightly smaller than the size of the WR-90 aperture is cut in the kapton, so that the kapton has minimal interference with millimeter wave propagation and therefore causes minimal reflections in the transmission line.

### 3.3.4 Reflectometer Horns

The reflectometer horns (figure 3-11) have dimensions of .36 × 1 cm, length of 2 cm, wall thickness of .05 cm, and are made from electric discharge machined oxygen-free copper blocks. Since the horns are near the plasma, disruption forces need to be considered. Due to their small size, the disruption loads on the horns themselves are small. Special attention, however, was needed to attach the reflectometer horns to the LH launcher and vacuum vessel walls. Disruption calculations for the case where the horns are electrically connected to the LH launcher indicated intolerable mechanical stresses, so a complicated assembly was needed to insulate the reflectometer horn and transmission line from other metallic surfaces. This assembly can be observed in figure 3-11. The reflectometer horn support is plasma sprayed to isolate it from the LH launcher or vacuum vessel. The stainless steel screws were isolated by alumina or zirconia washers and alumina sleeves. Ohm meter measurements were made to confirm that the reflectometer support was electrically isolated from the LH launcher and vacuum vessel wall.

The reflectometer horns were first designed to be 0.5 cm × 1 cm rectangular horn antennas with a wall thickness of 1 mm. A transient 3-D FEM simulation in COMSOL was used to model the horn to horn coupling where it was quickly identified that for a reflection layer located 6 mm from the horns, the reflected signal would be dominated by a double reflection (right hand side of figure 3-11). When the horn dimensions
were changed to 0.36 cm × 1 cm and the wall size reduced from 1 to .5 mm, the double reflection signal was reduced by a factor of 10. Knife-edging of the horns and other nearby metallic surfaces was done to reduce the possible double and triple reflections. Simulations of the horn to horn coupling (figure 3-12) in vacuum for the 0.36 cm × 1 cm apertures and a reflection layer 1, 2, 3, and 4 cm away are shown in figure 3-13. Standard $TE_{01}$ boundary conditions are used for the input and output ports. The mirror and horn surfaces were modeled by a perfect electric conductor and the other boundary conditions were made to be a perfectly matched layer (PML), so as to prevent reflections. The coupling losses were deemed acceptable. Direct cross coupling of the horns was simulated by putting the mirror extremely close to the horns. The simulated results showed that this was approximately -50 dB.

A WR-08 network analyzer was also used to experimentally measure the attenuation loss of the in-vessel WR-22 waveguide assembly including the horns (inside the dashed box of figure 3-7). A mirror was placed 1, 2, 3, and 4 cm away from both horns. Results for the experimental horn to horn coupling losses are shown in figure 3-13 where the expected ohmic attenuation losses (3-4 dB) from the approximately 250 cm
Figure 3-12: A sample 2-D slice of a 3-D FEM simulation of the electric field for the reflectometer horn to horn coupling in vacuum, for the case of a reflecting surface located 2 cm away from the reflectometer horns. The boundary conditions are labeled accordingly: perfectly matched layer (PML), perfect electric conductor (PEC), and ports.
Figure 3-13: Comparison between experiment (solid) and simulation (dashed) for horn to horn coupling. The labels indicate the distance from the horn to the mirror, with the lines color-coded in correspondence with the labels.
long WR-22 copper waveguide length have been subtracted out. The experimental results agree reasonably well with simulation, so it appears that the mode conversion losses are not a significant contributor to the waveguide losses. Disagreement could be due to many reasons including the fact that the network analyzer measurements were noisy since the calibration was only accurate to 2-3 dB. The network analyzer could not be calibrated for frequencies above 125 GHz, so the experimental results do not cover the full bandwidth of the system. Theoretical calculations are difficult for reflection layers less than 5 cm away, as the horn to horn coupling is in the near field regime. For a mirror placed 20 cm away, the experimental results agree within 1 dB of the theoretical loss, as calculated by standard far field rectangular horn coupling formulas [87]. Direct horn to horn cross coupling was also measured to be at -50 dB, consistent with the simulations. Horn to horn coupling losses are expected to decrease for increasing frequency, so the ideal horn to horn coupling is still expected to be better than -19 dB for frequencies greater than 125 GHz. Total transmission line and horn coupling losses are thus estimated to be at most 47 dB over the entire reflectometer bandwidth. Spectrum analyzer measurements using an in-vessel mirror also indicate that the transmission line and horn coupling losses are approximately 45 dB over the frequency range.

3.4 Density Profiles

After designing and implementing the reflectometer to make phase measurements, the density can be found by inverting equation 2.18. For the O-mode, which depends only on density and not on magnetic field, this can be done analytically using Abel inversion. This is shown in equation 3.2 [92]. For the X-mode, which depends on both density and magnetic field, the knowledge of the magnetic field profile is necessary for the inversion. A numerical, iterative algorithm [93] is needed for the X-mode
inversion and is shown in equation 3.3.

\[ r(\omega) = r_0 - \frac{c}{\pi} \int_0^{\omega'} \frac{d\phi}{d\omega'} \frac{d\omega'}{(\omega'^2 - \omega^2)^{\frac{3}{2}}} \quad O-mode, \]  

(3.2)

\[ r(\omega_{i+1}) = r_0 - f(\phi(r_i, r_{i-1}, r_{i-2} ... \omega_i, \omega_{i-1}, \omega_{i-2} ...), B(r)) \quad X-mode, \]  

(3.3)

where \( f \) is a function that depends on both phase and magnetic field information.

Unlike multiple channel reflectometer systems, frequency swept reflectometers have a large number of frequencies, which allows for very accurate inversion. The largest error of the inversion is in measuring \( r_0 \). This error source will be further discussed in section 3.4.3. If \( r_0 \) is known accurately, the inversion is usually highly accurate.

As mentioned in section 3.1.4, density profiles can be measured by both the differential phase and full phase techniques. The next two sections describe the analysis procedure for each technique.

### 3.4.1 Differential Phase Technique

The reflectometer differential phase I/Q detector measures \( I \equiv A\cos(\delta \phi(\delta f)) \) and \( Q \equiv A\sin(\delta \phi(\delta f)) \) signals. \( \delta f \) is the constant 500 MHz difference frequency and is different from \( f \), the 100-146 GHz reflectometer source frequency. The measured differential phase, \( \delta \phi(f) \) is equal to the sum of the plasma differential phase \( \delta \phi_p(f) \) and the waveguide differential phase \( \delta \phi_w(f) \).

\( \delta \phi_w(f) \) can be measured during non-plasma discharges by either placing a mirror a few cm away from the horn or through the use of a bypass loop and then estimating the phase from additional waveguide components. Typical I vs Q measurements are shown in figure 3-14, where the black points are the differential phase measurements for a 40 \( \mu \)s source frequency sweep through a bypass loop. The differential phase traces out the entire circle since different frequencies have different differential phases. The phase limiting amplifier keeps the amplitude of the signal approximately constant for a
Figure 3-14: Typical I vs Q measurements where black is the differential phase and red is the full phase measurement for a 40 $\mu$s sweep speed through a mirror calibration of the H-port reflectometer horn. The full phase and differential phase for frequency swept measurements trace out the entire ellipse since different reflectometer frequencies from 100-146 GHz have different phases. Full phase (blue) and differential phase (green) I vs Q measurements are also shown when the frequency is binned over a small frequency range. These phase measurements only trace out a portion of the ellipse.
Figure 3-15: Experimental data of the differential phase (difference frequency of 500MHz) over the reflectometer frequency through a bypass loop wide range of frequencies. The differential phase I vs Q measurements are also shown by the green points when the source frequency is binned over small frequency ranges. It can be observed that there is only a small spread in the phase measurement due to the binning of the frequency data. In the fitting routines, a minimum amplitude is used to reject spurious data caused by bit noise and other effects and the data are averaged over multiple frequency sweeps. By fitting an ellipse to the I and Q signals and transforming the ellipse into a circle of radius 1 and centered at the origin, $\delta \phi_w(f)$ (figure 3-15) can be calculated by taking the arctan(Q/I). It should be noted that the same ellipse parameters are used to fit $\delta \phi(f)$ and $\delta \phi_w(f)$.

The exact same method is used to get $\delta \phi(f)$ during a plasma discharge. An example of this is shown in figure 3-16. In part a) of this figure, the differential phase (red points) for the difference frequency of 500 MHz is plotted over the reflectometer frequency. The differential phase measurement ranges from $-\pi$ to $\pi$, so it is often informative to plot the differential phase measurement multiple times by adding constant 2$\pi$, 4$\pi$, and 6$\pi$ terms (shown in black) to the the red points to unwrap the phase measurement. A phase unwrapping algorithm and boxcar smoothing are then
Figure 3-16: a) Experimental data of the differential phase (difference frequency of 500MHz) over the reflectometer frequency range for a typical plasma discharge are shown in red. The same data is also plotted in black by adding a constant $2\pi$, $4\pi$, and $6\pi$ term. A fit of the measured differential phase is shown in green. The X-mode signal occurs only for frequencies greater than the lowest electron cyclotron frequency ($\sim 10^9$ GHz), so the frequencies below $\sim 10^9$ GHz are not used. b) The amplitude of the signal is shown over this plasma discharge. There is a steep rise in amplitude levels for frequencies greater than $\sim 10^9$ GHz.
applied to obtain the desired measurement, $\delta \phi(f)$ (shown by the yellow line).

There are many other interesting features in figure 3-16. The phase through the bypass loop is much less noisy than the phase during a plasma discharge due to the effect of density fluctuations. The amplitude of the plasma phase signal also abruptly rises at approximately 109 GHz. The frequency of this signal rise indicates the lowest X-mode R-cutoff frequency so useful information is only obtained for frequencies greater than approximately 109 GHz. These topics will be discussed in section 3.4.5. “Bumps” in the waveguide phase will be discussed in section 3.4.4.

After obtaining $\delta \phi(f)$, the plasma differential phase, $\delta \phi_p(f)$, can be obtained by subtracting out the measured waveguide phase $\delta \phi_w(f)$. The differential plasma phase can then be integrated to get the plasma phase and Abel inverted to get the density profile.

### 3.4.2 Full Phase Technique

Just like the differential phase technique, the full phase technique also uses an I/Q detector. For the full phase, $f=1.7$ GHz. If there is no phase noise, the exact same technique for differential phase can be applied. This technique is thus used for the full phase waveguide calibration. In figure 3-14, the red ellipse is the full phase measurement for a 40 $\mu$s source frequency sweep speed and the blue points are the full phase measurement for a source frequency binned over a small range. Due to the effect of density fluctuations, however, this arctan method cannot be used for plasma discharges (see section 3.1.4). The technique that is used in this thesis is similar to that described in reference 94.

For a signal $\sim \cos(\Omega t + \phi)$, the spectrogram or scalogram of the signal is often used to obtain the frequency of the signal, $d/dt(\Omega t + \phi) = \Omega + d\phi/dt$. For steady state signals, the instantaneous beat frequency, $d\phi/dt$, is zero, and $\Omega$ can be determined. For fast-sweeping reflectmeter density profile measurements, $\Omega$ is a constant and
$d\phi/dt$ changes as a function of frequency, so the spectrogram can be used to obtain $d\phi/dt$. The frequency sweep rate, $d\omega/dt$, where $\omega$ is the launched reflectometer frequency, is also well known, so the group delay, $d\phi/d\omega$, can be determined by using the simple relation $d\phi/dt = d\phi/d\omega \times d\omega/dt$. This group delay can then be integrated to get the desired reflectometer phase measurement. Variations of this technique such as the spectrogram [94], tomogram [95], and scalogram [96] are used in many reflectometer experiments in tokamaks. A scalogram approach using Morlet wavelet functions [16] is used for the SOL reflectometer on Alcator C-Mod.

This technique is sometimes used to distinguish between multiple components of the signal, such as possible double reflections that were discussed in section 3.3.4 [95]. It can also be used to distinguish the O and X-mode by their different group delay characteristics [97]. On Alcator C-Mod, this technique is used to reduce the effects of density fluctuations on the density profile measurement. For multiple frequency sweeps, the scalogram can be averaged over both the temporal and Fourier frequency domain. Since the phase fluctuations in plasma are believed to be at best weakly correlated in the temporal domain over multiple fluctuation correlation times, only the group delay of the density profile remains steady over multiple correlation times. The maximum Fourier component of the averaged scalograms thus preferentially rejects the group delay of the fluctuations and selects the group delay of the averaged density profile.

Figure 3-17a) shows an example of the full phase measurement for a typical plasma discharge that has been averaged over 25 frequency sweeps at a 40 $\mu$s sweep speed. The frequency of the maximum Fourier components in the scalogram is the desired beat frequency. The effects of the density fluctuations are greatly reduced, as evidenced by the absence of significant discontinuities in the phase measurement for the range of frequencies greater than approximately 109 GHz. If the Fourier components are not averaged over multiple frequency sweeps, discontinuities in the phase data often occur.
Figure 3-17: a) Experimental data of the full phase beat frequency measurement as a function of the reflectometer frequency for a typical plasma discharge. The X-mode signal only occurs for frequencies greater than $\sim 10^9$ GHz (vertical red dashed line), so the data below 109 GHz are not used. b) A steep rise in signal levels is shown for frequencies greater than $\sim 10^9$GHz

The amplitude of the plasma phase signal abruptly rises at approximately 109 GHz in figure 3-17, indicating that this is the lowest X-mode R-cutoff frequency. Frequencies less than $\sim 10^9$GHz therefore do not contain any useful plasma data. As with the differential phase, a boxcar smoothing of the phase is done, and the calibrated waveguide phase is subtracted from the phase measurement, to obtain the group delay. The group delay is integrated to get the total plasma phase, and Abel inversion of the plasma phase is used to obtain the density profile.

### 3.4.3 Full phase vs. Differential Phase

It is very difficult to compare the full phase and differential phase techniques due to the differences in hardware and analysis. It is therefore difficult to quantify if
the differential phase measurement actually reduces the effect of density fluctuation. The inverted density profiles are similar as well. One noticeable difference is that the differential phase analysis requires a phase unwrapping algorithm while the full phase analysis does not. When density fluctuations cause a large phase scatter in the signal, it proved empirically difficult to unwrap the differential phase robustly for a wide range of SOL density profiles. This situation occurs most often for low $\bar{n}_e$ discharges and is most likely due to the fact that a difference frequency of 500 MHz may be more optimal for high line averaged density discharges compared with low line averaged density discharges, leading to large phase scatter in the latter case. Different difference frequencies, other than 500 MHz, might give better results for low $\bar{n}_e$ discharges. For this reason only, the full phase analysis is preferred in this thesis, as it does not require a phase unwrapping algorithm.

In the future, a more sophisticated phase unwrapping algorithm and analysis routines combined with multiple frequencies may allow for a detailed comparison between the full phase and differential phase techniques.

### 3.4.4 Waveguide Phase Errors

On Alcator C-Mod, the calibration of the waveguide phase can be done either through a waveguide bypass loop (see figure 3-5) or a mirror inside the vessel. Some reflectometers on other tokamaks use the cross coupling between transmitted and launched waveguides as an in-situ calibration [95]. This in-situ calibration is difficult to do on Alcator C-Mod due to the double and triple reflections discussed in section 3.3.4. These spurious reflections are much smaller than the desired signal, but are still larger than the cross coupling signals. While the in-vessel mirror calibration is more desirable, it can only be done between campaigns. The bypass loop calibrations can be used to measure daily phase modifications in the electronics, but an interpolation of these modifications needs to be made over the path length that is different between the bypass loop and the plasma loop. It is thus important that the waveguide phase
Figure 3-18: Experimental data of the differential phase over the reflectometer frequency for various discharges. Note that the phase drift over time seems to be approximately constant for all reflectometer frequencies is reproducible over time, so that this interpolation between the daily measured bypass loop calibrations and yearly measured mirror calibration can be trusted over the course of a run campaign.

For the 2010-2011 campaign, however, there appeared to be a systematic drift in the differential phase (figure 3-18) over time. This drift appears constant over the entire 100-146 GHz frequency bandwidth of the reflectometer. After the 2010-2011 campaign, this offset was attributed to temperature induced frequency drifts in the fixed frequency oscillators. In table 3.1 the fixed frequency oscillators were on purpose slightly deviated and the differential phase at 128 GHz was recorded. Since the offset is approximately the same at all frequencies, 128 GHz was arbitrarily chosen. As shown in figure 3-5 frequency drifts in the 3.05, 6.25, and 6.3215 GHz oscillators only affect the plasma arm and not the reference arm. While the frequency drifts were $\sim 5$
### Table 3.1: Table of phase offsets (column 7 in degrees) from the reference case (row 2) due to minor deviations in the frequency of the 6.25 GHz (column 1), 6.3125 GHz (column 2), and 3.05 GHz (column 3) frequency oscillators are shown. These frequency drifts only affect the plasma arm and not the reference arm, so the detected 1.2 GHz (column 4), 1.7 GHz (column 5), and 500 MHz (column 6) signals are also shifted slightly in frequency. The correlation of the phase offset on the 500 MHz signal is highlighted.

<table>
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<th>Frequency</th>
<th>Frequency</th>
<th>Frequency</th>
<th>Frequency</th>
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<th>Frequency</th>
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<td>1.198680</td>
<td>1.700000</td>
<td>.500320</td>
<td></td>
</tr>
</tbody>
</table>

ppm/°C, measurements done at various fixed frequency oscillator frequencies confirm
that the measured phase offset is extremely sensitive to the $8(6.3125-6.25)$ GHz or
500 MHz difference frequency (figure 3-19). This is because 500.5 MHz-499.5 MHz
=1 MHz is equivalent to a $\lambda$ of 300 m. Over a 30 m long transmission line, this gives
roughly a $36^\circ$ difference in the differential phase between a 500.5 MHz and 499.5 MHz
signal. This estimate approximately reproduces the experimentally measured phase
drifts.

Subsequent controlled measurements done on different days confirm that the dif-
fferential phase calibration is reproducible to within $1^\circ$, as long as the frequencies are
within .5 ppm of the expected value. The electronics were therefore modified so that
a low noise 62.5 MHz crystal oscillator with frequency drifts less than .2 ppm was
used to generate the desired frequency difference. A schematic is shown in figure 3-20.
This upgrade, along with daily mechanical tuning of the other oscillator frequencies,
reduced this differential phase drift to less than a degree, and consequently provided
reproducible differential phase calibrations (within $1^\circ$) through the bypass loop over
the course of many days. This phase error is therefore not an issue starting with the
2011-2012 campaign.
Figure 3-19: The phase drift at a reflectometer frequency of 128 GHz is shown as a function of the 500 MHz difference frequency. A clear trend can be observed. The choice of 128 GHz is arbitrary as the phase shift is approximately the same for all reflectometer frequencies.

Figure 3-20: Schematic of the new electronics design to reduce the phase drifts in the reflectometer system
It needs to be noted that the VCO cannot be tuned mechanically. Over a day, the frequency drift of the VCO is up to $\sim 2$ MHz. Over a campaign, the frequency drift of the VCO can be up to $\sim 10$ MHz. After x16 multiplication, this can change the frequency of both launched signals by $\sim 20$-30 MHz over a day and 100-200 MHz over a campaign. This gives an additional $1-2^\circ$ phase uncertainty at each frequency. This phase error is small and does not significantly affect the reflectometer density profile shape measurement. It can affect the \( r_0 \) term and will be discussed more in section 3.4.5.

There are also large non-monotonic “bumps” in both the full and differential phase as a function of reflectometer frequency in figure 3-18 through the waveguide bypass loop, mirror calibration, and even the plasma phase. There are a variety of possible explanations for these bumps that include undesired responses in the electronics, substantial mode conversion or reflection in the waveguides, and/or standing waves caused by the large dimensions of the mirror. In the future, more work needs to be done to reduce the amplitude of these bumps, so as to reduce the systematic error. In this thesis, a wide bandwidth central average smoothing filter over the 100-146 GHz frequency range was consistently done to smooth over these phase bumps for both the plasma and waveguide calibration. By doing this, the measurement of the difference of the mirror and bypass loop phase calibration is equal to the estimated theoretical waveguide dispersion for the waveguide lengths between the mirror and the bypass loop. This at least confirms that the measurement is reasonable. While these bumps can give a large systematic error to any density profile, these systematic errors exist for all measurements, so they cancel out for density profile modifications.

3.4.5 Plasma Phase Errors

To evaluate plasma phase errors, it is informative to refer back to equation 3.3 as there are two different types of errors. Errors in \( r_0 \) gives mostly radial initialization errors, while errors in \( f(...) \) give density profile shape errors.
The accuracy of the shape of the density profile depends mostly on the quality of the phase data. In plasma discharges, as plasma density fluctuations can approach 100% in the far SOL, the phase noise due to fluctuations is much higher than the phase noise due to waveguide calibrations. This is shown in the comparisons of figure 3-15 and figure 3-16. Thus, it is standard procedure to average over many sweeps so that the phase noise is reduced. Section 3.4.2 discussed this approach. For steady state discharges, this usually gives reproducible density profiles shapes. The statistical errors in the phase are usually small, but can be large in discharges where the density fluctuations have a significant effect on the density profiles.

For most reflectometer systems worldwide, the uncertainty in $r_0$ is usually the largest error source [78]. This is also the case for the SOL reflectometer on Alcator C-Mod. For the X-mode R cutoff at $B_0 = 5-5.4$ T, the reflectometer can measure this initialization because the reflectometer frequency sweep starts below the lowest $\omega_{ce}$ in the outer SOL. Thus, for the lowest swept frequencies, the X-mode does not propagate until it reaches the lowest electron cyclotron frequency at the SOL. By measuring the frequency when the amplitude of the signal has a precipitous rise and equating it with the first cyclotron frequency ($\sim B_0/R$), the first cutoff layer can be found. This is the cause for the sharp rise in signal levels for frequencies around 109-111GHz in both figures 3-16 and 3-17. Below the first cyclotron frequency, the signal is dominated by reflections off the wall, so there is often not a coherent signal. The density profile information is contained only in the measurements after this first cutoff frequency.

This measurement depends on the measured reflectometer frequency and the magnetic field, so the errors in these two quantities need to be considered. There is still a frequency width of approximately 50-200 MHz associated with this rise. This is caused by Budden tunneling discussed in section 2.1.5. Since Budden tunneling is a 1-D analytic theory, and reflectometry has strong 2-D/3-D effects from fluctuations, the exact details for choosing the first cyclotron frequency is still unclear. This is still a topic of present day research [75]. Frequency drifts of the VCO (approximately
50-200 MHz) will also correspond to a ±1 mm error in the radial location of the first
cutoff layer even if $|B|$ was exactly known. The errors in $|B|$, however, are the most
significant factor. A .1% error in $|B|$ corresponds to approximately a .8 mm radial
shift. Magnetic ripple effects therefore need to be considered. More importantly, the
absolutely $B_0$ calibration is estimated to have a 1% uncertainty [98] and thus an 8
mm radial error. EFIT mapping can also give an additional 2-3 mm uncertainty in
radial location. Thus, the error in the magnetic field measurement is often the most
significant contributor to the uncertainty in the location of the first radial cutoff layer.

In some other experiments [84], instead of measuring the first cyclotron frequency,
a different assumption is used for the density profile up to some density, usually on
the order of $10^{16}$ to $10^{17}$ m$^{-3}$. On Alcator C-Mod, there may be another solution to
initialize the density profiles, at least for the reflectometer horns attached to the LH
launcher. On the LH launcher (figure 1-7), there are three pairs of Langmuir probes
that measure the density at one radial location. Since the probes are located at
toroidal and poloidal locations similar to those of the SOL reflectometer, the measured
densities should be similar. Even if the Langmuir probes have significant density
errors due to systematic errors, the steep density gradients on Alcator C-Mod ensure
that relatively large density errors are equivalent to relatively small radial errors,
so that by cross-calibrating to the Langmuir probes, the radial uncertainty of the
reflectometer measurement is reduced to an estimated 1-3 mm.

The importance of using the Langmuir probes as a constraint is shown in table
which examines the effects of radially shifting a typical SOL density profile up
to ±1 mm on Alcator C-Mod. The actual Langmuir probe is 1.5 mm in length, so
the simulated Langmuir probe density is calculated by taking the average of the first
1.5 mm of the reflectometer density profile in front of the LH launcher. As shown in
table a shift of ±1 mm changes the simulated Langmuir probe density by more
than a factor of 10. Since the reflectometer radial error bars are much larger than ±
1 mm, the Langmuir probes constraint greatly reduces the radial uncertainty for the
reflectometry measurements.
Table 3.2: Row 1 shows the radial distance that the measured density profile was shifted, with 0 being the actual measured density profile. Row 2 shows the simulated Langmuir probe density for each case.

<table>
<thead>
<tr>
<th>Radial Shift (mm)</th>
<th>-1</th>
<th>-.5</th>
<th>-.2</th>
<th>0</th>
<th>.2</th>
<th>.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($10^{17} m^{-3}$)</td>
<td>1.1</td>
<td>2.8</td>
<td>5.4</td>
<td>7</td>
<td>8.6</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

It should be noted that this method may not be reliable during ICRF operations, due to the effects of ICRF sheath rectification on the Langmuir probe measurements [99][100]. For cases with ICRF power, the Langmuir probe measurements are not usually valid. The method chosen here is to use the Langmuir probe data for an ohmic timeslice closest in time to the desired ICRF timeslice. The density profile during the ohmic timeslice is shifted to match the Langmuir probes. The relative shift in the measured frequency between the ohmic and ICRF timeslices can then be used to determine the initial radial location during the ICRF timeslice. This technique assumes that the magnetic field error is the same for both OH and ICRF cases, so the relative radial error will be only dependent on the reflectometer frequency errors, which correspond to a relative radial error of 1 to 3 mm. This method can also be used to constrain the data for LH discharges where the strong LH-induced poloidal density profile asymmetries invalidate the assumption that the Langmuir probes have similar densities to those measured by the reflectometer at that location. This will be further discussed in section 5.4.2.

3.4.6 Discussion of error bars and density profile figures in this thesis

Given the large uncertainty in the magnitude and source of the systematic errors, it is difficult to estimate error bars for the reflectometer density profile measurements. Comparison with other diagnostics is critical. As will be shown in the chapter [4], comparisons with the scanning probes and Thomson scattering give reasonable results.

As reflectometers have large systematic error bars, but usually small statistical
error bars, comparison between density profiles, especially comparisons between the shapes of the density profiles, can be done very accurately with reflectometry. This thesis focuses on comparing density profiles, so it avoids these systematic errors.

For all reflectometer figures in this thesis, with steady state or nearly steady state plasma parameters, statistical and inversion errors, but not systematic errors, are shown. Each reflectometer density profile measurement is an average of 25 sweeps over a 40 µs sweep period. Each reflectometer profile shown in these figures is therefore an average of many 1ms time-averaged density profiles. The shaded box in these figures indicate the ± 1 radial standard deviation of the collection of processed density profiles. As will be shown in chapter 4, these statistical error bars are usually small.

It should be noted that error bars will not be quoted in discharges that are not steady state. Because the statistical errors are usually small in steady state discharges, it is believed that the statistical error is also small in these discharges and that the density profile is varying due to fast plasma dynamics. Due to the small statistical error and large systematic error for X-mode reflectometry, it is well-suited for measuring density profile modifications and ideal for understanding the effects of LH and ICRF-induced ExB eddies on the density profile and LH coupling.

### 3.5 Density Fluctuations

Reflectometers are commonly used for density fluctuation measurements. A constant or staircase frequency is used and a spectrogram of the detected signal is used to visualize the phase fluctuations as a function of time and a function of the Fourier frequency components. More sophisticated techniques exist for measuring density fluctuations. For a swept frequency system, techniques have been developed to acquire the phase fluctuation level as a function of the radial wavenumber [101]. Correlation reflectometry can also be used to measure the radial correlation length of the density fluctuations [102]. This requires two frequency channels that are swept independently.
The phase fluctuation measurements are often used for qualitative analysis, but a detailed numerical simulation is needed to convert phase fluctuations into quantitative density fluctuation levels [103]. This is usually the most difficult step for reflectometer density fluctuation measurements.

Since density fluctuations are not the focus of this thesis, there has not been any substantial analysis of density fluctuations measurements. Proof of principle phase fluctuation measurements were done. During a low field discharge ($B_0 = 2.7$ T), the X-mode cutoff is at a higher density ($\sim 10^{20} m^{-3}$). When the reflectometer is kept at a constant frequency, a coherent fluctuation is observed at 100 and 200 kHz (figure 3-21). This frequency range is consistent with the quasicoherent (QC) mode observed on Alcator C-Mod [104].

It has also been observed with the X-mode reflectometer that the broadband turbulence in the edge and SOL decreases during LH operations. One example is shown in figure 3-22. In this discharge, a staircase input frequency was used to get an estimate of the radial density fluctuation profile. It can be seen that for all frequencies observed, the broadband density fluctuations decreases during LH operations. It needs to be noted that that since LH induces density profile modifications, the frequencies during the OH and LH time intervals correspond to different cutoff radii.
Broadband turbulence is observed to decrease at the edge and SOL during LH operations at low densities.

However, the decrease in low frequency turbulence was observed on all 4 reflectometer horns. As will be shown in chapter 5, LH power can increase the density at one horn and decrease the density at another horn, so the reflectometer frequency scans will probe substantially different radial locations for each of the 4 reflectometer locations. It is thus possible to conclude that LH power decreases the broadband turbulence over this entire region. This broadband decrease also occurs whether the reflectometer location is magnetically connected to the LH grill (LH-SOL reflectometer horns) or not (ICRF-SOL reflectometer horns).

The turbulence reduction is also observed with the GPI and RFA diagnostics that are both magnetically connected to the LH launcher. Given the different diagnostic techniques and different toroidal and poloidal locations, it is believed that this LH-induced turbulence modification is a global effect. It will be shown in chapter 5 that the LH-induced SOL density profile modifications observed by the LH-SOL reflectometer may be a local effect that is dominated by flows directly generated by the LH waves near the LH launcher.

A more detailed study of density fluctuations, comparison to other density fluctuation diagnostics, and understanding of LH-induced turbulence for a wide range of
plasma parameters on Alcator C-Mod should be done in the future.
Chapter 4

SOL Density Profiles on Alcator C-Mod

4.1 Dependence on Plasma Parameters

SOL density profile measurements will be presented in this chapter for a wide range of plasma parameters, including line averaged density, current, outer gap, and different main ion species. For all discharges shown here, the magnetic field was approximately 5-6 T, corresponding to a density range of approximately $5 \times 10^{16}$ to $6 \times 10^{19} \text{ m}^{-3}$ for the SOL reflectometer. The 100-146 GHz reflectometer frequencies are optimized to measure the SOL density profiles only in this magnetic field range.

The chapter is organized to first present results that have been well-known from previous measurements done in Alcator C-Mod and other tokamak experiments. Scans of $\bar{n}_e$ and $I_p$ are used to validate the reflectometer measurements with other density profile diagnostics, specifically Thomson scattering and Langmuir probes. The rest of the measurements in this chapter focus on parameters important for RF coupling and RF-SOL interactions. Variations in outer gap [34], atomic species [72], regimes (L and H-modes) [35], LH launcher location [12], or localized gas puffing [62]
are known to significantly affect RF coupling. The effect of these parameters on the SOL density profile are sometimes discussed and measured in other magnetic confinement devices, but detailed measurements have not previously been attempted on Alcator C-Mod. Detailed measurement and analysis of the effects of LH and ICRF power on the SOL density profile will be presented in chapters 5 and 6, respectively.

4.1.1 Line Averaged Density

For different $n_e$ in OH L-modes, there are a number of discharges with Thomson scattering and/or scanning Langmuir probe diagnostics available. Given the systematic uncertainties of the reflectometer measurements, it is necessary to compare with other diagnostics in well-known plasma conditions to verify that the reflectometer density profiles are reasonable. The Thomson scattering and scanning Langmuir probe diagnostics are discussed in section 1.4.5. These comparisons were done in ohmic discharges, so as to avoid as many difficulties as possible in diagnostic interpretation.

Comparisons of the density profiles from the reflectometer measurements with Thomson scattering is shown in figure 4-1 for two different $n_e$ (red and blue). Every Thomson scattering data point is plotted over this time period. The reflectometer density profiles are shown by the solid line. In spite of the scatter in the Thomson data, that may be partially due to decreased power in one of the Thomson lasers, the agreement between reflectometry and Thomson scattering appears reasonable, especially for the low $n_e$ case when the reflectometer density profiles overlap with the Thomson data. It is also reasonable that the density profile increases as $n_e$ density increases.

The A-port and F-port scanning probe comparisons with the reflectometer often show better agreement, as seen in figure 4-2. The agreement is good throughout the SOL. Disagreement does occur in two radial regions. In the region shadowed by the plasma limiter, the profiles do not agree. This is not surprising since the scanning
Figure 4-1: Comparison between reflectometer and Thomson scattering density profiles are shown for two different line averaged densities (red and blue). Symbols are the Thomson scattering measurements and lines are the reflectometer measurements.
Figure 4-2: Comparison between reflectometer and scanning Langmuir probe measurements are shown for two different $\bar{n}_e$. Symbols are the scanning probe measurements and lines are the reflectometer measurements. Blue and red color indicates the two different $\bar{n}_e$. The LCFS, plasma limiter, and LH launcher locations are denoted.
probes and the reflectometer are in different private flux regions, so the different diagnostics are probably reflecting toroidal density profile asymmetries. For plasmas near the separatrix, measurements might also be starting to deviate slightly. Probes often become emissive at the separatrix, so this may explain the disagreement, as Thomson scattering and reflectometer agree in this radial region (figure 4-1). It is especially encouraging that the density profile shapes from the reflectometers and probes agree reasonably well, as both diagnostics are very sensitive to the shape of the profiles. The toroidal asymmetries behind the plasma limiter also indicate the importance of a local density profile measurement for evaluation of RF coupling.

4.1.2 Current

As $I_p$ is decreased, the far SOL density usually increases and the density profile becomes broader [105]. This is shown in figure 4-3 for discharges with two different $I_p$ and similar $\bar{n}_e$. Both the reflectometer (line) and Thomson scattering (circles) data are shown. Agreement between the two diagnostics seem reasonable given the scatter in the Thomson data. It should be noted that the density profile shapes differ somewhat at the two plasma currents, consistent with previous Langmuir probe and Thomson scattering measurements on Alcator C-mod, and other experiments that show an increased far SOL density for increasing Greenwald fractions [106].

4.1.3 Deuterium vs. Helium plasmas

Since deuterium and helium have the same charge to mass ratio, the ICRF core physics behave similarly. Due to the different recycling properties between deuterium and helium, the SOL physics and density profiles often differ. Deuterium usually has a higher SOL density and consequently improved ICRF coupling [72]. Comparison of ICRF operations between these two species is therefore sometimes used to study ICRF coupling.
Figure 4-3: Comparison between reflectometer and Thomson scattering are shown for two different currents (red and blue). Symbols are the Thomson scattering measurements and lines are the reflectometer measurements.
Results are shown comparing deuterium and helium OH L-mode discharges in figure 4-4. The $\bar{n}_e$ is similar between these two discharges, and the SOL density profile in deuterium plasmas is substantially higher than in helium plasmas. Both the reflectometer and scanning probes show this trend. The two diagnostics also agree extremely well except in the private flux regions and near the LCFS. These results are consistent with those in reference [72].

4.1.4 H-mode

The transition from L-mode to H-mode can significantly alter the SOL density profiles. This is first shown for an EDA H-mode and then an ELM-y H-mode.

During H-modes, the density profile often forms a pedestal near the LCFS. Due to the reflectometer density profile coverage, only the base of the pedestal is usually measured. This is shown in figure 4-5. The Thomson and reflectometry data agree reasonably well. It should be noted that the data here were taken during a time interval without ICRF.

During ICRF heated ELM-y H-modes, the pedestal often collapses and recovers on a fast timescale (1-20 ms) on Alcator C-Mod. High time resolution reflectometry is often used to study the density profile dynamics between and during ELMs on other tokamaks [68][69]. Proof of principle X-mode reflectometer SOL density profile measurements are shown here in figure 4-6 with 120 $\mu$s time resolution. Since ELM dynamics often occur on a timescale faster than 120 $\mu$s, not all of the dynamics can be captured with this current measurement capability. Regardless, the rapid evolution of the density profile is captured through many ELM cycles.

This becomes even more evident when the profiles are plotted as a function of radius over a ELM cycle. Due to the fast time dynamics of ELM collapse and recovery, error bars are only shown for the approximately steady state time intervals that occurs approximately 10ms after an ELM event. The trends between the density profiles and
Figure 4-4: Reflectometer and scanning Langmuir probe density profile measurements are compared for helium (blue) and deuterium (red) plasmas at the same $\bar{n}_e$. Symbols are the scanning probe measurements and lines are the reflectometer measurements. The two diagnostics agree in both cases and show that the SOL density profile is higher in deuterium majority plasmas.
Figure 4-5: a) Comparison between the reflectometer and Thomson scattering are shown during L-mode and EDA H-mode (red and blue). Symbols are the Thomson scattering measurements and lines are the reflectometer measurements. b) Time history of $\bar{n}_e$. c) Time history of the ICRF power. The blue and red shaded rectangles show the time intervals during which the data are being compared.
D-alpha are clear, and are shown in figure 4-7a) and b). Before an ELM starts, the SOL density is low and the foot of the pedestal is steep. When the D-alpha signal peaks and the pedestal collapses, the SOL density increases considerably (red dashed line) because the particles in the pedestal have been transported into the SOL. The SOL density continues to increase until a few hundred $\mu$s after the peak of the D-alpha (solid red line). The dashed, solid, and dot-dashed red lines represent times when the density profile is rapidly evolving while the other colored lines represent time intervals where the density is not changing as rapidly. The SOL density then starts recovering to its original value (dot-dashed red line, yellow, and purple line). The SOL density then recovers to its original state after a few ms (green and cyan lines). It is interesting to note that the density profiles remain clamped a few mm in front of the LH launcher. The reason for this is unclear and has not been noted in the literature. The other trends are consistent with those in references [68][69].

4.1.5 Outer Gap

Large variations in outer gap result in strong modifications to the SOL density profile. This is an important parameter in RF coupling, since the distance through the evanescent layer significantly changes with outer gap. Reflectometry measurements on DIID [34] and TFTR [82] have shown this effect. During inner-wall limited (inner gap is 0 cm) OH discharges, the outer gap of Alcator C-Mod discharges can be varied from approximately 2 to 13 cm. The reflectometer measurements are shown in a three-dimensional contour plot in figure 4-8. For the timeslices indicated by the color dashed lines in this figure, the density profiles are plotted as a function of radius for different times in figure 4-9. It can be observed that as the outer gap gradually increases, the density profile gradually decreases as expected. The $\bar{n}_e$ was rising during this discharge, so this has some effect on the SOL density profiles.

While this was an OH discharge, the effects of the outer gap on RF coupling can be estimated by measuring the ICRF fast wave cutoff radius. For an 80 MHz
Figure 4-6: a) SOL density profiles are shown during multiple ELM events. Horizontal dashed black, horizontal short-dashed red line, and horizontal long-dashed red lines represent the radial location of the LCFS, plasma limiter, and LH launcher, respectively. b) Time history of the D-alpha brightness is shown during the same time interval as in part a).
Figure 4-7: a) SOL density profile dynamics are shown before and after an ELM event for multiple timeslices. Timeslices are represented by color: red timeslices indicating times when the density profile is rapidly changing. These colors also correspond to the times at which the profiles are plotted in b). The dashed vertical black box represents the approximate radial location of the LH launcher. b) D-alpha brightness is shown during this time interval.
Figure 4-8: a) SOL density profiles during an outer gap scan of an inner-wall limited OH discharge are plotted as functions of radius and time. The dashed color lines represent timeslices that are plotted in the next figure. The LCFS and plasma limiter locations are denoted by black dashed lines. While there was no active ICRF antenna, the ICRF fast wave cutoff radius for an 80 MHz frequency is denoted by the purple line for illustrative purposes. b) The line averaged density is plotted as a function of time. Dashed vertical color lines represent the times at which profiles are plotted in the next figure.
Figure 4-9: SOL density profiles as a function of radius during an outer gap scan. Colors represent different timeslices. Symbols represent the ICRF fast wave cutoff radius and density.

frequency, the fast wave cutoff radius is shown by the purple line in figure 4-8 and by colored asterisks in figure 4-9. The cutoff radius varies by approximately 5 cm during this outer gap scan. Using equation 2.23 for the case of the E-port ICRF antenna (f = 80 MHz, n|| = 10), variations of 5 cm in the cutoff radius would result in a factor of 2.5 difference in the ICRF antenna loading. It should be noted, however, that the density gradient outside the cutoff decreases with increasing outer gap. Since both the evanescent layer distance and density gradient are important factors in understanding ICRF coupling, a RF coupling code is necessary to fully understand these effects. Re-doing these outer gap discharges with RF power and comparing with RF simulation models should be done in the future.

It should again be noted that EFIT mapping errors are often a few mm radially and that the reflectometer error bars are often a few mm radially. Since the scanning probes, Thomson scattering, and reflectometer are located at different poloidal locations, EFIT mapping is necessary to compare the profiles. In figure 4-2, the probe data needed to be shifted by between 0-5 mm relative to the reflectometer data to get accurate agreement, presumably due to a combination of EFIT mapping errors and reflectometer radial errors. The Thomson scattering data was also shifted approxi-
mately 5 mm to give agreement with the reflectometer. Due to the radial errors, it is thus most informative that the trends and density profile shape do agree among diagnostics during this scan.

### 4.1.6 LH launcher location

Another parameter that can strongly modify the SOL density profile is the radial location of the LH launcher. On Alcator C-Mod, the LH launcher is usually positioned close to the LCFS to increase the density in front of the LH launcher and improve LH coupling. An example of this is shown in figure 4-10 for two extremely similar OH discharges (LH power is not applied), in which the LH launcher location was changed. When the LH launcher is close to the plasma (red line), the density and density gradient in front of the LH launcher are high. When the LH launcher is further away from the plasma, the density and density gradient are lower in front of the launcher. The two density profiles appear to start converging in the SOL.

It is interesting to note that the density profiles a few mm behind the plasma limiter are different for these two discharges even though the magnetic connection lengths behind the plasma limiter are the same for both discharges. This suggests that there may be other physical mechanisms, such as atomic physics, involved besides a simple diffusion and magnetic connection length argument.

### 4.1.7 Localized gas puffing

The trends in the reflectometer density profiles with $\bar{n}_e$, $I_p$, ELM’s, outer gap, and majority atomic species follow the expected behavior that has been observed in other tokamaks. The reflectometer can thus be used to measure density profile modifications from less well-known behavior such as localized gas puffing.

Localized gas injection is a technique that is often used to increase the local
Figure 4-10: Density profile for different LH launcher locations with otherwise very similar plasma discharges. Red shows the density profile when the LH launcher is close to the plasma and blue shows the density profile when the LH launcher is retracted from the plasma. The respective positions of the front of the LH launcher are shown by the vertical dashed lines.
density and improve ICRF coupling \cite{34,107} and LH coupling \cite{12,108} in many experiments. The ultimate goal is to increase the SOL density profile locally without making any global core plasma parameter modifications that affect plasma performance. While gas puff induced modifications of the ICRF and LH coupling have been noted in most experiments around the world, the local density profile modifications of gas puffing have rarely been measured. In particular, possible poloidal density profile asymmetries have never been explored. This has been measured for the first time on Alcator C-Mod.

Two gas capillary tubes have been installed adjacent to the top and bottom row of the LH launcher. The tubes are shown in figure 4-11. The gas plenum was injecting deuterium at a pressure of 10 psi for either tube, which corresponds to an injection
Figure 4-12: a) During OH L-modes, SOL density profile measurements are shown before and after an injection from the top gas puff tube. Measurements are made with the top reflectometer horn. b) A blow-up of the region inside the yellow box in a) is shown.

rate of approximately 14 torr-L/sec. The top reflectometer horn was used for these localized gas puffing experiments. It should be noted that this measurement was done in piggyback with another experiment, so the pressure of the gas tubes was actually high enough to cause an increase in $\bar{n}_e$. Plasma parameters were also changing between discharges, so comparisons can only be made within discharges.

In figure 4-12 SOL density profile modifications are shown during an OH L-mode when the top gas injector was used. The $\bar{n}_e$ was coincidentally decreasing as a function of time in this discharge prior to the gas puff, so there was a duration of time before and after gas injection with similar $\bar{n}_e$. In figure 4-12a), the density profile over the entire SOL is shown for cases before and after the gas injection. A blow-up of the SOL density profiles within the yellow region of 4-12a) is shown in figure 4-12b). For the same $\bar{n}_e$, the effects of the gas puffing on the SOL density profiles are shown by the differences between the black and red cases. This is especially evident near the LH launcher, where the density gradient increases after the application of the gas puff. As more deuterium gas is injected, $\bar{n}_e$ increases, causing a further increase in the SOL density profile. This is shown by the blue case. The top gas puff thus causes both local and global increases of the SOL density measured by the top horn.
In figure 4-13, SOL density profile modifications are shown for an OH L-mode when the bottom tube was used. The $n_e$ was again decreasing as a function of time in this discharge prior to the gas puff, so there was a duration of time before and after gas injection with similar $n_e$. In figure 4-13a), the density profile over the entire SOL is shown for cases before and after the gas injection. A blow-up of the SOL density profiles within the yellow region of 4-13a) is shown in figure 4-13b). For the same $n_e$, the effects of the bottom gas puff are minimal on the SOL density profile, as evidenced by the difference between the black and red lines. There is minimal changes on the SOL density profile near the LH launcher, at least in the location of the top horn, which is poloidally distant from the gas puff location.

In figure 4-14, SOL density profile modifications are shown for an ICRF L-mode when the top tube was used. The $n_e$ was decreasing as a function of time prior to the gas puff, so there was a duration of time before and after gas injection with similar $n_e$. In figure 4-14a), the SOL density profiles for the entire SOL are shown before and after the gas injection for the top horn. A blow-up of the SOL density profiles within the yellow region of 4-14a) is shown in figure 4-14b). As in the OH case measured by the top horn, the gas puff increases the local SOL density profile. After the application
of the gas puff in the ICRF case, however, the density gradient near the LH launcher does not always increase throughout that radial region. Qualitatively, the density gradient seems to decrease within 2 mm of the LH launcher. This appears to be different from the OH case, and possibly suggests that the effects of gas puffing on the SOL density profile differ with and without ICRF power.

These results indicate that the ionization mean free path of the neutrals is short enough that gas is ionized locally, and the particles travel along magnetic field lines on Alcator C-Mod. Only the horn that is closest to the gas puff measures any noticeable local density profile modifications. This suggests that for maximizing the effect of gas puffing for RF coupling purposes, the gas puff needs to be magnetically connected to ICRF antennas and LH launcher. This will be discussed in chapters 5 and 6.
Chapter 5

LH-induced transport

In this chapter, the effects of LH power on the SOL transport and SOL density profiles are examined in detail. The chapter is organized to first present experimental measurements of LH-induced flows and density modifications, and their dependence on various plasma parameters such as $B_0$, inner gap, and $\bar{n}_e$. The experimental measurements are then shown to be consistent with a LH-induced SOL absorption mechanism that drives ExB drifts. The ExB drift drives convective transport and poloidal density asymmetries, which forms striations of increased density that occur either above or below the center of each waveguide row, depending on the toroidal magnetic field direction. A diffusive-convective model has been developed and implemented to show that the inclusion of LH-induced plasma flow measurements into the model can explain the LH-induced poloidal and radial density modifications.

Following the discussion of LH-induced density modifications, the impact of the density modifications on LH coupling will be presented. A LH coupling model, using reflectometer density profiles as inputs, shows good agreement with experimental results at poloidal locations that are in front of (away from the striations), and not between (at or near the striations) waveguide mouths. The striations are also shown to cause increased SOL interactions that are imaged by video cameras at the G-H limiter, 160° away toroidally from the LH launcher, indicating that understanding these LH-
induced asymmetries are important LH-SOL interactions at toroidal locations other than the LH launcher.

5.1 LH-induced steady state plasma flow measurements

The gas puff imaging (GPI) diagnostic has been used to measure steady state poloidal flow during OH, ICRF, and LH discharges. The measurement principles and limitations are discussed in full detail in reference [20]. Only a brief summary of the flow results are included in this section.

The GPI diagnostic is a 4 cm x 4 cm radial and poloidal array. To measure the radial profile of the plasma flow, a spectrogram is done over both the temporal and poloidal fourier frequency domain to create a wavenumber-frequency spectrum at each radial location. A conditional spectrum is then taken along fixed velocity contours to measure the radial profile of the poloidal phase velocity. This measured phase velocity is shown to be equivalent to the poloidal ExB velocity for ohmic discharges [20], and this equality is assumed to hold in LH and ICRF powered discharges.

GPI results of LH-induced flows are shown in figure 5-1 during normal magnetic field direction (clockwise when viewed from above the vacuum vessel), OH and LH operation for three cases: \(\tilde{n}_e = 1 \times 10^{20} \text{ m}^{-3}\) with 600 kW of LH power, \(\tilde{n}_e = 1.2 \times 10^{20} \text{ m}^{-3}\) with 200 kW of LH power, and \(\tilde{n}_e = 1.2 \times 10^{20} \text{ m}^{-3}\) with 600 kW of LH power.

For this magnetic geometry, the 4 cm x 4 cm GPI view was magnetically mapped to the bottom of the top row and the top of the second row of the LH launcher. Since charged particles flow rapidly along field lines, it is expected that LH-induced plasma flows and potentials are constant along a field line. For both the low LH power (figure 5-1d) and low \(\tilde{n}_e\) (figure 5-1b) cases, the LH-induced plasma flow modification was minimal except in the far SOL near the LH launcher. For the high
Figure 5-1: The measured poloidal velocity profiles inferred from analysis of gas puff imaging. a)c)e) The measured poloidal velocity is shown during OH operation. The $\bar{n}_e$ is $1 \times 10^{20} \text{ m}^{-3}$ in a), $1.2 \times 10^{20} \text{ m}^{-3}$ in c), and $1.2 \times 10^{20} \text{ m}^{-3}$ in e). b)d)f) The measured poloidal velocity is shown during LH operation. The $\bar{n}_e$ is $1 \times 10^{20} \text{ m}^{-3}$ in b), $1.2 \times 10^{20} \text{ m}^{-3}$ in d), and $1.2 \times 10^{20} \text{ m}^{-3}$ in f). The LH power is 600 kW in b), 200 kW in d), and 600 kW in f).
and high LH power case (figure 5-1f), the LH-induced flow is driven throughout a substantial region of the far SOL. In all these cases, the LH-driven poloidal flow is in the electromagnetic drift direction (EDD), which is upwards for normal toroidal magnetic field direction (clockwise when viewing from above).

A theoretical model predicting LH-induced SOL flow modifications has not been extensively discussed in the literature, but the flow is believed to be due to LH-induced SOL absorption discussed in section 2.2.3. At high densities on Alcator C-Mod, the LHCD efficiency is observed to drop abruptly. One possible cause is SOL absorption, and the increase in experimentally measured flow modifications at high densities are consistent with the expected increase in SOL absorption at high LH power and high $n_e$. The upward flow direction is also consistent with the expected ExB drift direction of LH vortices, and with video camera emissivity measurements for typical magnetic field direction on Alcator C-Mod. This will be further discussed in section 5.3.

### 5.2 LH-induced density profile modifications

Given that LH is observed to modify the poloidal flow, the convective transport should result in density modifications and poloidal asymmetries (chapter 2). This section presents the density profile measurements that support this physical picture. The effects of LH power on the SOL density profiles are shown for various plasma parameters, such as $n_{||}$, LH power, magnetic topology, $n_e$, and magnetic field direction. Details of these results are also available in reference [109].

#### 5.2.1 SOL density behavior as a function of different LH power and launched $n_{||}$

The effects of LH power on visible emission from the SOL can be imaged with a video camera diagnostic that views the LH launcher. Figures 5-2a) and 5-2b) show
Figure 5-2: Unfiltered visible video camera images for a typical LH heated discharge are shown. a) $n_{||} = 1.4$. b) $n_{||} = 1.9$. Striations of increased brightness can be observed in both cases. Reflectometer horn locations are indicated by the red rectangles. $n_{||} = 2.3$ case is not shown, but is very similar to b). The direction of B is indicated.
two such images for two different values of \( n_{||} \). Striations of increased emissivity are routinely observed above the centers of two of the waveguide rows and roughly aligned with the direction of the total magnetic field. The striations are noticeable on all four waveguide rows at the left LH limiter. Reflectometer horn locations are also indicated by red rectangles in both images. Figure 5-2 also shows that the qualitative nature of these striations changes with the launched \( n_{||} \) of the LH waves. For \( n_{||} = 1.4 \), the striations are shifted upwards relative to those in the \( n_{||} = 1.9 \) case.

For \( n_{||} = 1.9 \) (figure 5-2b), the middle reflectometer horn views through one of the striations. For \( n_{||} = 1.4 \) (figure 5-2a), the middle reflectometer horn no longer views the striations. Density profile comparison among ohmic (OH), \( n_{||} = 1.4 \) LH, and \( n_{||} = 1.9 \) LH cases for a L-mode discharge using the middle reflectometer horn, are shown in figure 5-3 for \( n_e \) approximately equal to \( 8 \times 10^{20} \text{ m}^{-3} \) and 200-300 kW of LH power. As can be observed in figure 5-3b), there are minimal differences between the density profiles during the OH and \( n_{||} = 1.4 \) cases, but significant differences between the density profiles with \( n_{||} = 1.9 \) case compared to the other two cases. This suggests that the density profiles are significantly different near and away from the striations. Figure 5-3b) shows the density profiles throughout this discharge. The differences between the density profiles in the \( n_{||} = 1.9 \), \( n_{||} = 1.4 \) and OH cases shown in figure 5-3a) can be observed in the relevant time intervals in figure 5-3b). It should be noted that the effect of the LH power on the SOL density profiles is immediate, with the changes occurring in less than the 1ms time resolution of the diagnostic. In fact, the characteristic time of this LH-induced change for all observations shown in this thesis is less than 1ms. The \( n_{||} = 2.3 \) case (between 1.15 and 1.3 s) also shows similar density profiles to those of \( n_{||} = 1.9 \) case. The corresponding video camera image (not shown) for the \( n_{||} = 2.3 \) case is also similar to the \( n_{||} = 1.9 \) case.

For the \( n_{||} = 1.9 \) case, the top reflectometer horn is very close to a striation, while the bottom horn is far away from any striations. In figures 5-4a), 5-4b), and 5-4c), density profile measurements comparing OH versus LH powered L-mode discharges are shown for the top, middle and bottom horns, respectively. It should be noted that
Figure 5-3: a) Measurements through the middle horn during OH, \( n_{\parallel} = 1.4 \), and \( n_{\parallel} = 1.9 \) LH-powered L-mode SOL density profiles are shown by black solid, blue solid, and red dashed lines, respectively. The SOL density profiles for the \( n_{\parallel} = 1.9 \) L-mode greatly differ from the other two cases. The colors represent the time over which the density profile was averaged. These colors correspond to the colors in the shaded rectangles in b), c), d), and e). b) The density profile is shown as a function of time throughout this discharge. c) \( n_{\parallel} \) for this discharge is shown with the three cases in a) highlighted. d) LH power for this discharge is shown with the three cases highlighted. e) \( \bar{n}_e \) for this discharge is shown with the three cases highlighted.
Figure 5-4: a), b), c) Measurements comparing OH (black solid line) and LH (red dashed line) L-mode discharges at the top, middle, and bottom horns, respectively for 200-350 kW of LH power and $\bar{n}_e$ between $6.5-7.5 \times 10^{20}$ m$^{-3}$. 
Figure 5-5: a) SOL density profile is shown for this discharge as a function of time and major radius. b) LH power is shown for this discharge. c) $\overline{n_e}$ is shown for this discharge. The colored, shaded, rectangles in this figure corresponds to the time intervals over which the density profile is averaged in the colored lines in figure 5-6.

these are different discharges, but with similar global plasma conditions (200-350 kW of LH power and $\overline{n_e}$ between $0.6-0.65 \times 10^{20} \text{ m}^{-3}$ in OH and between $0.7-0.75 \times 10^{20} \text{ m}^{-3}$ in LH discharges) because only one reflectometer horn can be used during each discharge. For the middle horn that views the striations, there is a substantial density profile modification, especially a steep increase in density gradient and density approximately 2-4 mm away from the LH launcher, when LH power is applied. On the other hand, the bottom and top horns, which do not view through the striations, show minimal density profile modifications when LH power is applied.
Figure 5-6: a) SOL density profile is shown for the discharge in figure 5-5 for timeslices without LH power (black solid line), with 200 kW LH power (blue dashed-solid line) and with 600 kW LH power (red dashed line). b) Blow-up of the SOL density profile in the yellow rectangle of part a) is shown. c) The $I^2+Q^2$ signal, which is representative of the amplitude of the reflectometer signal, is shown here. It is clearly observed that the signal rises at different frequencies for each of the three cases.
Since these striations are visible on the video cameras only during the application of LH power, it is not surprising that increasing LH power will have a stronger effect on the density profile. In figure 5-5a, the SOL density profile is shown during a two-step LH power scan (figure 5-5b). When 200 kW of LH power is applied, the SOL density profile immediately increases near the LH launcher. Since the middle horn views one of the striations for the $n_{||} = 1.9$ case, 200 kW of LH power increases the density and density gradient a few mm away from the LH launcher. 600 kW of LH power further increases the density and density gradient a few mm away from the LH launcher. When the LH power is de-energized, the density and density gradient in the far SOL relaxes to its original value before LH power is applied. It is clear the LH power has a direct effect on the SOL density profiles.

5.2.2 High line averaged densities

Higher $\bar{n}_e$ cases ($\bar{n}_e > 1 \times 10^{20} \text{ m}^{-3}$) exhibit additional LH-induced SOL density profile modifications that are not present in the lower $\bar{n}_e$ cases. A blowup of the density profile in figure 5-6a, for the region around the LH launcher, is shown in figure 5-6b. When LH power is applied, a significant density increase occurs behind the LH launcher in the 2 cm toroidal gap between the LH protection limiter and LH launcher. Increasing LH power also raises the density even more behind the LH launcher. This density increase leads to surprising behavior in the reflectometer $I^2 + Q^2$ signal, as shown in figure 5-6c. For each of the three cases, the signal rises at different frequencies, indicating that the lowest cyclotron frequency is at different radial locations. This is because a lower initial frequency corresponds to an initial cutoff-layer further out in major radius because of the relationship between the cutoff frequency and the local $|B|$ field. This accounts for the density increase observed in figure 5-6b. It should be noted that the increased density behind the launcher, and the relative shift in the lowest cyclotron frequency, does not increase for OH discharges, LH powered discharges at lower $\bar{n}_e$, as in the $\bar{n}_e \sim 0.7-0.8 \times 10^{19} \text{ m}^{-3}$ case, or for any $\bar{n}_e$ LH powered discharge measured at reflectometer horns that are located
Figure 5-7: a), b), c) Measurement comparing OH (black solid line) and LH (red dashed line) L-mode discharges at the top, middle, and bottom horns, respectively, for 200-350 kW of LH power and $\bar{n}_e$ approximately equal to $1.6 \times 10^{20} \text{ m}^{-3}$
The LH-induced poloidal density profile asymmetries at higher $\bar{n}_e$ are also different from those in the lower $\bar{n}_e$ cases. Density profile measurements shown in figure 5-7(a), 5-7(b), and 5-7(c), comparing OH versus LH heated L-mode discharges, are shown for the top, middle, and bottom horns at 200-350 kW of LH power, $n_{\|} = 1.9$ and $\bar{n}_e$ between $1.2-1.4 \times 10^{20} \ m^{-3}$. LH seems to slightly raise the density for measurements at the top horn. The middle horn view shows significant increase in density and density gradient throughout the far SOL. In contrast, the bottom horn view shows a significant decrease in density in the far SOL when LH power is applied. The effect of LH power appears much stronger for high $\bar{n}_e$, especially for the bottom horn where LH power induces strong density profile modifications over a large radial region of the SOL.

5.2.3 SOL density behavior in inner wall limited vs. diverted discharges

Even for similar $\bar{n}_e$ between 1.3 and $1.4 \times 10^{20} \ m^{-3}$, significant differences in the LH-induced density profile modifications are observed for different magnetic topologies. Figure 5-8 shows the density profiles measured at the middle horn, with and without LH power, for an inner wall limited (IWL) discharge and a diverted discharge. The effects of LH power in the diverted discharge (black and red dashed lines) show very similar behavior to those seen in figure 5-5(d). LH power increases the density and density gradient a few mm away from the LH launcher. This density profile modification also occurs in the inner wall limited discharge, but to a much smaller extent than in the diverted discharge. It should also be noted that there are also differences in IWL and diverted cases during the ohmic phase of the discharges. Even if the density is the same near the LCFS, the SOL density is much lower in the IWL case than in the diverted case over a wide radial region of the SOL.
Figure 5-8: Measurements of the SOL density profile for the center horn, with and without LH power, are shown for IWL and diverted discharges. The four cases, IWL OH (solid black line), IWL LH (solid red line), diverted OH (dashed black line) and diverted LH (dashed red line) are shown. The vertical, short dashed black line and the vertical, solid black line represents the LH launcher location during diverted and inner wall limited cases, respectively.

Figure 5-9 shows the density profile modification during an inner gap scan, with LH power. As the inner gap is decreased from 1 cm to .6 cm, the density profile is not significantly modified. For inner gaps less than .6 cm, however, the far SOL density significantly decreases and the radiation temperature, $T_{rad}$, measured by ECE at a major radius of .88 m, also significantly increases. There is correlation between the LH-induced SOL density profile modification and the increased radiation temperature. Given that the increased radiation temperature is believed to be caused by LH-induced SOL absorption [12], LH-induced SOL absorption should also be correlated with LH-induced density profile modifications.

5.2.4 Reversed magnetic field direction

When the toroidal magnetic field direction is reversed (counterclockwise flow when viewed from above the vacuum vessel) so that it points from right to left in the video camera image, the pattern of striations is modified. The striations are now below
Figure 5-9: a) Measurements of the SOL density profile for the center horn for cases with and without LH power are shown as functions of time. Inner gap is scanned within the time interval with LH power. b) LH power and inner gap are plotted as functions of time. c) Nonthermal ECE at a major radius of approximately .88m is plotted as a function of time.
Figure 5-10: a) Visible video camera image of a typical LH heated discharge during reversed field operation. b), c), d) Measurements comparing OH (black solid line) and LH (red dashed line) L-mode discharges at the top, middle, and bottom horns, respectively, for 600 to 800 kW of LH power and $\bar{n}_e$ between $0.5-0.7 \times 10^{20} \text{ m}^{-3}$.
the center of each waveguide row instead of above the center of each waveguide row. This is observed in figure 5-10a). Because of the reflectometer horn locations, the bottom horn now view through a striation while the middle horn does not. The top horn is also close to a striation. It is observed that LH now causes increases in the density and density gradient near the LH launcher for the bottom horn. For measurements through the middle horn, LH power decreases the density near the LH launcher, opposite to the observation in normal toroidal magnetic field direction shown in figures 5-4 and 5-7. There is some change for measurements through the top horn. There is minimal change within the LCFS. It is thus clear that LH power causes density increases in localized bands and can decrease the density away from these bands.

5.3 Discussion of physical mechanisms

In the previous section, substantial LH-induced SOL density modifications, which vary with changes in $n_{||}$, LH power, $\bar{n}_e$, magnetic topology, and magnetic field direction, have been measured for the first time near the LH launcher in a tokamak. These SOL density profile modifications are correlated with LH-induced emissivity striations that are imaged with visible video camera. The density modifications also occur within 1 ms, much faster than the estimated 50 ms for the energy confinement time. These observations hint at a direct LH-induced effect on the SOL density profiles.

There have been many physical mechanisms proposed to explain LH-induced density modifications in the literature: ponderomotive forces [61], ionization [64], and ExB convective eddies [66]. Given the first observation of LH-induced density modifications in a tokamak, testing of these mechanisms is now possible. The experimental results suggest that ExB convective eddies dominate the density modification.

As discussed in section 2.2.3, emissivity striations have previously been observed in
other LH experiments, in linear machines [66], on Tore Supra [64] and on ASDEX [61].

Previous work indicates that this may be due to SOL absorption that either increases the thermal electron temperature or creates fast electrons in the SOL, causing LH-induced plasma potentials. Thermal effects are discussed in reference [66] and are believed to be due to LH-induced surface waves. References [63] and [64] present retarded field analyzer measurements of fast electrons, generated from a large negative \( n_{||} \) spectrum, which can possibly Landau damp at low temperatures in the SOL near the LH launcher. A population of a few percent of fast electrons can also greatly increase the plasma potential [110]. Regardless whether fast electrons or hot thermal electrons drive these plasma potentials, the potentials in turn can drive ExB convective flows or vortices that can then modify the transport and density profiles.

The effects of LH-induced plasma potentials on the density profiles are consistent with the density profile modifications observations. For increasing \( n_e \) on Alcator C-Mod, LHCD efficiency is greatly reduced [111]. In reference [111], Wallace et al also show that for the same \( n_e \), diverted discharges drive much less current than inner wall limited discharges. One possible explanation is LH-induced SOL absorption. According to the theory described by Motley, LH-induced SOL absorption drives a LH vortex [66]. If the SOL absorption is stronger in high \( n_e \) diverted geometries, then the density profile modifications should be stronger under these conditions. This may explain the observed GPI flow observations (figure 5-1) with increasing \( n_e \) and the observed increase in density profile asymmetries for high \( n_e \) diverted discharges versus low \( n_e \) discharges or inner wall limited discharges. In particular, the observed LH-induced density increase behind the LH launcher (figure 5-8) and density decrease in the far SOL (figure 5-7) are likely consequences of a convective transport mechanism like a LH vortex.

It is also observed that the LH striations in the visible camera images are always above the center of each waveguide row when the magnetic field is in the normal direction. This may be a bit unexpected, since the the highest LH electric field and power density should be at the center of each waveguide row. This observation is con-
consistent with a poloidal ExB drift driving the plasma upwards from the center of each waveguide row, as observed in GPI measurements. When the magnetic field direction is reversed, the striations are observed to be below the center of each waveguide row, again consistent with the ExB drifts now driving plasma downwards from the center of each waveguide row. Density profile measurements in both of these cases confirm this effect.

Further evidence of LH-induced density profile asymmetries can be seen in some of the Langmuir probes measurements. Different Langmuir probes can sometimes observe these poloidal density profile asymmetries. An example of this is shown in figure 5-11. At one of the Langmuir probes, LH power increases the density. At the other Langmuir probe, LH power decreases the density. As shown in figure 5-11b), the probe density during LH power can change by factors of about 2.
Plasma potential changes in the SOL have also been observed on Alcator C-Mod using a stationary emissive probe that is not magnetically mapped to the LH launcher. The potential increases strongly with decreasing $n_{||}$\,[52]. It is between 20 and 30 V for $n_{||} = 1.4$ and drops to approximately 5 V for $n_{||} = 1.9$ and 2.3. It is not clear why the plasma potential decreases with increasing $n_{||}$ or why there exists noticeable LH-induced plasma potential that is not mapped to the LH launcher. There have not yet been direct poloidal flow measurements made for $n_{||} = 1.4$ to date, but the strong plasma potentials at low $n_{||}$ may explain why the striations are located further upwards in the $n_{||} = 1.4$ case, as compared to $n_{||} = 1.9$ or 2.3 case.

The importance of including a LH vortex in explaining the observed density profile modifications will be discussed in the next section. In addition to the LH vortex, other physical mechanisms, such as ponderomotive forces and direct LH ionization have been discussed in the literature, as possible causes of LH-induced SOL density profile modifications \[60\][64]. These physical mechanisms can contribute to the observed SOL density profile modifications, but cannot explain all of the observed effects, especially the strong poloidal density profile asymmetries observed at high line averaged densities. The effect of the pondermotive force on SOL density profiles in Alcator C-Mod was studied in a previous paper \[60\]. It is expected to cause a density depletion that is limited in radial extent to the region within a few mm in front of the LH launcher. It cannot explain any of the observations that extend more than a few mm radially in front of the LH launcher or the poloidal density asymmetries. LH-induced ionization is expected to be a factor, and it may explain at least some of the LH-induced density increase near the striations. Ionization cannot explain the strong density decrease that is observed throughout the SOL at the bottom horn view when LH power is applied. Ionization is also unlikely to explain why the striations are observed below or above the center of each waveguide row instead of at the center of each waveguide row.
5.3.1 Diffusive-convective SOL density transport model

To illustrate the effects of a LH vortex on the SOL density profile, a 2-D (radial and poloidal) diffusive-convective model has been developed. Due to the large number of experimental unknowns, this model is not intended for direct comparisons between experiment and simulation, but rather to show the qualitative effect of the LH vortex on the SOL density profiles. The equations are:

$$\frac{\partial n}{\partial t} + \nabla \cdot (-D\nabla n + \nabla n) + \frac{n}{\tau_{||}} = 0 \quad (5.1)$$

$$\nabla = \frac{-\nabla \phi \times \vec{B}}{|B|^2}, \quad (5.2)$$

where \(n\) is the density, \(D\) is the diffusion coefficient, \(\nabla\) is the convective velocity, \(\phi\) is the plasma potential, \(\vec{B}\) is the total magnetic field, and \(\tau_{||}\) is the parallel magnetic connection length timescale, which is assumed to be equal to \(c_s/L_{||}\) where \(c_s\) is the sound speed and \(L_{||}\) is the magnetic connection length. For steady state cases, the \(\partial n/\partial t\) term is assumed to be 0. To simplify the model, the effects of ionization are not included, \(L_{||}\) is calculated based on typical Alcator C-Mod magnetic geometry, and a typical temperature profile is used for \(c_s\). \(D\) can vary from ~ 0.01 to 1 m\(^2\)/s in this model, based on previous work on Alcator C-Mod [106]. These parameters are assumed to be the same for both with and without LH power cases. For the purposes of gaining an understanding LH-induced SOL density profile modifications, an accurate estimate of these parameters is not required. The most important parameter is the convective velocity, \(\nabla\). This is the only variable that is assumed to change when LH power is applied. Without LH power, \(\nabla\) is assumed to be 0. With LH power, LH is assumed to create a plasma potential, \(\phi\), that drives \(-\nabla \phi \times \vec{B}\) drifts, and modifying the SOL density profiles. The radial profile of \(\phi\) can be estimated from the experimentally measured poloidal velocity measurements. For simplicity, the radial variation of the plasma potential is modelled as \(\phi_{max} \exp(|r - r_0|/L)\) where \(\phi_{max}\) is the maximum potential, \(r_0\) is the radial location of the maximum potential and \(L\) is
the e-folding length in the radial direction.

Based on the observations of LH-induced poloidal flows in section 5.1, \( r_0 \) is near the LH launcher, \( L \) is approximately 5-10 mm, and \( \phi_{\max} \) is \( \sim 10-50 \) V. The \( \phi_{\max} \) is assumed to \( \propto P_{RF}^{1/2} \). \( L \) is assumed to increase with \( \bar{n}_e \). This leads to an electric field on the order of 10 kV/m with convective velocities on the order of 1 km/s.

The poloidal variation of \( \phi \) is chosen to match the poloidal variation of the LH electric field for a \( TE_{10} \) waveguide made in vacuum. This has a cosine variation that is maximum at the center of the waveguide and 0 at the top and bottom edges of the waveguide. If the LH-induced plasma potential is near the LH launcher, this should be a good approximation \([65]\). There are then four poloidal peaks in \( \phi \), one for each of the four rows of the LH grill. Variation of the plasma potentials within each of the 16 column is also taken into account. Since the magnetic field line is tilted relative to the LH launcher, the plasma particles follow the magnetic field line, transversing different poloidal projections on each column of the LH grill. This poloidal variation is taken into account into the model by magnetically mapping all 16 columns of the LH launcher. There are thus 64 cosine terms for the \( 4 \times 16 \) grill waveguide, superimposed onto the toroidal midplane of the LH launcher.

The simulation domain of the problem was chosen to range radially from the LCFS to the LH launcher. This is shown in figure 5-12, where the colored regions show the extent of the simulation domain, and the white regions are outside the simulation domain. The top and bottom of the domain (not shown in figure 5-12) were chosen to be far enough away so that the convective velocities are close to zero at these edges. Boundary condition for the LCFS was set to be a constant density ranging from \( 5-8 \times 10^{19} \) m\(^{-3} \). The exact number was chosen based on the density measured by Thomson scattering or reflectometry at the LCFS. Boundary condition for the LH launcher was set to be 0. Boundary conditions for the top and bottom of the domain were set so that the particle flux normal to the surface is 0. The partial differential equations (5.1) is then solved using the diffusive-convective equation that is built
into COMSOL multiphysics package \[89\].

It should be noted that the diffusive-convective model is numerically unstable when the Peclet number \(\sim V\delta x/D\) is high where \(V\) is the magnitude of the convective velocity, \(D\) is the diffusion coefficient, and \(\delta x\) is the cell size of the simulation. Since this is a 2-D model, the cell size can be chosen small enough, so that the solution can be solved quickly without encountering numerical instabilities. Adjustment of the cell size was also used to verify the convergence of the solution.

Results of this diffusive-convective model are shown in figure 5-12 for \(L = 7\) mm and \(D = .25\) m\(^2\)/s in this case. Figure 5-12a) shows the radial and poloidal structure of \(\phi\) for this simulation, with a peak \(\phi\) of 20 V. Strong poloidal and radial drifts form convective eddies in front of the LH launcher, similar to the observations in \[66\]. For figure 5-12b),c), and d), the maximum \(\phi\) was 0, 20, and 20 V, respectively. Figure 5-12c) is a simulation for normal magnetic field direction while figure 5-12d) is a simulation for reversed field direction. Figure 5-12b),c), and d) show the density profiles as functions of \(R\) and \(Z\). Figure 5-12b) is characteristic of the case without LH power, so the density is a flux function. In figures c) and d), the effects of LH-induced ExB drifts are included in the density profile, and are representative of cases during LH powered discharges. The direction of the magnetic field determines whether the locations of the simulated striations are above or below the center of each waveguide row (shown by the 4 red-lined structures). These striations are roughly at the locations of the striations that are visible on the video camera emissivity images. It should be noted that the density is depleted in front of the middle of each row of the LH launcher, \textit{regardless} of the magnetic field direction. This is because when the convective transport is dominant, the particles follow the velocity contours. Reversal of the direction of the eddy does not change this effect. Since the eddy is localized in front of the LH launcher, the density is on average depleted in front of the waveguide mouths of the LH launcher. This density depletion near the mouth of the LH grill is important for LH coupling, and will be discussed in the next section.
The reflectometer views are field line mapped to the toroidal center of the LH launcher and are shown by the 3 dashed red lines in figure 5-12b,c,d). Figure 5-13a) shows the simulated density with LH power for the low density reversed field case, using \( L = 5 \) mm and maximum \( \phi = 30 \) V. The density profiles at the three reflectometer views for the simulated case without LH power (black line), and the simulated case with maximum \( \phi = 30 \) V in the reversed field direction, are shown in figure 5-13b,c, and d). This simulated density can be compared with the experimentally measured density in figure 5-10 as illustrated in figure 5-14. The bottom horn is closest to the simulated striations and shows an increased density. The middle horn is furthest away from a striation and has a decreased density. The top horn shows relatively little change in the density profile. Qualitatively, the diffusive convective model reproduces all of the experimental observations.

This simulation can be done not only in steady state, but also transiently in the COMSOL multiphysics package by including the \( \partial n/\partial t \) term in equation 5.1. The steady state case with \( V = 0 \) is used for the initial density profile. The density profiles reach steady state in approximately 100-400 \( \mu s \) after the LH-induced plasma potential is applied in the simulation. This is estimated to be on the order of the characteristic convection time, \( \tau_{\text{conv}} = \ell/V = (0.01 \text{ m})/(60 \text{ to } 300 \text{ m/s}) \), where \( \ell \) is the characteristic length scale of the convection and \( V \) is the maximum convective velocity in the simulation. The expected characteristic time for a LH vortex-induced density profile modification is approximately equal to the characteristic convection time scale, which is on the order of a few hundred \( \mu s \). This is consistent with experimental observations that the LH-induced density profile modifications occurs less than 1ms after LH power is applied.

The radial and poloidal structure of the plasma potential does quantitatively change the density profiles, but as long as the radial structure of the simulated plasma potential is chosen to be radially peaked near the LH launcher, and the poloidal variation of the plasma potential is chosen to be proportional to the expected LH electric field (cosine dependence), the plasma will always be displaced off the center of the
Figure 5-12: Results from simulations using the diffusive-convective model. Contour plots of various physical quantities are shown as a function of major radius and height. a) $\phi$ profile for $\phi_{\text{max}} = 20$ V. b) Density profile with $\phi_{\text{max}}$ equal to 0 V. c) Density profile with $\phi_{\text{max}}$ equal to 20 V in the normal magnetic field direction. d) Density profile with $\phi_{\text{max}}$ equal to 20 V in the reversed magnetic field direction. The three dashed red lines in each plot represent the views of the three reflectometer locations, mapped to the toroidal center of the LH launcher. The 6 red circles represent the LH langmuir probe locations. The outlines of the 4 waveguide rows are also shown, in red.
Figure 5-13: a) Simulated density profiles with LH-induced ExB drifts are shown for the reversed magnetic field case corresponding to figure 5-10. Plots of the density as a function of major radius are shown for $\phi_{max} = 30$ V, along the line of sight of the three dashed red lines in figure 5-12 b) Top horn; c) Middle horn; d) Bottom horn.
Figure 5-14: a)b)c) The simulated density profiles with LH-induced ExB drifts are shown for the reversed field case (figure 5-13), for the top, middle, and bottom horns, respectively. d)e)f) The experimentally measured density profiles with LH-induced ExB drifts are shown for the reversed field case (figure 5-10) for the top, middle, and bottom horns, respectively. The simulated LH-induced density profile modifications reproduces all the experimental trends.
waveguide. Empirically, the averaged density depletion at the grill depends on the density scale length, \((D\tau)_{1/2}\) and the eddy scale length, \(L\). The depletion is stronger for increasing \(L\) and decreasing \((D\tau)_{1/2}\). For accurate comparison between simulations and experiment, it is clear that future measurements of the plasma flow and/or potential, mapped to the LH launcher, will be required. In particular, comparison of the LH-induced flow, when \(n_{||} = 1.4\) and \(n_{||} = 1.9\), may illuminate why there are differences in density profiles with different \(n_{||}\). Measurement of plasma flows that are not mapped to the LH launcher will also be useful to diagnose possible non-local effects. The diffusive convective model implicitly assumes that these striations are caused by effects originating at the LH launcher. If there are effects that do not originate from the LH launcher, the cosine dependence of the poloidal plasma potential variations may not apply. For example, there are indications that ICRF-induced plasma potential may overwhelm the LH-induced plasma potentials in certain situations. This will be discussed in detail in chapter 6.

5.4 Implications for LH coupling

To evaluate the impact of LH-induced poloidal density asymmetries on LH coupling, a 2-D (toroidal and radial) slab LH coupling simulation has been used [112]. The simulated results reproduce the experimental results only when using the reflectometer measurement that is in front of the waveguide mouths.

5.4.1 LH coupling model

In COMSOL, a cold plasma model can be incorporated by using the built-in dielectric tensor. The density profile is thus not limited to only a linear density profile, as it is in some other simulation codes [29]. In this model, the density radial profiles measured with the reflectometer were used as inputs. The density profiles were assumed to be toroidally symmetric.
A typical simulation with this 2-D model is shown in figure 5-15. The FEM model is in principle 3-D, but the poloidal direction is made to be very thin. Periodic boundary conditions are set in the poloidal direction, so that the grill antenna has an infinite number of columns. The launched spectrum of the wave is thus controlled by the width of the waveguide and phasing between waveguides of the LH launcher. It is important to add collisions to damp the LH waves to reduce the spurious high $n_{||}$ peaks introduced by the periodic boundary conditions in the poloidal direction.

Benchmarking of this LH coupling code [113] was done and was shown to be in good agreement with another LH coupling code, TOPLHA [114].

### 5.4.2 LH coupling results

For the three discharges shown in figure 5-10 the experimentally measured density profiles during both OH and LH operations were used as inputs into the LH coupling code. The simulated and experimentally measured reflection coefficients for the density profiles are shown in table 5.1. The simulated reflection coefficient is on average...
Table 5.1: Row 2 shows the experimentally measured reflection coefficient (%) during LH operation. Rows 3, 4 and 5 show the simulated reflection coefficients (%) using the density profiles in figure 5-10 with (red) and without (black) LH power with the top horn, middle horn, and bottom horn, respectively.

<table>
<thead>
<tr>
<th>Density profile used</th>
<th>OH operation</th>
<th>LH operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td></td>
<td>26%</td>
</tr>
<tr>
<td>Top horn (sim)</td>
<td>14%</td>
<td>12%</td>
</tr>
<tr>
<td>Middle horn (sim)</td>
<td>11%</td>
<td>27%</td>
</tr>
<tr>
<td>Bottom horn (sim)</td>
<td>8%</td>
<td>15%</td>
</tr>
</tbody>
</table>

larger using the density profiles with LH power versus the density profiles without LH power. This is most obvious for the measurement through the middle horn where the large LH-induced density depletion causes a thick evanescent layer. This is consistent with previous experiments that showed a lower reflection coefficient, and improved LH coupling, for few watts of LH power (representative of the simulated reflection coefficients using the density profiles during OH operation as inputs) compared to a few hundred kilowatts of LH power (representative of the simulated reflection coefficients using the density profiles during LH operation as inputs [59].

The simulated reflection coefficients, using the density profiles with LH power, are on average still lower than the experimentally measured reflection coefficients by a factor of approximately 2. The simulation result, using the middle horn density measurements as inputs, does reproduce the experimentally measured reflection coefficients, while using bottom and top horn density profiles as inputs leads to an underestimate relative to the experimentally measured reflection coefficients. This may be because the LH-induced density depletion at the middle horn accurately reflects the averaged poloidal density in front of the waveguide mouths, as suggested by the diffusive convective simulations. The top and bottom horns view near the striations, and so do not represent the averaged density depletion in front of the waveguide mouth. Since LH coupling depends only about the local density in front of the waveguide, and not on the local density between waveguides, this convective mechanism can reduce the LH coupling.
The simulations and measurements are strongly suggestive that ExB drifts cause a density depletion in front of the 4 waveguide rows that reduces the LH coupling. Measurements and simulation at horn locations that view in front of the waveguide mouths, and not between waveguide mouths, reproduce the experimentally measured reflection coefficients within error bars. If more accuracy is required to understand the LH coupling problem, it is clear that the strong LH-induced SOL poloidal density asymmetries will require a poloidal array of Langmuir probes and reflectometer horns combined with a 3-D LH coupling model that can account for these poloidal asymmetries and averaged density depletion in front of the LH launcher. Given that LH coupling is reduced at high LH power and LH-induced striations are observed either above or below the center of waveguide rows on other facilities including Tore Supra, TdE, and ASDEX (section 2.2.3), the effects of these ExB drifts on LH coupling also should be evaluated for these experiments.

Given these experimental results for LH-induced ExB drifts and its implication on LH coupling, it is important that a first principles understanding at how LH power drives these eddies be developed. This is clearly an area of future research and will be briefly discussed in chapter 7.

5.5 Implications for LH-SOL interactions

5.5.1 Increased plasma-wall interactions

To improve LH coupling, the LH launcher is often moved closer to the plasma. This solution, however, can increase the heat flux at the LH launcher. The LH-induced striations, in particular, can enhance the heat flux at the LH launcher and at other material surfaces. This has been measured using IR cameras on Tore Supra [65] and visible cameras on Alcator C-Mod [115]. On Tore Supra, the IR camera observes increased temperature at the striation locations that are above or below the center
For $B_0 = 5.4$ T, $I_p = 400-800$ kA, LH powered discharges on Alcator C-Mod, striations are observed with a camera viewing the G-H Limiter (figure 5-16). The visible camera is filtered to observe Mo-I line at 550.6 nm in order to monitor erosion of material surfaces. The camera also sees background continuum emission, however, so the increased light is either due to increased heat flux of the material surfaces or increased molybdenum erosion rates. To confirm that these striations originate from the LH launcher grill, magnetic field line mappings from the striations on the 4 rows of the LH launcher to the GH limiter are shown for the $B_0 = 5.4$ T, $I_p = 400$ kA case. Comparison between the magnetically mapped striations from the LH launcher in figure 5-17 to the striations viewed at the GH limiter in figure 5-16 show good agreement. As the plasma current is increased, the mapping between the LH launcher and GH limiter is modified, and the striations appear at different locations. At $I_p = 800$ kA, the striations are no longer visible on the G-H limiter video camera.

5.5.2 Reducing LH-SOL interactions

To improve LH coupling, it is common to use localized gas puffing. In this paper, it was reported that a column of gas capillary tubes, located adjacent to the LH launcher, provided the best results in improving LH coupling. This is most likely because the gas puff ionizes locally, and the charged particles then travel along the magnetic field lines, so that the gas puff induces local density profile modifications that are magnetically connected to the capillary tubes. Given the results on Alcator C-Mod for localized gas puffing (section 4.1.7) and LH-induced ExB drifts (section 5.2), a column of localized gas capillaries can be used to increase the local density and possibly improve LH coupling. Furthermore, puffing at multiple gas capillaries located adjacent to each waveguide row may also reduce the strong density profile asymmetries within each waveguide row. The gas puffs can be tailored to the expected density profile asymmetry. Since the LH-induced ExB drifts may still produce striations with
Figure 5-16: LH-induced striations are observed on the GH limiter using a visible camera filtered at 550.6 nm Mo-I. Striations are highlighted by the white ellipses [115]. a) $B_0 = 5.4T$, $I_p = 400kA$ case. b) $B_0 = 5.4T$, $I_p = 500kA$ case. c) $B_0 = 5.4T$, $I_p = 650kA$ case. d) $B_0 = 5.4T$, $I_p = 800kA$ case. Other regions of increased brightness at the midplane are observed during all discharges. The physical mechanism for this is believed to be due to the reduced distance from the LCFS to the plasma limiter at the midplane, but is still an area of current research [115].
Figure 5-17: Magnetic field line mapping from the 4 rows of the LH launcher to the GH limiter for a $B_0 = 5.4\,\text{T}$, $I_p = 400\,\text{kA}$ discharge. The striations on the LH launcher and GH limiter are highlighted by the yellow circles. The striations on the GH limiter are at similar locations to the experimental measurements in figure 5-16a).
increased density and heat fluxes, it may also be possible to use localized gas puffing, combined with impurity seeding \[116\] at these nozzles, to reduce the plasma-wall interactions. These are interesting options that have not yet been tested and can be considered for future LH studies.
Chapter 6

ICRF-induced transport

In this chapter, the effects of ICRF power on the SOL transport and SOL density profiles are examined in detail, using the same diagnostics and modeling tools as shown in chapter 5. This chapter is organized by first showing experimental measurements of ICRF-induced flows and density modifications. These experimental results will highlight the importance of magnetic field line mapping in order to understand ICRF-induced plasma density, plasma flow, and LH coupling results. In particular, a dedicated experiment shows that simultaneous operation of the LH launcher and an ICRF antenna, magnetically connected to the LH launcher, can significantly degrade LH coupling performance. This degraded coupling is correlated with strong ICRF-induced density depletion on the top-middle row of the LH launcher, that only occurs for the D and E ICRF antennas, which are magnetically connected to the LH launcher. When the LH launcher is not magnetically connected to the active ICRF antenna, both the density and LH coupling is minimally modified.

The inclusion of the ICRF-induced ExB drifts into the diffusive-convective model developed in chapter 5 will then be shown. The model can reproduce many experimental trends, but overpredicts the magnitude of the measured density profile modifications, possibly due to uncertainties in the flow measurements, density measurements and/or uncertainties in the model.
6.1 ICRF-induced steady state plasma flow measurements

As discussed in chapter\[2\] ICRF power is expected to increase plasma potentials due to ICRF sheath rectification. Gradients of these plasma potentials will drive ExB convective eddies. These ExB eddies can be measured by the GPI diagnostic, and are shown to have complicated poloidal and radial dependencies. A typical radial profile of the poloidal plasma flow is shown in figure [6-1a) without ICRF power and in figure [6-1b) with ICRF power. Without ICRF power, the poloidal plasma flow is downwards (ion diamagnetic drift direction or IDD) for typical Alcator C-Mod toroidal magnetic field direction in the SOL (clockwise when viewed from above). This is expected theoretically if the sheath potential, $V_{sh}$, is approximately equal to $3T_e$, since $T_e$ decreases with increasing major radius in the LFS SOL. When ICRF power is added, as observed in figure [6-1], the experimentally measured poloidal velocity is now upwards for some radial regions in the far SOL. The measured amplitude of the poloidal velocities are also substantially higher with ICRF power than without ICRF power. By using a magnetic field line connection program to map the GPI views to the toroidal locations of the ICRF antennas, the radial location at which the poloidal velocity switches sign is shown to be approximately located at the radial location of the ICRF limiters [20]. In reference [20], the plasma potential, $V_{sh}$, is estimated to have a peak magnitude of approximately 200-300 V in these cases.

The measured poloidal flows in figure [6-1] have been compared with theoretical models, with mixed results in reference [20]. The theoretical prediction of $V_{sh} \sim \int E_{||RF} dl$ is based on a 3-D finite element model of the RF parallel electric field, using the exact geometry of the D and J antennas [10]. The poloidal variation, and ICRF power dependence of $V_{sh}$ is reproduced by the models [20] and shown in figure [6-2], where the vertical position, $z_{ave}$, is the projected vertical location at the toroidal location of the given ICRF antenna, and is calculated by assuming that the plasma potential is equal along a magnetic field line from the GPI view to the given ICRF
Figure 6-1: a) The measured poloidal velocity during OH operation is shown. b) The measured poloidal velocity during toroidally aligned J-port ICRF operation is shown in b). The location of the ICRF limiters is determined by a magnetic field line connection program to the measured GPI location.

antenna. A scan of $z_{ave}$ is achieved by varying the plasma current and keeping the toroidal magnetic field constant. The agreement between theory and experiment in figure 6-2 of the poloidal variation of the plasma potential is remarkable. The ICRF power dependence of the plasma potential is shown in figure 6-3 where the colored, squares represent the experimental measurements, and the colored lines represent a fit of the experimental data to the expected plasma potential scaling with ICRF power ($V_{sh} \sim \sqrt{P_{ICRF}}$). The fit matches the experimental data.

While the theoretical predictions reproduce the measured poloidal variation and power dependence of the experimentally measured ICRF-induced poloidal flows, however, the theoretical predictions do not agree with the experimental results for comparisons between the field-aligned J ICRF antenna and toroidally-aligned J ICRF antennas. Figure 6-3 shows that the measured sheath potentials are higher for the field-aligned J ICRF antenna relative to the toroidally-aligned J ICRF antenna. On the other hand, the theoretical models (shown in figure 6-4) predict that the
Figure 6-2: The simulated (lines) and experimentally measured (symbols) poloidal profile of the plasma potential is shown for toroidally aligned J (green) and conventional D-antenna (blue) operation [20]. $z_{ave}$ is the projected vertical location at the toroidal location of the given ICRF antenna, and is calculated by assuming that the plasma potential is equal along a magnetic field line from the GPI view to the given ICRF antenna.
Figure 6-3: The measured plasma potentials (colored squares) are compared for the field aligned (blue) and toroidally aligned (red) J ICRF antennas [117]. The colored lines are a fit to the experimental data, with the plasma potential scaling with $\sqrt{P_{ICRF}}$. 

**Field-aligned J antenna**

**Toroidally aligned J antenna**
sheath potentials shall be lower for the field-aligned J ICRF antenna relative to the toroidally-aligned J ICRF antenna. Emissive probe measurements \[118\] also show that ICRF-induced sheath potentials can reach 50 V at a radial location 4 cm outwards of the ICRF limiter, which is inconsistent with the model prediction \[10\] of negligible ICRF-induced potentials at this radial location. These results suggest that the model is missing important physics \[118\] \[48\].

6.2 ICRF-induced density profile modifications

While the exact physics details of ICRF-induced sheath rectification in complicated magnetic geometry may be unclear, experimental measurements clearly indicate that ICRF-induced plasma potentials occur. These plasma potentials can form convective cells in turn, causing convective transport and density profile modifications. This
is the hypothesis that has been widely discussed in the ICRF community (section 2.2.2), but has not been previously tested on any experiment with multiple poloidal and toroidal resolution density measurements.

In this section, experimentally measured ICRF-induced density profiles modifications are shown for the D, E, and field-aligned J ICRF antennas at multiple reflectometer locations. The measured density modifications are radially localized, limited to a few mm in front of the LH launcher. In this region, ICRF power often causes density depletion in front of the LH launcher. On the other hand, density in the near and far SOL often increases because $\bar{n}_e$ rises, perhaps due to outgassing of the active ICRF antennas or other plasma wall interactions. The importance of magnetic field line mapping from the reflectometer measurement location to the active ICRF antenna will be shown. In particular, since the convective transport depends on the gradient of the plasma potentials, and the plasma potentials peak at the top and bottom of a given ICRF antenna, the ICRF-induced density modifications are strongest on magnetic field lines that are mapped to the top and bottom of the given ICRF antenna, but can be also observed on magnetic field lines that are magnetically mapped at other poloidal locations.

Since the ICRF-induced plasma potential is expected to be constant along a magnetic field line, except in the thin sheath region where the magnetic field lines intersect with a material interface, it is important to understand the magnetic mapping from the active ICRF antenna to the reflectometer horns. Field line mapping is shown in figure 6-5 for 6 cases: 3 different plasma currents at 2 different reflectometer locations. The three different plasma currents are $I_p = .6$ (cyan line), .8 (yellow line), and 1 MA (purple line) and the two different locations are the ICRF-SOL reflectometer horns and LH-SOL top reflectometer horns. For $I_p = .6$ to 1 MA at $B_0 = 5.4$ T, all the reflectometer horns are magnetically connected to various poloidal locations of the D, E and J ICRF antennas. The three LH-SOL reflectometer horns are magnetically mapped to different locations on the D and E ICRF antennas, but are not mapped to the J ICRF antenna. The ICRF-SOL reflectometer horns are magnetically connected
6.2.1 Density measurements at different reflectometer horns

Measurements through the top horn are shown in figure 6-6a) during a 1 MA L-mode discharge without ICRF (black solid line) power, with D (red dashed dotted line), with E (blue dashed line), and with J (green long dashed line) antennas. ICRF power does not significantly modify the density shape or density in the near SOL, but the SOL density profile is depleted in front of the LH launcher for operation of all ICRF antennas. Density during active D or E ICRF antenna operation shows a significant depletion in front of the LH launcher at the top reflectometer horn, most likely because the top reflectometer horn is magnetically connected to regions of high sheath potential (top of D and E ICRF antennas). Addition of J ICRF power also
Figure 6-6: a) SOL density profiles during a $I_p = 1$ MA discharge without ICRF (black solid line) power, with D (red dashed dotted line), with E (blue dashed line), and J (green long dashed line) ICRF operations. b) A blow-up of part a) inside the yellow rectangle is shown here. c) $\bar{n}_e$ is shown for this discharge. d) ICRF power is shown for this discharge.
Figure 6-7: a) SOL density profiles during a $I_p = .8$ MA L-mode discharge: without ICRF power (black solid line); with D+E (red dashed dotted line); and with J (green long dashed line). $\bar{n}_e$ is approximately $0.85 \times 10^{20}$ m$^{-3}$ during OH operation, but rises to approximately $0.95 \times 10^{20}$ m$^{-3}$ when ICRF power is added.

depletes the density in front of the LH launcher at the top reflectometer horn, but to a lesser extent than with the D and E ICRF antennas. This is consistent with the fact that the top reflectometer horn is magnetically mapped to a region of lower sheath potential (below the J ICRF antenna).

Measurements through the bottom horn are shown in figure 6-7 during a .8 MA L-mode discharge without ICRF (black solid line), with D+E (red dashed dotted line), and with J (green long dashed line) antennas. $\bar{n}_e$ is approximately $0.85 \times 10^{20}$ m$^{-3}$ during OH operation, but rises to approximately $0.95 \times 10^{20}$ m$^{-3}$ with the addition of ICRF power. This line averaged density increase probably accounts for the density profile modifications in the edge plasma. Addition of ICRF power from any ICRF antenna does not modify the density profile significantly in the near or far SOL. This may be reasonable since the theoretical model \cite{10} predicts that the bottom horn is magnetically connected to regions of low sheath plasma potentials, such as the middle
Figure 6-8: ICRF-induced SOL density profile modification for OH (black solid line), D+E (red dashed dotted line), and J antennas (green long dashed line) measured using ICRF-SOL reflectometer horn. $I_p$ is .6 MA and $\bar{n}_e$ is $1.3 \times 10^{20} \text{ m}^{-3}$.

Measurements through the ICRF-SOL reflectometer horn are shown in figure 6-8 without ICRF (black solid line), with D+E (red dashed dotted line), and with J (green long dashed line) antennas for $I_p = .6 \text{ MA}$ and $\bar{n}_e = 1.3 \times 10^{20} \text{ m}^{-3}$. ICRF power depletes the density in front of the H-port reflectometer horn, raises the density radially outwards of the ICRF limiter, and minimally modifies the density radially inwards of the ICRF limiter for both J and D+E ICRF antenna operation. The small density modifications radially inwards of the plasma limiter are consistent with the fact that the ICRF-SOL reflectometer horn is magnetically connected to regions of low sheath potential at the middle of the J-ICRF antenna, and to vertical locations that are poloidally distant from the D and E ICRF antennas. The small density modifications radially outwards of the ICRF limiters are not consistent with this picture, possibly
Figure 6-9: a) SOL density profile measured by the bottom reflectometer horn during a $I_p = 1$ MA discharge without ICRF (black solid line) power, with D+E (blue dashed dotted line), and J (green long dashed line) ICRF operations. Because the measured plasma potentials do not agree with the theoretical predictions at radial locations outwards of the ICRF limiters, as discussed previously in section 6.1.

### 6.2.2 Density measurements for reversed toroidal field direction

Reversal of the toroidal magnetic field direction should reverse the poloidal ExB drift direction, which is expected to modify convective transport. This is shown in figure 6-9a) during a $I_p = 800$ kA L-mode discharge without ICRF (black solid line) power, with D+E (blue dashed line), and with J (green long dashed line) antennas, using measurements at the top reflectometer horn. The density rise in the near SOL is most likely due to the increased $\bar{n}_e$. Strong density depletion is observed in the far SOL.
in front of the LH launcher. The qualitative nature of these density modifications is similar to the density modifications in the normal magnetic field direction case (figure 6-6), and will be shown to be consistent with the convective transport model (section 6.4).

Magnetic field line mapping, as well as the exact spatial structure of the ICRF-induced plasma potentials, is thus important in explaining these density modification results. This will become even more evident in the next section, which discusses the effects of ICRF power on SOL density profile during LH+ICRF powered discharges.

6.3 Effects of ICRF power on SOL density profiles and LH coupling during simultaneous LH+ICRF operation

Density profile comparisons between LH and LH+ICRF powered discharges are also of substantial interest due to the effects of ICRF power on LH coupling. As shown in the section 6.2, the application of ICRF power often depletes the density in front of the LH launcher, so it is not surprising that the addition of ICRF power can reduce LH coupling efficiency. Previous experiments on JET [119], Tore Supra [120], EAST [121], and Alcator C-Mod [12] have demonstrated this effect when the active ICRF antenna is magnetically connected or adjacent to the LH launcher. It is suggested in all these papers that ICRF sheaths cause convective transport and density profile modifications; however, all the experiments lacked diagnostic coverage to examine the ICRF-induced density profile modifications in front of the LH launcher. A dedicated experiment was thus carried out on Alcator C-mod to confirm the LH coupling results and examine the ICRF and LH-induced density profile modifications and their effects on LH coupling during simultaneous LH and ICRF operation. Results from this experiment reproduce the LH coupling results on previous experiments, and show
that the LH coupling is correlated with strong ICRF-induced density depletion when the active ICRF antenna is magnetically connected to the LH launcher, and minimal ICRF-induced density modification when the active ICRF antenna is not magnetically connected to the LH launcher.

This experiment was carried out mostly over one dedicated run day. During each discharge of the experiment, only the timing of the LH power and timing of each of the three ICRF antennas was modified, so that there were time intervals with LH, LH+D, LH+E, and LH+J operation. In a given discharge, the global plasma parameters were kept as constant as possible. From discharge to discharge, various plasma parameters that affect LH coupling or ICRF sheath rectification were varied. $n_e$ was adjusted from $0.6-1.2 \times 10^{20} \text{ m}^{-3}$, and outer gap was varied from 0.6 to 1.8 cm to modify LH coupling and the local SOL density profiles in front of the LH launcher. The variation of outer gap also affects the ICRF coupling and ICRF-plasma interaction. $I_p$ was scanned from 0.6 to 1 MA to alter the magnetic mapping between the ICRF antennas and the LH launcher. Varying $I_p$ also affects the SOL density profile shape. The LH launcher location was also adjusted over the range from 1-4mm behind the plasma limiter, to scan the radial structure of the ICRF sheath potential and to modify the local SOL density profile in front of the LH launcher. The order of the ICRF antennas was also permuted to account for possible hysteresis in the plasma discharges. Various other plasma parameters were kept constant during the run day. Hydrogen minority ICRF heating ($\sim 5\%$ hydrogen) in deuterium majority plasmas was the heating scheme for all discharges. The launched $n_\parallel$ for the LH waves was 1.9. ICRF power and LH power were approximately 0.5 MW and 0.2 MW, respectively, and the discharges remained in L-mode. $B_0$ was at 5.4 T so that the 100-146 GHz X-mode reflectometer measures the SOL. LH reflection coefficients, SOL density profiles at the top horn, and visible video camera images of the LH launcher were monitored for each discharge.

Only one reflectometer horn can be used for each discharge, so the top reflectometer was used on this dedicated run day because it is magnetically connected to the top of the D and E ICRF antennas (refer to figures 6-2 and 6-5), which are expected to
Figure 6-10: a) LH reflection coefficients are shown during LH, LH+D, LH+E, and LH+J operation over a single discharge (discharge #8 in table 6.1). (b) Net LH power is shown over this discharge. c) ICRF power and antenna order is shown during this discharge. d) Line averaged density is shown during this discharge.

be at poloidal locations of the high ICRF-induced plasma potentials. Due to the expected poloidal density asymmetries, it will be shown that it is important to measure at all three horn locations. Measurements comparing LH and LH+ICRF operations on all three horns will be shown from an experiment on a different day.

A typical discharge for these experiments is shown in figure 6-10. Except for the timing of the LH launcher and three ICRF antennas, all other plasma parameters were kept as constant as possible. In this discharge, the LH launcher is operational from .75 to 1.25 s, J antenna is operational from .825 to .95 s, E antenna is operational
from 1 to 1.125 s and D antenna is operational from 1.175 to 1.3 s. During LH and LH+J operations, the LH reflection coefficients were ~ 20-30%. Application of the J ICRF antenna had minimal effect on LH coupling. During LH+E operation, the reflection coefficient increased to ~ 30-45% and during LH+D operation, the LH reflection coefficient was even higher at ~ 40-55%. For all ICRF antennas, the LH reflection coefficients respond within a few ms after the ICRF antenna is energized or de-energized. This characteristic timescale was observed for all discharges. It is faster than any core transport timescale and is consistent with the LH and ICRF-induced ExB convective timescale discussed in section 5.3.1.

A summary of results for the set of discharges on this dedicated run day are shown in table 6.1. Discharge number, $\bar{n}_e\ (10^{20}\ m^{-3})$, $I_p\ (MA)$, outer gap (cm), LH launcher location behind the main plasma limiter (mm), ICRF antenna order as well as reflection coefficients for the four cases of LH, LH+D, LH+E, and LH+J operation are shown. The reflection coefficient shown in table 6.1 is averaged over the entire time interval when a given ICRF antenna is energized.

Before discussing the effect of ICRF power, it is important to discuss how other plasma parameters affect LH coupling. With all other parameters fixed during LH operation, the reflection coefficient decreases with increasing $\bar{n}_e$ and decreasing launcher location behind main plasma limiter. This is expected, as these two parameters have a significant effect on the local SOL density profile. During LH+ICRF operation, the outer gap may have an effect on LH coupling. For discharges 7 to 9, decreasing the outer gap in these discharges did not significantly affect LH coupling during LH or LH+J operation, but strongly affected LH coupling during LH+D and LH+E operation. The outer gap may thus have an effect on the ICRF sheath rectification process. Given the limited dataset, though, this needs to be verified in another experiment.

By far the most obvious trend is the difference in the reflection coefficients during LH, LH+D, LH+E, and LH+J operation. For all discharges shown, the LH reflection coefficients are highest with LH+D operations. This is consistent with the fact that D-
Table 6.1: A table of the results on this dedicated run day. The plasma parameters for each discharge are shown along with the resulting reflection coefficients on the LH launcher. In order from left to right, discharge number, $\bar{n}_e \ (10^{20} \ m^{-3})$, $I_p \ (MA)$, outer gap (cm), LH location (mm behind plasma limiter), ICRF order, reflection coefficient during LH operation (%), reflection coefficient during LH+D operation (%), reflection coefficient during LH+E operation (%), and reflection coefficient during LH+J operation (%). The - symbol indicates that the LH or ICRF faulted and that there was no data during that time interval.
port ICRF antenna is adjacent to the C-port LH launcher. The reflection coefficients during LH+E operation are always second highest. LH and LH+J operation result in similar LH reflection coefficients, which is consistent with the fact that the J-port ICRF antenna is 144° away toroidally from the C-port LH launcher. Reflection coefficients during LH+E operation differ depending on the plasma discharges. The reflection coefficients for all the discharges are plotted in figure 6-11 for LH (black), LH+D (red), LH+E (blue), and LH+J (green) operations.

To further illuminate the differences in coupling between LH+ICRF and LH operations, the coupling efficiency of LH+ICRF operation is calculated by the ratio of the net LH power during LH+ICRF operation over the net LH power during LH operation normalized for the same input LH power. This coupling efficiency is an indicator of the deleterious effect of ICRF power on LH coupling. It is plotted in figure 6-12 for all discharges from the run day. Operations with LH+D resulted in a reduced 55-85% coupling efficiency relative to operation with only LH. Operation with LH+J had similar coupling efficiency as operation with only LH. Operation with LH+E resulted in 60-100% coupling efficiency relative to operation with only LH.
Figure 6-12: The coupling efficiency, calculated as the ratio of the net power during LH+D (red triangles), LH+E (blue circles), and LH+J (green squares) operations over the net power during LH operation normalized for the same input power, is shown for each discharge.

Since LH coupling differs substantially between LH+D and LH operation, the resulting SOL parameters should differ too. This can be observed on visible video camera imaging measurements. For the discharge shown in figure 6-10, the visible video camera images are shown in figure 6-13(a), (b), (c), and (d) for LH, LH+J, LH+D, and LH+E operations, respectively. Striations typical of LH only operations (section 5.2) are observed during LH and LH+J operation. As discussed in section 5.2, these striations occur due to the effect of LH-induced convective eddies on the density profile within each launched waveguide row. When J antenna is active, the SOL emissivity does not appear to be strongly affected. During LH+D and LH+E operation, however, the striation on the top middle row of the LH launcher disappears. This is strongly suggestive that when D and E ICRF antennas are active, the additional ICRF-induced flows and plasma potentials, combined with the LH-induced flows, modify the SOL at the LH launcher. It is therefore clear that the inclusion of both LH-induced and ICRF-induced flows are necessary to understand the SOL density profile modifications.

In chapter 5, a strong correlation between emissivity striations and density mod-
Figure 6-13: Visible video camera images are shown during a) LH only, b) LH+J, c) LH+D, and d) LH+E operation. Striations for the middle two waveguide rows are observed during LH and LH+J operation. The Striation for the top-middle waveguide row disappears during LH+D and LH+E operation.
Figure 6-14: a) Density profile measurements are shown during LH (black solid line), LH+D (red dashed dotted line), LH+E (blue dashed line), and LH+J (green long dashed line). b) A blow-up of the density profiles inside the yellow box of a) is shown.
ifications was established. Reflectometer locations that view through a striation will observe strong density increases and reflectometer locations that do not view through a striation can observe strong density depletion. A similar correlation also occurs here during LH+ICRF operation. The video camera does not show significantly different brightness at the top horn during LH, LH+D, LH+E, and LH+J operation. This is reflected in the density profile measurements shown for this discharge in figure 6-14a). There is small density depletion in front of the LH launcher and density addition in the far SOL for all LH+ICRF operations. The density addition during ICRF operation is partially due to the increased $\bar{n}_e$. A blow-up inside the yellow box of figure 6-14a) is shown in figure 6-14b). The density depletion is most prominent during LH+D operation. These small density profile modifications and brightness modifications in the far SOL were consistent for all discharges throughout the dedicated experiment.

The video camera images do suggest significantly different emission at other poloidal locations during LH, LH+D, LH+E, and LH+J operation. In particular, at the middle horn, the striation disappears during LH+D and LH+E operation, suggesting that there is a strong density depletion in that region. Since the top horn was used during the dedicated run day, additional reflectometer measurements were made on a different run day using all three LH-SOL reflectometer locations during OH, LH, and LH+D operation on three similar, but not identical discharges. The results are shown in figure 6-15. Comparison of the density profile during OH (yellow dashed lines) and LH (black solid lines) operation shows that LH power increases the density at the middle horn, decreases the density at the bottom horn, and marginally modifies the density at the top horn. This is consistent with the LH-induced ExB drifts and plasma potentials picture presented in chapter 5. When ICRF+LH power is applied (red dot dashed line), the density modifications at the top horn in the near and far SOL are small, similar to those seen in figure 6-14. On the other hand, the density during LH+D operation is significantly lower than the density during LH operation at the middle horn throughout the entire SOL. This is consistent with the
Figure 6-15: Density profile measurements at all three reflectometer horn locations during a $\bar{n}_e=1.4 \times 10^{20} \text{ m}^{-3}$ discharge with OH (yellow long dashed line), LH (black solid line), and LH+D (red dot dashed line) operations. a) top horn. b) middle horn. c) bottom horn.
disappearance of the striation on the top middle row during LH+D (red dot dashed lines) operation in figure 6-13. Additional ICRF power also slightly increases the density relative to operation with only LH at the bottom horn. The strong ICRF-induced density depletion at the middle horn only occurs during LH+D and LH+E operation and is consistent with reduced LH coupling in these scenarios relative to LH and LH+J operation.

6.4 Implications of ICRF-induced density profile modifications on understanding ICRF sheath models

For a wide range of plasma parameters, a significant number of density profile modifications during ICRF and LH+ICRF powered discharges have been observed. The ICRF sheath rectification and convective cell process is important in explaining some of these density profile modifications. ICRF can increase or decrease densities at different radial and poloidal locations, which is consistent with a convective transport mechanisms. The reflectometer measurements indicate that density profile modifications do occur on field lines not mapped to the active ICRF antenna (figures 6-8 and 6-6) if the field lines are below or above the ICRF antenna. This is possibly because the convective transport depends on the gradient of the plasma potentials. Since the plasma potentials peak at the top and bottom of the ICRF antennas, the convective transport can result in density profile modifications over a much larger poloidal distance than the height of the antenna. This can be accounted for in a diffusive-convective model, such as the model discussed in section 5.3.1.

Density profile modifications also occur at radial locations where the field lines do not map to the active ICRF antenna, due to intersections with LH protection limiters, ICRF protection limiters, or plasma limiters. For example, the field lines in the far
SOL between the H-port reflectometer horn and the D and E ICRF antennas often intersect the AB limiter, but density profile modifications are still observed in the far SOL locations (figure 6-8). One likely explanation is that ICRF-induced plasma potentials occur even on magnetic field lines that are intersected by limiters [118]. This could be due to radial penetration of plasma currents [48], effects of fast waves [118], and/or other mechanisms for the plasma potentials to ignore limiting surfaces.

This ICRF convective transport picture can be simulated using the diffusive-convective model developed for LH powered discharges in section 5.3.1. The only difference between the LH and ICRF case is the inputted plasma potential. For the poloidal profile of $V_{sh}$ in the ICRF case, the theoretical model in figure 6-2 can be used for the D and E ICRF antennas. The theoretical model in reference [110] can be used for the field aligned J ICRF antenna. Measurements from the GPI diagnostic can be used to estimate the radial profile of $V_{sh}$. A magnetic field-line mapping program is necessary to map the GPI radial views and simulated poloidal velocity profile of $V_{sh}$ to the toroidal location of the LH launcher. Based on the observations of the ICRF-induced poloidal flows, $r_0$ is near the ICRF limiter, $L$ is approximately 5-10 mm and $\phi_{max}$ is approximately 100-300 V.

Results using the diffusive-convective model are shown in figure 6-16, comparing the density profile without D ICRF power (figure 6-16a), with D ICRF power (figure 6-16c) during normal toroidal magnetic field direction, and with D ICRF power (figure 6-16d) during reverse magnetic field direction. The inputted plasma potential is shown in figure 6-16a).

Results are also shown in figure 6-17 comparing density profiles with LH power (figure 6-17a), and with LH+D power (figure 6-17d). The inputted plasma potentials for figure 6-17c) are shown in figure 6-17a), while the inputted plasma potentials for figure 6-17d) are shown in figure 6-17b).

The simulations are consistent with many of the experimental observations, such as the fact that the density can be reduced in the far SOL, at the location of the
Figure 6-16: Simulations comparing density profiles during OH and D ICRF antenna operation. 
a) Plasma potential during D ICRF antenna operation. 
b) Density profile during OH operation (no plasma potential) 
c) Density profile with ICRF-induced plasma potentials in normal magnetic field direction. The ICRF-induced plasma potential is magnetically connected from D port ICRF antenna to the C-port LH launcher. 
d) Simulation of density profile with ICRF-induced plasma potentials in reversed magnetic field direction. The reflectometer lines of sight are shown by the dashed red lines, while the LH waveguide grill outlines are shown by the solid red lines.
Figure 6-17: Simulation comparing density profiles during LH and LH+D operation. a) Plasma potential during LH operation. b) Plasma potential during LH+D operation. c) Density profile with LH-induced plasma potential. d) Density profile with the addition of both LH-induced and ICRF-induced plasma potentials. The ICRF-induced plasma potential is magnetically mapped from D port to the C-port LH launcher. The reflectometer lines of sight are shown by the dashed red lines, while the LH waveguide grill outlines are shown by the solid red lines.
top horn, regardless of the toroidal magnetic field direction, consistent with experimental measurements in figures 6-6 and 6-9. The simulated density modifications are strongest near the peak plasma potential, but the convective transport can modify the density even at locations of weak plasma potential. This may explain why the density can be modified even if the active antenna is not magnetically connected to the reflectometer horn. The strongest density modifications are observed both in experiment and in simulation to be near to the peak of the plasma potential. Addition of ICRF power can also significantly modify the simulated LH-induced striations, as observed in figures 6-17c) and d).

The simulation, however, predicts substantially stronger density modifications than are observed in the experimental measurements. For example, figure 6-16d) predicts a substantial density depletion throughout the entire SOL at the top horn during reversed toroidal magnetic field direction ICRF operation. In fact, the simulated density is usually strongly modified in the simulations throughout the entire SOL at the top and middle reflectometer horn locations. Neither of these simulation results have been observed experimentally.

This could possibly be because the simulation results are sensitive to the inputted plasma potentials, which is based off of both modeling of $\int E_{\|} dl$ [10] and GPI measurements. The GPI measurements were also done on a limited range of plasma parameters (scans of $I_p$ and ICRF power), so these results may not always reflect the range of plasma parameters scanned in the above density measurements. There are also significant questions about this sheath rectification model, given that it did not reproduce the expected results for the field aligned ICRF antenna. Inaccuracies in the simulated spatial structure of the plasma potential will lead to inaccurate simulated density profile modification results.

Given these uncertainties, the ExB convection model may still be the dominant physical mechanism driving ICRF-induced density modifications. Other mechanisms besides ICRF sheath rectification may still play a role, however. One possibility is
ponderomotive forces. While this force is expected to be insignificant for fast wave heating, it would always decrease the density in front of the LH launcher at all poloidal location, which is consistent with the density depletion in front of the LH launcher that is observed on all discharges.

6.5 Possible solutions to improve LH coupling

Regardless of the possible physical mechanisms, these experimental results do clearly show that ICRF modifies the SOL density profiles, flows, potentials, and LH coupling, especially for radial and poloidal regions that are actively mapped to the ICRF antenna. The J ICRF antenna is not magnetically connected to the LH launcher, and it does not significantly modify the LH reflection coefficients. On the other hand, the D and E ICRF antennas are magnetically connected to the LH launcher and do significantly modify LH coupling. These results are approximately consistent with results from JET, Tore Supra, and EAST.

To quantitatively understand how ICRF power affects LH coupling is difficult. This requires measurement of the radial and poloidal variations of both the ICRF and LH-induced plasma potentials and density modifications. For the ICRF case, the poloidal variation of the ICRF-induced plasma potential seems to match simulations, but the radial variation does not. There is also a significant plasma potential radially behind the plasma limiter. These contributions need to be understood before it will be possible to quantify the effects of ICRF-induced ExB drifts on the SOL density profiles.

To improve LH+ICRF operations, the simplest conceptual solution is to allocate the LH launcher and ICRF antennas so that they are not magnetically connected. In fact, it may even be necessary to make sure that the LH launcher is not magnetically connected to regions near the ICRF antenna, as ICRF power does modify the density profiles on magnetic field lines just below and above the ICRF antenna, and even
behind limiters. If this cannot be done, other solutions will require a more detailed physics understanding of ICRF and LH-driven plasma potentials. An additional poloidal array of reflectometer horns and/or Langmuir probes adjacent to or in front of the LH launcher will be useful in further diagnosing the poloidal asymmetries. GPI and emissive probes will be useful in diagnosing ICRF and LH-induced plasma potentials. 3-D convective transport models and 3-D LH coupling codes that take into account the poloidal density profile asymmetries will also need to be developed to predict LH coupling on future experiments.

Another solution is to implement a poloidal column of localized gas puffs adjacent to the LH launcher to optimize the density at different poloidal locations, as discussed in chapters 4 and 5. Tailoring of the localized gas puffs, for example by puffing away from the striations to reduce the poloidal density asymmetries, might be used to improve LH coupling.

Another possible solution is to radially locate the LH launcher far away from the radial peak of the ICRF-induced convective cells. The ICRF-induced density profile modifications will then occur far in front or, far behind the LH launcher, at radial locations that do not significantly alter LH coupling. This appears difficult for two reasons. Firstly, experimental measurements of ICRF-induced plasma potentials [118][20] show peaks of the ICRF plasma potential both near the ICRF limiter and at radial locations far behind the ICRF limiters. It may therefore be difficult to find the optimal radial location for the LH launcher to be far away from all ICRF-induced convective cell. Secondly, LH coupling and heat flux handling are already very sensitive to local density conditions, even without ICRF power. If the LH launcher is significantly far away from the LCFS, optimal localized gas puffing will be required to couple the LH power without modifying global plasma parameters [62]. If the LH launcher is close to the LCFS, increased heat fluxes will occur.

One other solution is to design an ICRF antenna that will reduce the ICRF sheath potentials. Based on our prior understanding of sheath physics, the goal of the field
aligned J ICRF antenna is to reduce sheath potentials, thereby reducing core impurity contamination. The resulting ICRF-induced SOL density profile modifications should also be reduced. As shown in references [123][117], the field aligned ICRF antenna does reduce core impurity contamination, but it does not appear to reduce the ICRF sheath potentials. Understanding these observations will require further research. Due to the fact that the sheath potentials are not reduced, it is most likely that a field aligned ICRF antenna will not help in improving LH coupling during simultaneous LH+ICRF operation.
Chapter 7

Summary and Future Work

7.1 Summary

The goal of this thesis is to study and understand the interactions of LH and ICRF power with the SOL in order to understand LH and ICRF coupling. To achieve this, a reflectometer was built at multiple poloidal and toroidal locations to measure SOL density profiles and profile asymmetries on Alcator C-Mod. This thesis details the design, implementation, analysis, and first results of the reflectometer. Reflectometer density profiles are shown to compare favorably with Langmuir probes and Thomson scattering for a wide range of plasma parameters, such as $\bar{n}_e$, $I_p$, and majority atomic species. SOL reflectometer density profile measurements were then shown in ELM-y H-modes and localized gas puffing where the Langmuir probes and Thomson scattering did not have the temporal or poloidal spatial resolution to capture these effects. In particular, localized gas puffing is shown to create local SOL density modifications and poloidal density profile asymmetries.

After validating the reflectometer density profiles, the impact of LH power on the SOL density profiles near a LH launcher is observed for the first time in a tokamak. Measurements of LH-induced density profile modifications are shown for different $n_{||}$,
$B_t$ direction, $\bar{n}_e$, and inner gap. In particular, LH power creates strong emissivity striations that are approximately aligned with the total magnetic field and are visible above the center of each waveguide row in normal toroidal magnetic field direction. Striations are observed below the center of each waveguide row in reversed toroidal magnetic field direction. Density is shown to increase at a striation and decrease away from the striations, leading to strong LH-induced density profile asymmetries.

Given the recent observations of LH-induced SOL absorption in Alcator C-Mod as well as theoretical discussion in the literature, it is likely that LH-driven SOL absorption can drive a spatially varying plasma potential that leads to ExB convective transport at each waveguide row. The resulting convective transport is the main cause of the observed density profile modifications and poloidal density asymmetries. A 2-D diffusive-convective model was built to examine the effects of LH-induced ExB drifts on the density profile. The model reproduces this experimental trend and conclusively shows that the density profile modifications are largely caused by ExB convective transport. The simulation and experimental results also suggest that these LH-driven ExB drifts can modify and possibly reduce LH coupling. Using the measured reflectometer density profiles from the three poloidal reflectometer locations as inputs into a 2-D (radial and toroidal) LH coupling model, it is shown LH coupling is strongly sensitive to poloidal density profile asymmetries. This results strongly suggests that poloidal density profile asymmetries need to be included in modeling LH coupling.

As in the LH case, ICRF power is also observed to create ExB drifts and density profile modifications. Since the reflectometer locations are not located at the ICRF antennas, field line mapping is critical in understanding the reflectometer observations. This is most obvious during simultaneous ICRF and LH operation. A dedicated experiment has been done to compare LH coupling during operation with LH, LH+D, LH+E, and LH+J antennas. LH coupling is strongly reduced during LH+D operation, but is not significantly modified during LH+J operation. This is consistent with video camera images and reflectometer measurements where the adja-
cent D ICRF antenna removes an emissivity striation and depletes the density while the J ICRF antenna does not modify the emissivity striation. This density depletion may be the cause for the reduced LH coupling during simultaneous LH+D operation.

It is noted however that the understanding of ICRF-driven density profile modifications is incomplete. The 2-D diffusive convective model that reproduced the trends for the LH only case was also used in the ICRF case. While certain qualitative features are reproduced, the simulation predicts a much larger density modification than observed in experiments. This needs to be reconciled in the future.

7.2 Future Work

This section highlights possible future work in furthering the main goal of this thesis to study and understand ICRF/SOL and LH/SOL interactions in order to understand and improve LH coupling.

7.2.1 Extensions to H-mode and I-mode regimes

In this thesis, there has not been significant work done on understanding the behavior of LH coupling in H-mode and I-mode regimes, where the injection of LH power is used to tailor the current profile in steady-state, non-inductive scenarios. This is mostly due to the fact that to enter H-mode and I-mode on Alcator C-mod, more than one ICRF antenna is often necessary. This may any analysis of LH coupling difficult, as the use of different ICRF antennas will give different results (refer to chapter 6). On a dedicated run day, however, it is possible to get H-modes without an ICRF antenna or possibly with only one ICRF antenna, possibly by putting the strike point in a slot-divertor configuration to reduce the H-mode power threshold [124]. Studying LH coupling in these scenarios will be highly useful.
7.2.2 Understanding LH and ICRF driven flows

Reflectometry and GPI measurements suggests that the LH-driven flows may be consistent with a SOL-driven absorption mechanism. Stronger LH-induced density and flow modifications and decreased non-thermal emission are all observed at high $\bar{n}_e$, and inner gap. Figure 5-9 is an example of this correlation between LH-induced density profile modification and non-thermal emission. Understanding this LH-driven SOL absorption mechanism is obviously critical to improving LHCD, but it may also be critical to understanding LH-driven SOL convective flows, SOL density profile modifications, and LH coupling. Possible theories such as ponderomotive forces, solitons [125], parametric decay, SOL collisional absorption, and SOL driven fast electrons should be explored. Diagnostics that can both examine the impact of the SOL on the LHCD and vice-versa will be needed to understand this LH SOL-driven absorption mechanism.

Continued theoretical and experimental invesigation can also be carried out in the ICRF case. The theoretical investigation of ICRF sheaths and the resulting convective cells is still incomplete; a complete non-linear ICRF sheath model will be valuable. It is possible that a complete theory may capture some of the unexplained trends observed with the GPI and reflectometry diagnostics. It is important to not disregard other possible physical mechanisms, including ponderomotive forces.

Further simultaneous poloidal, toroidal and radial spatial resolution measurements with GPI and reflectometer will also be useful. Given the strong radial and poloidal variations in the plasma potentials, any additional spatial information will be extremely valuable.

7.2.3 Improved understanding of LH coupling

Current LH coupling models incorporate the geometry of the LH launcher [113]32 but they only assume that the density profile vary radially. Given the experimental
and simulation evidence in this thesis, it is clear the LH coupling models need to include poloidal density asymmetries and the effects of convective transport. Upgrades of diffusive-convective transport and LH coupling codes to three dimensions will be illuminating and highly informative to future experiments.

7.2.4 Reflectometry upgrades

Reflectometry upgrades may also be useful to continuing this work. Motorizing the waveguide switches or including multiple electronic sets may allow for poloidal resolution measurement within each discharge. More poloidal and toroidal reflectometer horn locations will also allow for a larger poloidal and toroidal coverage to diagnose density profile asymmetries.

Direct detection of ICRF and LH waves may also allow for study of parametric decay or other ICRF and LH-induced SOL absorption mechanisms that contribute to the observation of ICRF and LH-induced SOL flows and densities. This upgrade has been tried in proof of principle experiments [73][126] including Alcator C-Mod [77]. One similarity with all these attempts is that they only used fixed frequency reflectometers. A full sweeping reflectometer, such as the one used in this thesis, would allow unprecedented measurements of both density profile and wave measurements, allowing for direct tests of ICRF and LH models.
Bibliography


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