SOL Reflectometer for Alcator C-Mod

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Abstract

The study of antenna-plasma interactions during RF heating and current drive is greatly influenced by the SOL density profile. A swept-frequency X-mode reflectometer is being built for Alcator C-Mod to measure the SOL density profiles in front of the new Lower Hybrid Launcher and the new ICRF antenna. Six pairs of launchers will give measurements at the top, middle, and bottom of both the ICRF and LHRF antennas. The system is planned to operate between 100 and 146 GHz at sweep rates from 10 µs to 1 ms and will cover a density range of approximately $10^{16}$ to $10^{20}\text{m}^{-3}$ at 5-5.4 T. Due to the strong density fluctuations in the SOL, the system will use both differential phase and full phase techniques to get the best possible measurement. Design and preliminary test data from the electronics and waveguide runs will be presented. A 3-D ray tracing code to study the expected reflectometry measurement of the density profile will also be shown.
Motivation

Ion cyclotron and lower hybrid range of frequencies are and envisioned to be utilized for plasma heating and current drive, respectively, in present and future experiments.

One of the challenges facing ICRF and LHRF utilization in present experiments and future reactors is efficient and reliable transfer of power to the core plasma.

- Waves require the presence of the plasma for propagation.
- Coupling structures are close to the plasma.

Coupling is strongly influenced by the edge density and density profile.

- The density and density profile set the distance to and the input impedance at cut-off layer for ICRF.
Motivation

At high power, ICRF and LHRF modify the edge density and density profile
- Nonlinear phenomena can modify the edge density and density profile
- Phenomena could result in up-down asymmetry of density profiles
- Parametric decay instability, particularly for LHRF, becomes important as the wave accessibility limit is reached
- Measuring radial width of PDI modes could validate PDI model

Shaped plasmas and extended coupling structures could complicate efficient coupling
- Flux tube connection length influences plasma density on a particular flux tube
- RF biasing of flux tubes could result in up-down asymmetry of density profiles local to the antenna

Seek to measure the local density and density profile utilizing high temporal and spatial resolution reflectometry

Utilize density profile data in conjunction with antenna electrical measurements to validate ICRF and LHRF coupling and antenna models
Reflectometry Basics

Full-phase reflectometry
\[ \phi(\omega) = 2 \frac{\omega}{c} \int_{r_0}^{r(\omega)} N(r, \omega) dr - \pi / 2 \]

Differential phase-reflectometry
\[ \Delta \phi(\omega) = \phi(\omega) - \phi(\omega - \Delta \omega) \]

where \( N \) is the R cutoff and \( r(\bullet) \) is distance of cutoff layer
Our Reflectometer

Measurement Requirements

- Measure the density profile in the scrape-off-layer
  - Density at last closed flux surface $\approx 10^{20}$ m$^{-3}$
- Measure at the RF antenna and the LH antenna
- Allow measurement of density fluctuations and parametric decay instabilities

Design Parameters based on Requirements

- Use X-mode with a frequency range of 100 – 146 GHz
  - Yields density range of $10^{16}$ to $10^{20}$ m$^{-3}$ at 5.0 – 5.4 T
- Use differential-phase measurement to minimize effects of large density fluctuations in the SOL
  - Use 500 MHz difference-frequency
- Also provide full-phase measurement for profiles and fluctuations
- Use sweep speeds of 10 µs to 1 ms
Differential Phase vs. Full Phase

Density fluctuations are the largest error source in measuring density profile.
- Lead to phase jumps
- For differential-phase, difference frequency, \( \Phi \), has to be chosen so that the density fluctuation radial correlation length is greater than separation in cutoff layers.

Sweep Speed
- For full phase, sweep time has to be fast enough to effectively “freeze” out the fluctuations.
- Differential phase can be fast or slow, but slow sweeps may be advantageous
- During slow sweep, measure differential-phase through multiple cycles of the density fluctuations

By using both techniques, we hope to get as accurate a measurement as possible.
Reflectometer Electronics

CMOD Reflectometer 100–146 GHz
Electronics Design

• Arbitrary sweep signal generator with voltage controlled oscillator (6.350-9.175 GHz) sends out broadband frequency source.
• Source goes through carefully selected mixers, and filters so as to reduce undesirable intermodulation products.
• 6.25 and 6.3125 GHz sources provide the two different frequency signals.
• State of the art Virginia Diode high frequency broadband multipliers generate the final 100-146 GHz operation.
• Second harmonic mixers provide heterodyne detection to get an accurate signal.
• I&Q detectors are used to get phase information
Transmission Line System

• Use WR-08 waveguide switches to select the waveguide run to either the ICRF or the LHRF antenna
• Also use WR-08 switches to select between the upper, mid-plane or lower reflectometer launchers
• Waveguide runs utilize WR-90 and WR-22 waveguide with TE$_{01}$ polarization (tallguide)
  - Approximately 0.1 dB/m theoretical loss for WR-90 tallguide for 100-146GHz
  - Approximately 0.8 dB/m theoretical loss for WR-22 tallguide for 100-146GHz
• Will use WR-90 E-plane and H-plane 90° miter bends
  - 4–8% mode conversion in the H-plane 90° miter bends
  - 13–17% mode conversion in the E-plane 90° miter bends
• Will use WR-08 (TE10) to WR-22 (TE01) tapered transitions
  - 7.6 cm length gives approximately -28-dB mode conversion
• Also use WR-22 (TE01) to WR-90 (TE01) tapered transitions
  - 40 cm length gives approximately -19.5-dB mode conversion
Waveguide Layout
ICRF Transmission System

• Use Horn Antennas
  - Aperture: 0.5 cm wide x 1.0 cm high
  - Antenna Gain: 17-dB
  - Estimated ideal horn to horn coupling: -18-dB

• Round-Trip Transmission Line:
  - 15 m of WR-90 tallguide
  - 3 m of WR-22 tallguide
  - 1.8 m of WR-08
  - 1 WR-90 tallguide 90° H-plane miter bend
  - 4 WR-08 waveguide switches
  - 8 WR-08 to WR-22 tallguide tapered transitions
  - 4 WR-22 tallguide to WR-90 tallguide tapered transitions
  - Estimated round-trip waveguide attenuation is <-25-dB

• Estimated Total WG and Antenna Coupling Loss: -43-dB
  - With plasma, estimated total return loss: -43-dB to -63-dB
LH Transmission System

• Use Direct Launch from WR-22 Tallguide
  - Aperture: 0.5 cm wide x 1 cm high
  - Antenna Gain: 17-dB
  - Estimated ideal horn to horn coupling: -18-dB

• Round-Trip Transmission Line:
  - 25 m of WR-90 tallguide
  - 3.8 m of WR-22 tallguide
  - 1.2 m of WR-08
  - 1 each of WR-90 tallguide 90° H-plane & E-plane miter bends
  - 4 WR-08 waveguide switches
  - 6 WR-08 to WR-22 tallguide tapered transitions
  - 4 WR-22 tallguide to WR-90 tallguide tapered transitions
  - Estimated round-trip waveguide attenuation is <-24-dB

• Estimated Total WG and Antenna Coupling Loss: -46-dB
  - With plasma, estimated total return loss: -46-dB to -66-dB
ICRF Antenna with Reflectometer

Wukitch: Poster session
LH Launcher with Reflectometer
Density Profile Reconstruction

\[ \phi(\omega) = 2 \frac{\omega}{c} \int_{r_0}^{r(\omega)} N(r(n_e, B), \omega) dr - \pi / 2 \]

where \( r \) is distance of the cutoff layer at frequency, \( \omega \). \( X \) mode reflectometry measures the phase, \( \phi \), for the reflection of a wave from the R cutoff.

- From the measured \( \phi \) from the reflectometer, and calculated \( B \) from \( \text{EFIT} \), standard Abel inversion of the above equation will give us a density profile.

- This density profile reconstruction is standard for reflectometer midplane launchers. For top and bottom reflectometer launchers, 3D ray tracing may be needed to assess the accuracy of this Abel Inversion for nonstandard launch directions.
H-Mode Cutoff Layers

- 115, 125, 135, 145 GHz layers
- 120, 130, 140 GHz layers
- Flux Surfaces
- Reflectometry Horn Locations
L-Mode Cutoff Layers

115,125,135,145 GHz layers
120,130,140 GHz layers
Flux Surfaces
Reflectometry Horn Locations
3D Ray Tracing

- 3D ray tracing is needed due to the curvature of the cutoff layers
  - Ray trajectories may bend, which is not accounted for in Abel inversion method.
  - Cutoff layers shape follow the total magnetic field (vertical) for low densities and flux surfaces (assuming density is a function of flux) for high densities. Thus, reflection from cutoff layers may be complicated

- For tokamak geometries, ray tracing equations are:

\[
\begin{align*}
\frac{dr}{dt} & = - \frac{\partial D}{\partial k_r} \\
\frac{d\theta}{dt} & = - \frac{\partial D}{\partial \omega} \\
\frac{d\phi}{dt} & = - \frac{\partial D}{\partial \omega} \\
\frac{dk_r}{dt} & = - \frac{\partial D}{\partial r} \\
\frac{dm}{dt} & = - \frac{\partial D}{\partial \theta} \\
\frac{dn}{dt} & = - \frac{\partial D}{\partial \phi} \\
\frac{dD}{dt} & = 0
\end{align*}
\]
Sample LH Ray Trajectories
Phase Calculation

Following a treatment by Hacquin¹, the reflectometer phase can be calculated in three ways.

1. 1D: 1D phase calculation assuming $r(\omega)$ is straight.

$$\phi(\omega) = 2 \frac{\omega}{c} \int_{r_0}^{r(\omega)} N(r, \omega) dr - \pi / 2$$

2. 1D (r): 1D phase calculation following main ray trajectory

$$\phi_{1D}(\omega) = \frac{\omega}{c} \int_{\text{traj}} k_r dr + m d \theta + n d \phi - \pi / 2$$

3. 3D (r): 3D phase calculation by integration of ray trajectories that start at transmission horn and end up at receiving horn.

$$\phi_{3D}(\omega) = \text{Arc tan} \left[ \frac{\text{Im}(I_{\text{rec}})}{\text{Re}(I_{\text{rec}})} \right]$$

$$I_{\text{rec}} = \int \int_{y, z} E_{\text{ref}}(y, z) E_{\text{rec}}(y, z) \exp(-i \phi_{1D}(\omega))$$

$$E_{\text{ref}}(y, z) \propto \exp[-m_0^2 \rho^2 - n_0^2 \rho^2] / 2$$

$$E_{\text{rec}}(y, z) \propto \exp[-(y - y_{\text{rec}})^2 - (z - z_{\text{rec}})^2] / 2 \rho^2$$

MidPlane Launcher

Small errors between all the phase calculations produce barely perceptible differences when Abel inverting density profile
Top/Bottom LH Launcher

Top

Bottom

Graphs showing the frequency dependence of different models (1D, 1D (r), 3D (r)) for both top and bottom cases. The graphs compare the phi (fringes) and difference (%) across various frequencies (110 to 150 GHz).
Density Profile

Top Launcher/Bottom Launcher is similar

Large errors at low frequencies provides a bit of scatter when doing the inversion for different phase calculations. However, as the errors go away at higher frequencies, the Abel inverted density profile still match very well.
Insights into Profile Inversion

• Differences in phase calculations are small especially as the frequency increases
  – For middle launcher, as concluded by Hacquin, the difference between 1D (phase) and 3D (r) are small enough that standard 1D Abel inversion should give accurate results.
  – Same is generally true for top and bottom LH launchers, except for launch at frequencies just above the cyclotron frequency.

• At low frequencies, the error is extremely large for top and bottom launcher
  – The difference between the horn’s angle (designed to be perpendicular to flux surfaces) and the cutoff layer for low frequencies (vertical) creates this error.
  – As long as the cutoff layer is close to the flux surface shape, Abel inversion is adequate.
Future Work

• Reflectometer Electronics being assembled and tested now
  – System testing to be done early 2009
• In-antenna waveguide runs and antennas in progress
  – Transmission line system conceptual design complete
  – Full layout for LH to be done by December
• Installation of Reflectometer electronics and waveguide run planned for early 2009
  – Allow testing of full system before installation of the LHRF antenna
• Installation of the LHRF antennas scheduled for April, 2009
  – In situ testing and calibration will be performed after this installation
• Installation of the ICRF antennas scheduled for 2010

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