Diagnostic development to measure parallel wavenumber of lower hybrid waves on Alcator C-Mod


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21st Topical Conference on Radiofrequency Power in Plasmas
April 27 – 29, 2015

Work supported by US DoE Cooperative agreement DE-FC02-99ER54512 at MIT using the Alcator C-Mod tokamak, a DoE Office of Science user facility, and by Japan/U. S. Cooperation in Fusion Research and Development.
Motivation: Measurement of parallel wavenumber ($k_{||}$) of lower hybrid waves

- Lower Hybrid Current Drive (LHCD) system at 4.6 GHz in Alcator C-Mod operates at ITER-relevant frequency, B-field, densities, and configurations.

- $k_{||}$ of LH waves is set by the relative phase of the electric field between the adjacent waveguides (grills), and determines wave propagation and damping mechanisms.

- Direct $k_{||}$ measurements away from the launcher could help study the evolution of $k_{||}$ in tokamaks and understand the role of spectral broadening mechanisms such as scattering by turbulence or parametric decay instabilities.

- We are developing an array of magnetic loop probes, which will allow measuring the $k_{||}$ and polarization of LH waves in the scrape-off layer.
An array of magnetic probes allow measuring the phase and polarization of LH waves.

Array of Loop probes

\[ \Delta x \]

\[ \vec{B}_1 = \vec{B}_0 e^{i\varphi_1} \]
\[ \vec{B}_2 = \vec{B}_0 e^{i\varphi_2} \]
\[ \vec{B}_3 = \vec{B}_0 e^{i\varphi_3} \]

\( \Delta x \) determines the relative phase \( \Delta \varphi \) of the measured signals among the probes.

- Magnetic loop probes measures the induced voltage due to time varying magnetic flux, as indicated by Faraday’s Law:
\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]

- An array of probes along the background magnetic field line will provide the relative phase among the measurement locations.

- In Alcator C-Mod, the launched n|| from the LH grill antenna is typically 1.9, which translates into \( \lambda_{||}/2 = 17.2 \text{ mm} \), implying that the relative distance among the probes need to be \( \sim 5 \text{ mm} \).
A magnetic loop antenna has been developed in-house.

- A probe has been designed in the University of Tokyo [1].
  - Inner diameter of the circular coil: 1.2 mm
  - A shield minimizes noise pickups. A slit on the surface of the shield allows wave field propagation to the coil.
  - Diameter of the shield: 5 mm
  - Dimension of the slit on the shield: 4 mm x 0.5 mm

- A vacuum-compatible version is in-house fabricated
  - Inner conductor to the outer stainless steel jacket is silver solder brazed.
  - The solder employed was Easy-flo 35 (35% silver, melting point of 1124 degrees Fahrenheit).

Slotted waveguides are used to examine the probe response.

- The surface of the WR187 waveguide \((a = 47.55\, \text{mm} \times b = 22.15\, \text{mm})\) on the narrower dimension side has been slotted to place the probe and calibrate the probe.
  - Bandwidth of the WR187 waveguide: 3.95 – 5.85 GHz
  - The cover holds the magnetic probe, and covers the slotted surface of the WR187 waveguide.

- Using a network analyzer, TE10 mode is excited at one end of the waveguide. By connecting the other end of the network analyzer to the probe, one measures S-parameters of the probe.
The probe has a reasonable flat frequency response in the frequency range of interest.

- At the fixed location in the slotted waveguide, the frequency response of the probe was examined with a network analyzer.

- The probe shows a flat response within 4.5 – 4.7 GHz.
  - No anomalous resonance behavior between 4 and 5 GHz.

- It also shows the linear variation in phase as a function of frequency.
The probe can be also used to measure the polarization of the wave.

- Define $\theta$ to be the angle between the surface normal vector of the coil and the $B$-field fluctuation vector.
  - The angle determines the area that the probe coil intercepts the $B$-field.

- When $\theta = 0$ deg, $S_{21}$ is -55 dB.
- Measurements show that the probe is sensitive to the polarization by ~25 dB, and follows the $\cos^2 \theta$ dependence.
Phase response of the probe: by translating the magnetic probe along the waveguide, the wavenumber of the B-field is compared to the theory.

- By moving the cover along the waveguide with the probe fixed, the probe measures the phase variation.

- For the TE10 mode in the WR187 waveguide, the propagation constant is \[ \beta = \sqrt{k^2 - \left(\frac{\pi}{a}\right)^2} = 70.11 \text{ (1/m)} \] at 4.6 GHz, where \( k \) is the wavenumber.

- The measurement indicates that \( \beta = 69.94 \text{ (1/m)} \), which is in good agreement with the theory.
The probe measurement capability is strongly sensitive to the relative distance from the shield end to the waveguide surface.

- The figure on the left-hand side shows the distance \(d\) between the probe shield to the inner surface of the WR187 waveguide.

- As \(d\) increases, the probe end is outside of the waveguide region, and S21 decreases significantly.

- This implies that when the probe is placed between the protective tiles, it needs to be placed right behind the protect tile for the maximized response.
The radially movable probe system (Surface Science Station or S3) will be utilized to mount the array of the magnetic probes.

- One big advantage of S3 is its radially movable capability [1].
  - S3 had previously been used to study waves in the ion cyclotron range of frequencies.

- It is located at the K-port, which is about 3 ports (or 108 degrees toroidally) away from the LH launcher at the C-port.
- This location could be an ideal location to intercept the LH resonance cone on the first pass from the launcher to the plasma.

A new probe head is under fabrication to mount magnetic probes and Langmuir probes.

- Two rows of three magnetic probes will be mounted on the probe head.
- The top row will be sensitive to wave fields associated with $\vec{B}$ perpendicular to the background magnetic field.
- The bottom row will be sensitive to wave fields with $\vec{B}$ parallel to the background magnetic field.
Langmuir probes will be also installed to measure plasma density and temperature.

- On the S3 probe head, Langmuir probes will be also placed to measure the local density and temperature at the measurement location.

- S3 has been designed to use the existing upper divertor probes.

- The probe tip geometry needs to be considered. The cut in the probe tip is such that the cutted plane is nearly parallel to the field line (~ 10 deg.)

- To find a surface normal vector $\vec{n}$ of the plane of cut, which resides in the same plane that are normal to both $\vec{B}$ and $\vec{B}_\perp$, one can give the following two constraints.
  
  $\vec{n} \times \vec{B}_\perp = 0$
  
  $\vec{n} \cdot \vec{B}_n = |\vec{n}||\vec{B}_n| \cos 10^\circ$
Ray tracing [1] simulations indicates that the S3 is expected to detect the LH wave-fields with low n∥ at high densities.

\[ \text{Launched } N_{\parallel} = -2.1 \]

\[ \text{Launched } N_{\parallel} = -1.75 \]

\[ \text{Launched } N_{\parallel} = -1.7 \]

\[ \text{Poloidal location of S3} \]
We expect that the measured power with the probe will be around -10 dBm.

• The power density of the LH resonance cone is 33 W/mm$^2$, assuming the net power of 1 MW with the grill surface area of $3 \times 10^4$ mm$^2$.
  • Grill consists of 4 rows of 18 waveguide grills with the dimension of 7 mm x 60 mm.

• Assuming that the probe intercepts the LH resonance cone, the power that passes through the slit of the magnetic probe is 66 W.
  • The area of the slit is 2 mm$^2$ (= 4 mm x 0.5 mm)

• Based on the bench test, we expect that the S21 of the probe will be about 60 dB, indicating that the measured power will be 0.066 mW, or -12 dBm.
An Intermediate Frequency (IF) stage employs two-step frequency down-conversion processes to directly digitize LH signals.

- Each channel consists of two mixing stages to frequency down-convert the signals at 4.6 GHz to 250 MHz. The amplification in the IF stage is 20 dB with an amplifier.
- The output signals will be directly fed to a fast speed digitizer (100 Msample/sec)
An example of the frequency down-converted signals using the IF chains is shown below.
The IF system can be expanded to multiple chains to measure the relative between the channels.

- Two independent IF stages are fed with a RF source at 4.6 GHz with a phase-shifter at one channel.

- The output voltage and the relative phase have been monitored.

- The relative phase between the two channels maintain its accuracy for a wide range of input power (~50 dB).
Six channel IF chains will be used in the experiment.

- The first three channels will be used to measure signals with the three probes sensitive to $\vec{B}$ perpendicular to the background magnetic field.

- The rest three channels will be used to measure signals with the three probes sensitive to $\vec{B}$ parallel to the background magnetic field.

- With this approach, we would not be able to measure whole frequency spectra (4.4-4.7 GHz).

- However, by controlling the frequency output of the tunable oscillator, we can study the pump frequency and wavenumber spectra ($4600 \pm 12.5$ MHz) and sideband spectra ($4570 \pm 12.5$ MHz) independently.
Local Oscillator (LO) system to generate 4.9 GHz signals.

- A voltage controlled oscillator will be remotely controlled with a function generator.
- Using a 6-way splitter, it outputs the LO signals at +4 dBm.
- This will allow selecting different frequency range of the input signals around at 4.6 GHz.
Another LO system to generate the fixed signal at 275 MHz.

- The frequency of this VCO is fixed to 275 MHz.
- We used a voltage regulator and a pot to control the bias voltage.
- Using a 6-way splitter, it outputs the LO signals at +4 dBm.
A high speed digitizer is capable of taking data with multiple triggering in a single plasma discharge.

- 8-channel 14-bit 100 Msample/s PXI Express digitizer
- Input range: -2 – 2 V
- One trigger input
- 512 MB onboard storage memory
- Data captured for 10 msec is 16 MB (8CH x 100 MS./s x 2 Byte x 10 msec)
- Thus, the onboard memory can take up to 0.32 sec continuously.

- However, we plan to take the segmented data by triggering the digitizer 10 times within a shot.

- In each triggering event, we will take data for $\Delta t_1=20$ µsec (= 2048 points at the rate 100 Msample/sec) with the waiting time of $\Delta t_1=30$ msec.
The system has been tested as a whole.

- The electronics has been installed on a 19-inch rack.
- We are making a final assembly (e.g., adding SMA feedthroughs and installing 120V power service line).
- Below shows an example of the raw signal acquired with the digitizer at 100 MS/sec, after they are frequency down-converted from 4.6 GHz to 25 MHz. (So there are 4 data points in one cycle)

![Digitizer](image.png)

![IF Section](image.png)

![LO @4.9 GHz](image.png)

![LO @275 MHz](image.png)
The system is capable of resolving the phase difference among the channels.

- Signals at 4.6 GHz is fed to the two channels. The digitizer has been triggered multiple times.
- The FFT spectra shows that both channels have the main peak at 25 MHz. The signal to noise ratio is about 60 dB.
- During the 10 triggering events, the relative phase between the channels shows the stable response.
- One key issue would be calibrate the system well enough: We plan to use a slotted waveguide to calibrate an array of the probes.
Summary and Future Work

- $k||$ measurements of LH waves could help us understand the wave propagation and absorption mechanisms.

- Magnetic loop probes, specific to the C-Mod tokamak environment have been developed.

- Electronics that down-convert the signals at 4.6 GHz to 25 MHz have been developed, which are capable of resolving the dominant (or single) parallel wavenumber spectrum at the given frequency. Polarizations of the waves will be also examined.

- Future Work: The probe head is under final fabrication to mount Langmuir probes. We will also bring the rack to the C-Mod cell soon.