Microwave imaging reflectometry for transport study on KSTAR

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Density Fluctuation Measurement for Turbulence Study

- Accurate measurement of plasma density and electron temperature fluctuations is critical to understand the mechanism of anomalous transport based on turbulence.

- 2-D microwave imaging reflectometry (MIR) can overcome deficiencies of the conventional 1-D reflectometry used for density fluctuation measurement.

X. Garbet et al., NF 47, 1206 (2007)
Microwave Reflectometry

- Incoming wave is reflected at the cut-off layer.
- Reflected waves contain information of the shape of the cut-off layers.
- Fluctuating phase of the reflected signal is
  \[ \tilde{\phi} = k_o \int_0^{r_c} \frac{\tilde{\varepsilon}(r)}{\sqrt{\varepsilon_o(r)}} dr \]
  where \( k_o \) is probe beam wave number,
  \( \varepsilon(r) = \varepsilon_o(r) + \tilde{\varepsilon}(r) \) is plasma permittivity.
- The interpretation is straightforward in 1-D fluctuation but complicated in 2-D fluctuation due to interference.

\[ \Rightarrow \text{requires imaging reflectometry} \]
Microwave Imaging Reflectometry (MIR)

- Probing beam illuminates extended region of cutoff layer.
- The beam front curvature is matched to that of cutoff surface (toroidal and poloidal) for optical robustness.

- The cutoff layer is imaged onto the detector array, reducing inference effects.
- The MIR system can detect density fluctuations in the larger amplitude and shorter wavelength owing to the imaging optics.
Multi-Frequency MIR system

Multi-frequency conventional reflectometry (1-D):
- size (correlation length), wavelength, and flow velocity of fluctuation or wave in radial direction
- only detect fluctuations in small amplitude and long wavelength (or wave number)

Single frequency MIR system (1-D):
- size, wavelength, and flow velocity of fluctuation or wave in poloidal direction
- enhanced detecting capabilities in the fluctuating amplitude and wavelength

Multi-frequency MIR system (2-D):
- size, wavelength, and flow velocity in poloidal cross section

T. Munsat et al., PPCF 45, 469 (2003)
Design of the KSTAR MIR system
X-mode Cut-off Layer

Radial position of X-mode cut-off layer (r/a): 0.4 ~ 0.8
Radius of curvature: 700 ~ 1000 mm.
KSTAR MIR System

- **Design parameters:**
  - probe beam frequencies: 88±1 and 92±1 GHz (ultimately 5 frequencies)
  - detection channel: poloidal 16 and radial 2 (ultimately 5)
  - spatial resolution: poloidally ~0.8 cm and radially ~5 cm
  - maximum detectable wave number: poloidally 2 cm⁻¹ and radially 0.3 cm⁻¹
  - time resolution: 0.25 μs (4 MS/s digitizer)
  - maximum detectable frequency: 2 MHz
Detectable wave number range

- **Maximum wave number (a):**

\[ k_\theta = \frac{2\pi}{\lambda} = \frac{2\pi}{(a/2)} = \frac{4\pi}{a} = \frac{12.56}{6 \text{ cm}} \sim 2.1 \text{ cm}^{-1} \]

- **Minimum wave number in case (b):**

\[ k_\theta = \frac{2\pi}{\lambda} = \frac{2\pi}{(2a)} = \frac{\pi}{a} = \frac{3.14}{6 \text{ cm}} \sim 0.52 \text{ cm}^{-1} \]

0.52 cm\(^{-1}\) $\leq k_\theta \leq 2.1$ cm\(^{-1}\)

- **Ion gyro radius for B = 3 T is**

\[ \rho_i = 0.13 \sim 0.47 \text{ cm} \text{ (for } T_i = 0.3 \sim 3 \text{ keV)} \]

\[ k_\theta \rho_i = 0.07 \sim 0.91 \text{ at } r/a = 0.57 \]

\[ k_\theta \rho_i = 0.08 \sim 0.96 \text{ at } r/a = 0.8 \]
Cut-off layer fluctuation due to density fluctuation

\[ \frac{\delta n_e}{n_e} = +5\% \rightarrow \delta R_{\text{cutoff}} = 8.4 \text{ mm} \]

\[ \frac{\delta n_e}{n_e} = +5\% \rightarrow \delta R_{\text{cutoff}} = 5.3 \text{ mm} \]
Cut-off layer fluctuation vs. density fluctuation

\[ \delta R = 1.7 \text{ mm (} \delta \text{ phase} = 2 \pi) \text{ is equivalent to } \delta n/n \sim 0.9 \% \text{ at } r/a \sim 0.57 \]

\[ \delta R = 1.7 \text{ mm (} \delta \text{ phase} = 2 \pi) \text{ is equivalent to } \delta n/n \sim 1.5 \% \text{ at } r/a \sim 0.8 \]
ECEI and MIR Systems at G- & H-port
Design of MIR System

- The MIR and ECEI system share the zoom lenses.
- The dichroic plate, a kind of high pass filter, will be used to separate the MIR and ECEI signals.
Launching and receiving optics

ECEI zoom lenses

Launching lens

Launching optics

Subtrait lens

Receiving optics

Receiving lens

Detector array
Schematic of Hardware System

Two-frequency probing source

- 16+16 dBm coupling:10 dB
- 10+10 dB
- 8+6 dBm
- 0+0 dBm
- 87 ≈ 89 GHz P = +1 dBm
- 15.16 - 15.50 GHz P = +10 dBm

Synthesizer: 14.50 - 14.83 GHz P = +11 dBm

X5

Main facility room

LO source

- 88 - 90 GHz P = 0 dBm
- 14.67 - 15.0 GHz P = +10 dBm

Directional coupler (-1.5 dB)

- 16 dBm
- 10 dBm
- 4 + 4 dBm

1.8 - 3 GHz fundamental balanced mixer (C.L. = -10 dB)

- 30 mW
- (-15 dBm)

-1 dB

Array box (16 chs)

Assume -30 dBm to be coupled to each antenna

Two-frequency probing source

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One of 16 detection channels

-1 GHz diplexer (-3 dB)

0.3 - 1 GHz BPF

Tracking circuit

12-way Power divider

-56 ~ -12 dBm

Digitizer

16 chs
4 MS/s
14 bits
100 KHz
r/± 0.25 V

Reference channel

-1 GHz diplexer

0.3 - 1 GHz BPF

Tracking circuit

12-way Power divider

-56 ~ -12 dBm

Digitizer

16 chs
4 MS/s
14 bits
100 KHz
r/± 0.25 V
Laboratory Test of the preliminary optics and electronics
Laboratory test setup of prototype MIR system
Corrugation phase measurement of reflecting wheel

Corrugated reflecting wheel:
Corrugation wavelength ~ 50 mm
Corr. depth ~ 1.9 radian ~ 0.6 π
~ 0.3 \( \lambda_0 \) (\( \lambda_0 = 3.4 \) mm)
Reflected beam from corrugated wheel

Corr. depth vs circumference measured by dial gauge.

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<th>l (mm)</th>
<th>depth [mm]</th>
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<tr>
<td>865</td>
<td>1.82</td>
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<td>1.72</td>
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<tr>
<td>950</td>
<td>1.08</td>
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</table>

• corr. depth = max – min = 1.04 mm
• corr. wavelength = 50 mm

\[
\cos(\omega_{RF}t) \\
\lambda_0 = 3.4 \text{ mm}
\]

\[
\cos\left[\omega_{RF}t + \frac{2\pi}{\lambda_0} 0.3\lambda_0 \cos(\omega_{wheel}t) + \frac{2\pi}{\lambda_0} L\right] \\
= \cos\left[\omega_{RF}t + 0.6\pi \cos(\omega_{wheel}t) + 1.85L\right]
\]
Reflected beam from corrugated wheel

- probe beam = \( \cos(\omega_{RF} t) \)  \( (\omega_{RF} = 88 \text{ or } 92.5 \text{ GHz}) \)
- LO beam = \( \cos(\omega_{LO} t) \)  \( (\omega_{RF} = 89 \text{ GHz}) \)
- wheel corrugation phase = \( \varphi_{\text{corr}} = 0.6\pi \cos(\omega_{\text{wheel}} t) \)  \( \leftarrow \) corrugation depth = 1.2 \( \pi \)
- beam path length phase = \( \varphi_{\text{path}} = 2\pi/(3.4 \text{ mm}) \) \( L \text{ [mm]} = 1.85 \text{ L [mm]} \)

- reflected beam = \( \cos[\omega_{RF} t + \varphi_{\text{corr}} + \varphi_{\text{path}}] \)
  \( \downarrow \) \textbf{(first stage: array)}

- IF_detection (by array) = \( \cos[(\omega_{RF} - \omega_{LO})t + \varphi_{\text{corr}} + \varphi_{\text{path}}] \)
- IF_reference (by mixer) = \( \cos[(\omega_{RF} - \omega_{LO})t ] \)
  \( \downarrow \) \textbf{(second stage: IQ demodulator)}

- I signal (by IQ box) = \( \cos(\varphi_{\text{corr}} + \varphi_{\text{path}}) = \cos[0.6\pi \cos(\omega_{\text{wheel}} t) + 1.85L] \)
- Q signal (by IQ box) = \( \sin(\varphi_{\text{corr}} + \varphi_{\text{path}}) = \sin[0.6\pi \cos(\omega_{\text{wheel}} t) + 1.85L] \)
Comparison btw experimental data and analytic calculation

- I signal = amp * cos(φ_corr + φ_path) * amplitude modulation + offset_I
- Q signal = (amp*elongation) * sin(φ_corr + φ_path) * amplitude modulation + offset_Q
- amplitude modulation = [1 + amp_mod * cos(ω_modulation t)]
Test of IQ system

Ideal case

Test result of the IQ system
Summary

- A microwave imaging reflectometry (MIR) system is being developed for transport study in KSTAR plasma and will be installed in late this year.
  - detection channel: poloidal 16 and radial 2 (upgraded to 5 in 2013)
  - spatial resolution: poloidally ~0.8 cm and radially ~ 5 cm
  - time resolution: 0.25 μs
  - maximum detectable wave number: poloidally 2 cm⁻¹ and radially 0.3 cm⁻¹
- Preliminary design of the imaging optics and electronics has been finished and prototypes of them is being tested.
- Numerical simulation study together with the laboratory experiment is being conducted for characterization of the imaging optics and analysis of measured data.