Advanced Laser Diagnostics for Electron Density Measurements

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\begin{itemize}
  \item Introduction
  \item Cotton-Mouton polarimeter on CHS
  \item Two color laser interferometer
\end{itemize}

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On LHD, a 13-channel 119-\(\mu\)m CH\(_3\)OH far infrared laser interferometer has been routinely operated for the precise measurements of the electron density profile.

The maximum densities of over 4 x 10\(^{20}\) m\(^{-3}\) were achieved by using pellet fueling and LID pumping.

A poloidal polarimeter system has been designed for the measurements of current density profile in ITER.

Proposed laser oscillation line is 119-\(\mu\)m CH\(_3\)OH, but the beam bending effect due to plasma density gradient is large.

Laser oscillation lines around 50\(\mu\)m are considered to be suitable from the consideration of the beam refraction and signal-to-noise ratio.
Choice of probe beam wavelength

- The optimum wavelength suitable for interferometry/polarimetry can be selected from the following considerations
  - Phase shift: \( \varphi = 2.82 \times 10^{-15} \lambda \int_{z_1}^{z_2} n(z) \, dz \)
  - Cutoff frequency: \( n_c = 1.11 \times 10^{15} / \lambda_0^2 \) (m\(^{-3}\))
  - Beam bending effect:
    \[
    \alpha_m = \sin^{-1} \left( \frac{n_o}{n_c} \right) \approx \frac{n_o}{n_c} = 8.97 \times 10^{-16} n_o \lambda^2
    \]
    \[
    \lambda \leq 1.16 \times 10^{10} \left( Z_o n_o^2 \right)^{-1/3} m
    \]
    (Example: \( Z_o = 3.8 \) m, \( n_e(0) = 1 \times 10^{20} / m^3 \) leads to \( \lambda < 330 \) \( \mu \)m)
  - Mechanical vibration: \( \Delta \phi = 2 \pi \Delta L \lambda^{-1} \)
  - Faraday rotation: \( k \parallel B \)
    \[
    \Omega = 2.62 \times 10^{-13} \lambda^2 \int_{z_1}^{z_2} nB_\parallel \, dz
    \]
  - Cotton-Mouton effect: \( k \perp B \)
    \[
    \varepsilon = 2.45 \times 10^{-11} \lambda^3 B^2 n_e \Delta z
    \]

- At \( B = 2.64 \) T:
  - \( n(0) = 4.2 \times 10^{20} m^{-3} \)
  - \( T(0) = 0.87 \) keV
  - \( \beta(0) = 4.2 \% \)

\[ d = 2 \left( \frac{\lambda Z_o}{\pi} \right)^{1/2} \rightarrow Z_o \alpha_m \leq 2 \left( \frac{\lambda Z_o}{\pi} \right)^{1/2} \]
Selection of Wavelength for ITER Diagnostics

Dependence of phase difference by CM effect on wavelength of laser

\[ \phi_{\text{CM}} [\text{rad.}] = \phi_{O} - \phi_{X} \]

\[ = 2.4 \times 10^{-20} \lambda [\text{mm}]^3 \int n_e [\text{m}^{-3}] B_{\perp} [\text{T}]^2 \, dl [\text{m}] \]

Ne=1x10^{20} m^{-3}, B_0=5.3 T, L=4 m
Selection of Wavelength (continue)

\[ \int dl B n_e \]

\[ \lambda \int n_e dl \]

\[ \lambda^2 \int n_e B dl \]

\[ \lambda^3 \int n_e B^2_\perp dl \]

<table>
<thead>
<tr>
<th>Measurement</th>
<th>57 μm</th>
<th>119 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>20 fringes</td>
<td>43 fringes</td>
</tr>
<tr>
<td>Rotation</td>
<td>14 deg.</td>
<td>60 deg.</td>
</tr>
<tr>
<td>Cotton–Mouton</td>
<td>5.7 deg.</td>
<td>52 deg.</td>
</tr>
<tr>
<td>Displacement</td>
<td>0.9 mm</td>
<td>4 mm</td>
</tr>
</tbody>
</table>

\[
Ne=10^{19}+1\times(1-\rho^2)10^{20}m^{-3}, \\
B_0=5.3T, L=4m, I_p=15MA
\]

\[
Ne=10^{19}+2\times(1-\rho^2)10^{20}m^{-3}, \\
B_0=5.3T, L=4m
\]
Cotton-Mouton Polarimeter for Electron Density Measurement with HCN laser on CHS

• Path length from the laser to optical frame is about 15 m.
• Dielectric waveguide (φ 47 ID) made of acrylic resin is used to transmit laser beams. The transmission efficiency is totally about 80%.
• Detectors are schottky barrier diodes.
Measurement Method of CM effect

Probe signal:  \[ I_{\text{probe}} = \left[ \sin\{(\omega + \omega_b)t + \phi_O\} + \sin(\omega t + \phi_X) \right]^2 \]
\[ \propto \cos\{\omega_b t + (\phi_O - \phi_X)\} + \text{Const.} \]
\[ = \phi_{\text{CM}} \]

Reference signal:  \[ I_{\text{ref}} \propto \cos(\omega_b t) + \text{Const.} \]

Phase difference due to Cotton-Mouton effect can be measured as a phase difference between probe and reference signal.

Free from amplitude variations due to oscillation instabilities of laser and beam deviation.

• Beat signal of 1 MHz

• Simultaneous measurement system of an interferometer and a CM polarimeter with the same plasma center chord in order to check the absolute value of CM phase difference. This is almost same as the system proposed on W7-X.
Measurement Results

After improvement of cross and back talks

Phase difference due to Cotton-Mouton effect can be measured successfully.

The result of the polarimeter is almost consistent with that of the interferometer except initial phase of the discharge. Amplitude of phase variations is within $\pm 0.5$ deg. with time constant of 1.0 ms. Interferometer shows fringe jump errors twice ($t=135,144$ ms).

Cf. $\delta \phi_{CM} = 1$ deg. with $\Delta t = 10$ ms

JET CM Measurement
Development of a new two color FIR laser diagnostics

**cw FIR laser system**

CO\textsubscript{2} Laser
- Cavity length: 3 m
- Discharge length: 1.25 x 2
- Output coupler: ZnSe, 20 m radius curvature
- Grating: 150 g/mm, blazed at 10.6 \textmu m

FIR Laser
- Cavity length: 2.9 m
- Laser tube: 25 mm inner diameter
- Input coupler: gold-coated copper M.
- Output coupler: Silicon hybrid coupler

**The Highest Output Power**

<table>
<thead>
<tr>
<th>cwFIR laser</th>
<th>cwCO\textsubscript{2} laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power [W]</td>
<td>Line 98.8</td>
</tr>
<tr>
<td>Total</td>
<td>24</td>
</tr>
<tr>
<td>57.2-\textmu m</td>
<td>(1.6)</td>
</tr>
<tr>
<td>47.7-\textmu m</td>
<td>(0.8)</td>
</tr>
<tr>
<td>Pressure [Pa]</td>
<td>CO\textsubscript{2}+N\textsubscript{2} (33%/67%) 1.9</td>
</tr>
<tr>
<td>Total</td>
<td>He 7.1</td>
</tr>
<tr>
<td>CH\textsubscript{3}OD</td>
<td>44</td>
</tr>
<tr>
<td>He</td>
<td>Pressure [hPa] 37.2</td>
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<tr>
<td>Laser wall temperature [°C]</td>
<td>6.4</td>
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<tr>
<td></td>
<td>Current [mA] 55</td>
</tr>
<tr>
<td></td>
<td>Water temperature [°C] 22</td>
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</table>
Two color FIR laser Interferometer

- 57.2 μm is optimum value to avoid refractive effects in high density operation of LHD and future fusion devices.
- Both laser beams pass the same optical path in the interferometer without any optical path difference.
- One detector simultaneously detects the beat signals of both laser oscillation lines.

\[ E_1^\perp E_2^\perp \]

\[ V_R \propto \cos(\Delta \omega t) \]

\[ V_P \propto \cos(\Delta \omega t + \phi) \]

\[ \Delta \phi = \frac{\pi}{\lambda n_e} \int_{z_1}^{z_2} n_e(z)dz = 2.82 \times 10^{-15} \int_{z_1}^{z_2} n_e(z)dz \]
Detection of two-color beat signals

Two color beat signals detected by Ge:Ga photoconductor.

Beat frequency;
- 0.6 MHz for 57 µm
- 1.2 MHz for 48 µm

The frequency of the beat signals can be changed with the cavity length and pressure of the FIR laser.
Demonstration of Two color FIR laser Interferometer

One detector simultaneously detects the beat signals of both oscillation lines, and each interference signal can be separated electrically – the 57.2 μm at 0.6 MHz and the 47.6 μm at 1.6 MHz.

Two color FIR laser interferometer work was successful in demonstration of mechanical vibration compensation.

Optical path length was modulated by using a piezo-electric transducer.
A Cotton-Mouton polarimeter has been developed on CHS, combining with an interferometer.

The measurement results of the polarimeter show a good agreement with the interferometer.

A two color FIR laser interferometer is under development for high density plasmas on LHD. Simultaneous operation at 57.2μm and 47.7μm is confirmed.

Two color beat signals are simultaneously detected by using a Ge:Ga photoconductive detector.

Two color FIR laser work was successful in demonstration of mechanical vibration compensation.