Upgrade of Far-Infrared Laser-Based Faraday Rotation Measurement on MST

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Key measurement resolution issues have been identified and improved:

(1) Conservation of circularly polarized wave

(2) Co-linearity of two probe waves

(3) Stability of intermediate frequencies between lasers affecting the Faraday rotation measurement

Improved diagnostic performance for simultaneous polarimetry (Faraday rotation) – interferometry measurements is demonstrated
MST Reversed-Field Pinch (RFP) is toroidal configuration with relatively weak toroidal magnetic field $B_T$ (i.e., $B_T \sim B_p$)

\[ q(r) = \frac{r}{R} \left( \frac{B_T}{B_p} \right) < 1 \]

$R_0 = 1.5 \text{ m, } a = 0.51 \text{ m, } I_p < 600 \text{ kA}$

$B_T \sim 3-4 \text{ kG, } n_e \sim 10^{19} \text{ m}^{-3}, T_{e0} < 2 \text{ keV}$

$\tau_E \sim 10 \text{ ms, } \beta = \langle p \rangle / B^2(a) = 15\%$
Interferometer: density

\[ \phi \sim \int n\, dl + \int \tilde{n}\, dl \]

Faraday rotation: magnetic field

\[ \Psi \sim \int n\vec{B} \cdot \, d\vec{l} + \int n\vec{b} \cdot \, d\vec{l} + \int \tilde{n}\vec{B} \cdot \, d\vec{l} \]

Simultaneously measure both equilibrium and fluctuating quantities

11 chords, separation 8 cm, phase resolution 0.05 degree,

time response up to 1\mu s
New RF-Excited CO\textsubscript{2} laser Installed

RF-excited, sealed CO\textsubscript{2} laser at 9.27 µm (GEM select 100, Coherent Inc.),

DC power supply for RF source

RF source

Water cooling lines

New CO\textsubscript{2} laser has no flowing gas, more stable and easy to operate (turn-key)
Three FIR cavities are pumped by one CO$_2$ Laser

- FIR cavities are UCLA-made and provide reasonable FIR power as long as CO$_2$ is stable.

- DC motors controlling cavity length will be replaced by pico-motors (PZT control) in near future.

- permits pc-based control of laser output.

- plan to add power and frequency feedback stabilization on the 3-cavity output.
FIR beam profiles 155 cm from laser head

Divergence: 13.8 mrad, beam waist: 2 cm.

Beam overlapping is NOT distinguishable on mm scale.
Probe Beams are transported to MST using waveguide.

over-mode dielectric waveguide, 7.5 cm diameter
Circularly polarized beams are launched just before entrance window.

\(\lambda/4\) waveplates are placed after beams pass mesh beamsplitter to avoid distortion of circularly polarized waves.
Circularly-polarized beams can be distorted by wire-mesh beam splitters

Calibration curve

Circularly polarized beam are split into 11 beams by mesh-splitters
(strong nonlinearity)

Linearly polarized beam are split into 11 beams by mesh-splitters
(no polarization distortion)
Measurement Principle: Dodel and Kunz approach

\[
\Phi_L(x) = \Phi(x) + \Psi(x) = c_I \int n_e dl + c_F \int n_e B_{\parallel} dl
\]

\[
\Phi_R(x) = \Phi(x) - \Psi(x) = c_I \int n_e dl - c_F \int n_e B_{\parallel} dl
\]

Launch two, independent (not phase locked), co-linear, frequency-offset (~1 MHz), orthogonal, circularly-polarized (R- and L-) waves into plasma using Dodel and Kunz method

[Infrared Phys. 18,1805(1978)]

\[
\Psi_{\text{Faraday}} = \frac{\Phi_L - \Phi_R}{2} = 2.62 \times 10^{-13} \lambda^2 \int n_e B_z \, dz \quad \Rightarrow \quad \frac{n_R - n_L}{2}
\]

\[
\Phi_{\text{Interferometry}} = \frac{\Phi_L + \Phi_R}{2} = 2.82 \times 10^{-15} \lambda \int n_e \, dz \quad \Rightarrow \quad \frac{n_R + n_L}{2}
\]
Co-linearity of Two Probing Beams

\[ \Phi_L(x + \Delta x) - \Phi_R(x) \approx \Delta \Phi(x) + 2\Psi(x) \]

Finite offset between two beams

Error associated with co-linearity of two beams

Faraday Rotation

\[ \Delta \Phi(x) \sim \Phi(x) \frac{\Delta x}{a} \]

For \( \Delta x = 1 \text{ mm} \), \( \Delta \Phi(x) \sim 2 \text{ degree} \), comparable to Faraday rotation angle!!

Careful alignment is extremely important!!
Frequency changes during plasma discharge

Without discharges

With discharges

Power spectrum three wave system

Faraday rotation

L-wave

R-wave
Phase errors arising from IF instability

Intermediate Frequency [IF] is the frequency difference between the 2 probe beams

\[ f_{IF} = f_L - f_R \approx 1 \text{ MHz} \]

\[
I_{\text{sig}} \sim E_L E_R \cos \left[ 2\pi (f_L - f_R) t + 2\Psi(t) + 2\pi \left( \frac{f_L - f_R}{c} \right) L_1 + \phi_{L0} - \phi_{R0} \right]
\]

\[
I_{\text{ref}} \sim E_L E_R \cos \left[ 2\pi (f_L - f_R) t + 2\pi \left( \frac{f_L - f_R}{c} \right) L_2 + \phi_{L0} - \phi_{R0} \right]
\]

\[ \phi(t) = 2\Psi(t) + 2\pi \frac{\Delta f}{c} \Delta L \]

Phase errors due to IF drift is \(~0.01^\circ\) for MST FIR system

\[ \Delta f = 20 \text{ kHz}, \Delta L = 1 \text{ m} \]
## Combined Polarimeter-Interferometer Diagnostic

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Interferometer and polarimeter provide critical constraints to equilibrium reconstruction.
Density Fluctuations in Improved Confinement Plasmas

![Graph showing density fluctuations and other parameters over time.](image-url)
High-frequency, short-wavelength coherent mode observed in Improved confinement plasmas

- $m=1$, $n=20$ mode tends to prefer deeper reversal plasmas.
Faraday rotation and density measurements

Simultaneous measurement for 11 vertical chords
Simultaneous density and magnetic fluctuations measurement

Magnetic and density fluctuations associated with tearing modes

Density fluctuations associated with tearing modes

Magnetic coils at edge
Equilibrium and Fluctuations are simultaneously resolved

Interferometer

Polarimetry

\[ \tilde{\Phi}_{\text{Interferometry}}(x) = \int (n_o + \tilde{n}) \, dl \]

\[ \tilde{\Psi}_{\text{Faraday}}(x) = \int n_o \tilde{B}_o \cdot dl \]

\[ + \int \tilde{n} \tilde{B}_o \cdot dl + \int n_o \tilde{b} \cdot dl \]
Internal structure of magnetic and density fluctuation associated with tearing mode is resolved with FIR System

\[ \Phi_{\text{Interferometry}}(x) = \int \hat{n}dl \]

\[ \Psi_{\text{Faraday}}(x) = \int \hat{n}B_o \cdot dl + \int n_o \vec{b} \cdot dl \]
OUTBOARD HELICAL STRUCTURE

2D density inversion code

1100915018

2D density inversion consistent with helical equilibrium

\[ \chi^2 = 155.40 \]
Evidence for Non-Axisymmetric Equilibrium in MST

**HELICAL Structure LFS**

Faraday rotation @ 24ms

- Faraday Rot. [deg.]
- R - R_o [cm]

![Graph showing Faraday rotation](image)

- Experimental density
- ZFP vs time
- Dominant mode phase
- Dominant mode amplitude

**UCLA**
Identification of 3D Effects in MST Equilibrium

**HELICAL Structure HFS**
Faraday rotation @ 26ms

- **Faraday Rot. [deg.]**
- **R-R₀ [cm]**
- **Inverted density**
- **ZFP vs time**
- **Impact parameter [m]**
- **dominant mode amplitude**
- **dominant mode phase**

**Graphs:**
- Plot of Faraday rotation vs R-R₀.
- Inboard (exp) and inboard (recon).
- Experimental vs simulation.
- Dominant mode amplitude over time.
- Dominant mode phase over time.
Identification of 3D Effects in MST Equilibrium

Measured axis shift

Expected axis shift from reconstruction

Faraday Rot. [deg.]
R-R_o [cm]
Evidence for Non-Axisymmetric Equilibrium in MST

Measured axis shift

- Faraday Rot. [deg.]
- R-R₀ [cm]

Expected axis shift from reconstruction

Experimental density

inboard

outboard
Summary

Three fundamental technique issues for a successful implementation of Faraday rotation measurements in plasmas have been resolved in a upgraded FIR system on MST.

1. Distortion of circularly polarized wave;
2. Co-linearity of two probing beams;
3. Instability of intermediate frequency.

New physics studies are being initiated with improved diagnostic. Application also underway for C-Mod tokamak and planned for ITER.