FIR Polarimetry on the Alcator C-Mod Tokamak

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for the Alcator C-Mod Group
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Outline

• Motivation
• History
• Specifications
• Alcator C-Mod
  – Machine parameters
  – Current drive system
– Theory and Detection Technique
  – Faraday rotation
  – Cotton-Mouton Effect
  – Detection technique
– Three chord layout
– Diagnostic Components
– Sources of Error
– Some results
– Plans
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I will be describing the C-Mod Polarimeter only, and not any of the other excellent systems at work on other machines around the world.
Motivation

• Advanced Scenarios for tokamak operation depend on our ability to control plasma current density profiles, which then requires that we measure them in detail

• On Alcator C-Mod this requirement is being met using a combination of magnetics, MSE and polarimetry
  • MSE diagnostic provides localized multi-point measurement of the field line angle
  • Polarimetry provides line integrated measurements of Faraday rotation
  • MSE and Polarimeter results have been used separately as constraints to EFIT reconstructions (still being developed)

• Current profile control on C-Mod relies on the use of lower hybrid waves to drive current
History

• FIR Lasers procured in 2008
• First physics results during FY2011 and FY2012 campaigns
  • Attempted termination of C-Mod Program in March of 2012 (why??)
    • Highest magnetic field in any diverted tokamak
    • Highest volume averaged pressure in any tokamak
    • Highest parallel divertor heat flux (reactor relevant)
    • ITER divertor design modeled after C-Mod divertor
    • Discovered two naturally elm-less high energy confinement modes (EDA H-mode, I-mode)
    • Equilibrated electron and ions (high density, reactor relevant)
    • All rf driven heating (ICRF) and current drive (Lower Hybrid) (as probable for a reactor)
    • Very low cost of operation
• No C-Mod research operation in 2013
• Research operations began again in 2014, but with limits on diagnostic and machine upgrades  ---
  no advanced outer divertor for example
• FIR lasers move from experimental cell to lab adjacent to the cell in late 2014
• 2016: Polarimeter back in operation
Specifications

• We would like to make useful polarimetry measurements over a wide range of C-Mod parameters
  • Densities from 0.5 to 2.0 $\times 10^{20}$ /m$^3$
  • Plasma currents from 400 to 2000 kA
• A laser wavelength of 117.73 $\mu$m (2.539 THz) was chosen
  • Large Faraday rotation (5 to 50 degrees)
  • Small plasma refraction (< 1 mm at retro-reflector)
  • Availability of detectors
  • Availability of commercial lasers
• Bandwidth should be in the MHz range (fluctuations)
• Detection phase noise level should be < 0.1°
  • Changes in current profiles cause changes in rotation of several degrees
  • Not there yet but close (~ 0.1°)
Alcator C-Mod Tokamak

C-Mod was commissioned to continue the study of the high field approach to fusion

- Fusion gain and power density scale dramatically with field
- Compact high field designs

Investigation of
- Transport/confinement
- Boundary and surface physics
- ICRF heating
- RF Current Drive (LH)
- Disruption research
- Advanced Divertor (500 MW/m²)

Design Parameters
- TF field 9 T (8.19)
- Plasma current 3 MA (2.16)
- Major/Minor radius of 0.67/0.21 m
LHCD on Alcator C-Mod

- Launcher waveguide phasing and radial position adjusted to couple LH waves to plasma
- 12 klystrons feed the launcher: 3 MW source power (4.6 GHz)
Important Polarimetric Effects

- The two most significant polarization effects we expect on C-Mod are the result of Faraday rotation and the Cotton-Mouton Effect.
- Faraday rotation is a rotation of the polarization vector of the beam as it propagates along the magnetic field.
- The Cotton-Mouton effect converts a linearly polarized beam into an elliptical one as it propagates perpendicular to a magnetic field.
- On C-Mod we have magnetic field components both along and perpendicular to the beam path, so both effects are present.
- For C-Mod the most important effect is the Faraday rotation since it is a measure of the poloidal field and therefore the plasma current profile.
Faraday Rotation

• Consider a linearly polarized beam passing through a magnetized plasma along the direction of the field.

• The beam can be resolved into R- and L-circularly polarized components which see a different index of refraction in the plasma resulting in a rotation of the polarization vector given by

\[ \alpha_f = C_f \lambda^2 \int n_e B \cdot d\ell \]

• Where \( C_f = 2.62 \times 10^{-13} \text{ Rad/T} \), \( n_e \) is the plasma density, \( B \) is the magnetic field, and \( \lambda \) is the laser wavelength (SI units). The integral is taken along the beam path through the plasma.

• We have rotations of up to 50 degrees in C-Mod (117.73 \( \mu \text{m} \)).
Faraday Rotation

Linearly Polarized EM wave can be resolved into R- and L-circularly polarized components

\[
\alpha_f = \frac{1}{2} \int (k_+ - k_-) \, dl = \frac{1}{2} \int (N_+ - N_-) \frac{\omega}{c} \, dl \approx \frac{e^3}{8\pi^2 c^3 m^2 \varepsilon_0} \lambda^2 \int n_e B_{||} \, dl
\]

\[
\alpha_f = 2.62 \times 10^{-13} \lambda^2 \int n_e B_z \, dz
\]
Cotton-Mouton Effect

• Consider a linearly polarized beam passing through a magnetized plasma perpendicular to the field

• This beam can be resolved into E- and O-mode beams which experience different phase-shifts as they propagate through the plasma, resulting in a phase difference given by

\[ \phi_{cm} = C_{cm} \lambda^3 \int n_e B_{\perp}^2 \, dl \]

• \( C_{cm} = 2.46 \times 10^{-11} \) Rad/T^2/m

• Maximum phase difference occurs with the polarization vector oriented 45° to the magnetic field

• The differential phase-shift converts the polarization from linear to elliptical

• We have measured differential phase-shifts of up to 6 degrees in C-Mod

• Since we know \( B_{\perp} \) well in our geometry (the toroidal field), the Cotton-Mouton Effect has promise as a density measurement
Cotton-Mouton Effect

- **CM effect** \((\mathbf{B}_\perp)\): measure the phase difference between o-mode and x-mode eigenstates (ellipticalization of the laser beam)
- If you know \(B_\perp\), you can extract \(n_e\)

\[
\phi_{cm} = C_{cm} \lambda^3 \int n_e B_\perp^2 \, dl
\]
Faraday Rotation Detection Technique

- Two FIR lasers operate with a 2 MHz frequency difference
- Beam from upper laser passes through $\frac{1}{2} \lambda$ wp producing vertically polarized beam
- Polarizer combines beams
  - Two orthogonal coaxial beams
  - Approximately equal intensities
- Beams pass through $\frac{1}{4} \lambda$ wp and become two counter-rotating circularly polarized beams
  - Resultant beam is linearly polarized rotating at $\frac{1}{2} f_r$, the reference freq
  - Reference and probe signals are at 4 MHz

Faraday Rotation Detection Technique

Detection Technique Insensitive to Cotton-Mouton effect and to signal amplitude variations
Polarimeter Chords in C-Mod

- Six retro-reflectors are mounted on the C-Mod inner wall
- A z-cut quartz window, A/R coated on the air side is used to transmit FIR beams into the vessel
- Chords most often used are in red
- A pneumatically actuated shutter protects retro-reflectors when they are not needed
2012 C-Mod Polarimeter Configuration

- Air-tight enclosures shown
- Panels easily removable for alignment
- Lower table holds lasers, collimation optics, and reference detector
- Upper table holds
  - $\frac{1}{4} \lambda$ waveplates
  - Reference mixer
  - Probe mixers
  - TPX focusing lenses
- 1.2 cm thick magnetic shield encloses the lasers (400 G to 20 G)
- 20db acoustic blankets cover both enclosures
Three Chord Upper Table Layout

- FIR beams enter at the top of the layout diagram
- Two beam-splitters and a mirror direct three beams though ¼ wave-plates and TPX lenses
- Turning mirrors near bottom of diagram direct beams to inner wall retro-reflectors
- Beam-splitters pick off returning beams and direct them to Off-axis parabolas (OPA) and mixers
2016 C-Mod Polarimeter Configuration

- Lasers moved to a diagnostic lab
- Magnetic shielding no longer required
- Acoustic effects on lasers reduced
- Beamline, upper table in cell, and laser table, purged with dry air (Relative humidity < 5%)
  - Critical to operation with longer beam propagation lengths
  - Makes alignment more difficult
Components: Lasers

- Two commercially produced CO$_2$ pumped FIR lasers are used
- FIR power of 100 to 140 mW each
- 117.73 $\mu$m (difluoromethane: CH$_2$F$_2$)
- Tuneable approx $\pm$7 MHz around line center
- PZT controls cavity length
  - 100 Hz bandwidth allows fast frequency lock between lasers
  - But 230 Hz resonance in the mounts can be a source of phase error
Components: Laser Frequency Control

- Signal from reference mixer goes through 3 db splitter
- One leg is delayed relative to the other
- Pick delay such that mixer output is proportional to deviation from desired reference frequency (4 MHz)
- Integrator signal drives PZT to set 1st laser frequency
- Vendor electronics maintains 2nd laser at center-line
Components: Mixers

- Developed for C-Mod
- Planar Schottky diode technology
- No fragile whisker contacts
- Spurious reflections less than CCR detectors
- Pyramidal horn couples power to a WR-0.4 waveguide
- 100-200 V/W
- Elliptical polarization response
- Beam waist 0.27 mm
Components: Vacuum Window

- 3.5 mm thick, 10 cm diameter, z-cut quartz
- AR coated on air side with 0.02 mm LDPE
- Polarimeter beams are incident on window over a ±20° range
- Coating greatly reduces transmission sensitivity to angle of incidence

![Graph showing transmission vs incident angle with and without coating]
Components: Mesh Beam-splitters

- A wide range of beam-splitter mesh densities were tested with both horizontally (H) and vertically (V) polarized light.
- The mesh was then rotated in its mount sweeping out the curves shown.
- A 400 lines/inch (15.75 l/mm) mesh was chosen because of its smooth angular response and ~40/60 split of power.
Components: Polarizers, Wave-plates, and Lenses

- The polarizers are free-standing 10 mm diameter tungsten wires spaced 25 mm apart
  - Very efficient, very little loss
  - Good extinction ratio (> 100)
- The wave-plates are AR coated quartz plates
  - $\frac{1}{4} \lambda$ wp transmission 90%
  - $\frac{1}{2} \lambda$ wp transmission 85%
- The lenses are plano-convex TPX components machined to our specifications by a local vendor
  - Focal length of 3 m
  - Uncoated transmission ~ 85%
Components: Shutter and Retro-Reflectors

- Commercially available retro-reflectors
  - Gold coated glass substrate
  - 13 mm aperture
- Shutter assembly protects optics during boronizations
  - Pneumatically activated with push-pull bellows
  - Helium gas/Vacuum
- $Z = 4$ to 39 cm along inner C-Mod wall
Components: Retro-Reflectors

- Retros performed well during 2011 and 2012 campaigns
- Some erosion/deposition
- Shutter was kept closed during boronizations
- Shutter was kept closed when inner-wall limited discharges were part of the run plan
Sources of error: Longitudinal Vibrations

• Changes in the pathlength of the beams traversing the plasma will affect the measurements. If both beams experience the same pathlength change, $\Delta L$, the Faraday Rotation signal, with a reference frequency, $f_r$, will show a phase angle error of

$$\Delta \varphi = 2\pi \Delta L \frac{f_r}{c}$$

• On C-Mod $\Delta L$ must be less than 1 cm for this error to be less than 0.1°, with $f_r$ at 4 MHz

• Interferometric measurements indicate movement at the 100 $\mu$m level, so we do not expect longitudinal vibrations to be an issue on C-Mod.
Sources of error: Transverse Vibrations

• If the path travelled by the beam from one laser is not exactly the same as the path of the other beam, phase errors can occur for very small path length differences (fraction of laser wavelength).

• We expect such errors in cases where one laser experiences vibrations not seen by the other laser, resulting in angular deviations in just one beam path. A rough estimate of this effect is

\[ \Delta \varphi = 2\pi[1 - \cos(\theta)] \frac{L}{\lambda} \]

• Where \( L \) is the distance between the lasers and the detector, \( \lambda \) is the laser wavelength, and \( \theta \) is the angular deviation of the beam.

• Angular deviations at the \( \mu \text{Rad} \) level can result in phase errors at the \( 0.1^\circ \) level.
Sources of error: Laser Lock

- If the frequency separation, $f_r$, between the two lasers changes, a phase error in the rotation measurement can be estimated as

$$\Delta \varphi = 2\pi L \frac{\Delta f_r}{c}$$

- Where $L$ is the separation (both optical and in cabling) between the reference and probe detectors

- Addition of cable delays (in our case to the ref detector leg) can eliminate this issue
Sources of error: Spurious Reflections

• Spurious reflections into the detectors and back to the lasers will cause phase errors in the rotation measurements

• Spurious power levels at 1% of the signal level can result in unacceptable phase error

• Absorbers are used throughout the beam path to minimize reflections (at beam-splitter locations for example)

• The optical design and alignment has been optimized to minimize these effects

• The planar diode mixers contribute much less to this problem than corner cube detectors used previously
First Results (2011)

- Operation with forward and reversed fields provides zero-order check of diagnostic
- Measurements agree with simulated signal from EFIT ($B_{pol}$) and Thomson Scattering ($n_e$) profiles
- Effect of 800 kW lower hybrid pulse clearly seen
TF effect

- Given the same density and plasma current, we measure the same Faraday rotation independent of Toroidal field.
- Traces at 5.4 and 7.5 T are shown.
- Neither Cotton-Muton effect nor misalignment relative to the toroidal field are affecting the Faraday rotation measurement.
Synthetic Polarimeter from EFIT (no LHCD)

• \( \alpha_{syn} = c_f \lambda^2 \int n_e B_{||} dl \)
  - \( n_e \): Thomson Scattering (TS)
  - \( B_{||} \): normal EFIT (no internal constraints, \( q_0 \sim 0.95 \))

• **Synthetic signals** agree with measurements throughout the discharge for all three chords.
Synthetic Polarimeter from EFIT (with LHCD)

- Measurements and synthetic signals
  - A large discrepancy (~40%) between the measurement and synthetic signal for FR#1 during LHCD
  - Discrepancy disappears in ~200 ms (a current relaxation time), when LH turns off
- Internal magnetic field from EFIT is inaccurate during LHCD
Density Scan: driven current dramatically decreases at high density

- Faraday rotation change during LH for chord#1 decreases with density: lower current drive efficiency with increased density (implied earlier from HXR array)

- LH wave interaction with edge plasma is believed to become important at high density and waves do not penetrate into core

- High field side launch of LH waves is being considered as a solution to this issue
Fluctuation measurements by polarimetry

\[ \alpha = c_f \lambda^2 \int n_e B \cdot dl \]

\[ \alpha = \alpha_0 + \delta \alpha, \; n = n_0 + \delta n, \; B = B_0 + \delta B \]

\[ \delta \alpha = c_f \lambda^2 (\int \delta n B_0 \cdot dl + \int n_0 \delta B \cdot dl + \int \delta n \delta B \cdot dl) \]

- **Integral measurement** with both density and magnetic fluctuations mixed together
- Complement other density fluctuation diagnostics: PCI, fast TCI, reflectometer
- Only diagnostic for core magnetic fluctuations (external magnetic coils for edge magnetic fluctuations)
- Chord along midplane would be sensitive mostly to magnetic fluctuations
Broadband fluctuations during EDA H-modes

- Quasi-coherent mode (QCM) observed on all three chords during EDA H-mode, consistent with PCI and reflectometer measurements.
- Chord#1, #2 observe broadband fluctuations but not chord#3 → core fluctuations.
- PCI and reflectometer do not see the broadband fluctuations.
- Core magnetic fluctuations???

ICRF Power drives plasma into EDA at 0.6 s.
LH power alters fluctuation levels

- QCM frequency chirps down and is more coherent during LH
- broadband fluctuations are suppressed by LH
- These effects observed at densities much too high for current drive
First 2016 Data

• Good results during FY2016 plasma startup runs
• Improved baselines
• Resolution approaching 0.1° (BW ~ 1 kHz)
• However, signal noise levels are higher than in 2012, resulting in reduced sensitivity to fluctuations (we are currently investigating the cause of this issue)
Summary

• A polarimeter has been developed and implemented on Alcator C-Mod
  • Development of new detectors
  • Development of frequency locking system for the lasers
  • Techniques developed to suppress mechanical/acoustic/magnetic effects on lasers and optical components
• It has been used to study lower hybrid current drive
• It has been used to study fluctuations during H-mode discharges and seen suppression of broadband fluctuations during lower hybrid experiments
Plans

• C-Mod Operation will continue until 9/30/2016

• Until then
  • Lower hybrid current drive experiments will resume soon
    • Polarimetry
    • MSE
    • Develop current profiles using polarimeter and MSE data as constraints
  • We hope to get more data showing suppression of fluctuations during high density operation with LH
  • Verify (or not) the magnetic nature of the core fluctuations (shift plasma vertical position)