Imaging spectro-polarimetry of plasmas

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ITC18 December 2008
Outline

- Coherence imaging systems
  - Principles and methods
  - Doppler spectroscopy (CXRS)
  - Spatial heterodyne coherence imaging systems
- Polarization spectroscopy
  - Imaging Motional Stark Effect Polarimetry (MSE)
    - Measurements on magnetized lamp
    - First imaging results on TEXTOR tokamak
  - Zeeman assisted Doppler imaging (Divertor)
What is coherence imaging?

- When spectral information content is small (M unknowns), it suffices to image the optical coherence (interferogram) of the light emission at a small number (N>M) of optical delays.

- CI systems are static and/or modulated single or multiple-delay imaging polarization interferometers which employ various multiplex techniques to capture N>M images sufficient for high-resolution 2D and 3D plasma spectroscopy.

Why measure optical coherence?
- Interferometers have throughput advantage (for R>100)
- Robust alignment, birefringent optics
- time/space multiplex methods – 2D imaging
- Can be deployed for fluctuation studies (Doppler, MSE)
Coherence imaging utilizes polarization interferometers

Waveplate (phase delay $\phi$ or time delay $\tau$)

Input light

Image plane

$S = I(1 + \zeta \cos \phi)$

$\zeta(\tau) =$ Fringe contrast $\Rightarrow$ temperature

$\phi =$ Fringe phase $\Rightarrow$ flow

- Produce multiple interferometric images $\Rightarrow$ extract required information
  - Temporally modulate time delay, sinusoidal or step
  - Angular multiplex to produce 4 independent quadrature images
  - Separate the beams to produce spatial fringe pattern
Quadrature Doppler imaging on H-1  
*(Angular multiplex)*

Angle multiplexing through a polarization interferometer produces quadrature images of the interferogram at the 4 corners of a CCD camera.
Savart plate introduces lateral phase shear that generates straight parallel fringes
Possible to generate spatial modulation in multiple directions
Demodulate for brightness, contrast, phase ➔ plasma properties
Injected beam atoms feel induced electric field in frame of the beam $E = \mathbf{v} \times \mathbf{B}$

- Splitting of H$_\alpha$ and Doppler shift
  - $\pi$ and $\sigma$ components are orthogonally polarized. $\sigma$ is parallel to $(\mathbf{v} \times \mathbf{B})$ so orientation gives pitch angle of B

- Apply multiple narrowband filters & measure pitch angle. Typically 10-20 spatial channels

- An interferometric filter allows time resolved imaging of the magnetic field orientation
Polarization and interferometry

Recall simple polarization interferometer:

If input is polarized already, remove the first polarizer

Resulting interferogram fringe contrast depends on polarization orientation:

\[ S = I(1 + \zeta \cos \phi) \]

\[ S = I(1 + \zeta \cos 2\theta \cos \phi) \]
Shearing polarization interferometer

Replace simple waveplate with shearing (Savart) waveplate

\[ S = I \left[ 1 - \zeta \cos2\theta \cos\phi(x) \right] \]
For one of the multiplet components, the interferometer output is:

\[ S_1 = I_1 (1 + \zeta_1 \cos 2\theta \cos \phi_1) \]

For the orthogonal component (\(\theta + \pi/2\), slightly different wavelength), it is

\[ S_2 = I_2 (1 - \zeta_2 \cos 2\theta \cos \phi_2) \]

For MSE triplet, after adding the interferograms, the nett signal contrast depends on the component contrast difference \(\zeta_1 - \zeta_2\).

Choose optical delay \(\tau\) (plate thickness - equivalent to spectrometer dispersion) to maximize the contrast difference \(\zeta_1 - \zeta_2\)

i.e. interferometric filter period matches multiplet component spacing
Model of TEXTOR isolated full energy Stark multiplet and associated nett contrast

Nett contrast decreases as the splitting decreases
But good contrast across full field of view (edge to center)
**Static double heterodyne polarimeter**

Impose orthogonal carriers in x (coherence $\phi$) and y (polarimetric $\theta$) directions.

Compact optics attached as filter to coherent imaging fibre cable.
Imaging measurements of polarization angle based on Zeeman effect in a magnetized Zn lamp

\[ S = 1 + \zeta (1 + \sin\phi_y) \cos(\phi_x + 2\theta) + \zeta (1 - \sin\phi_y)\cos(\phi_x - 2\theta) \]

Step vary the polarization angle \( \theta \) (i.e. magnetic field tilt angle)

Demodulate pattern \( \Rightarrow \theta \)
Demodulated polarization angle image

Image and demodulated magnetic field angle (nominally 25+/-2 degrees)
Distortions of polarization angle due to glass envelope

Nett contrast ~0.25
Spectrally isolate the central $\sigma$ component
Measure its polarization orientation $\rightarrow$ B orientation. Know Btor, extract Bpol $\rightarrow$ of order 20 discrete channels is typical.
$\rightarrow$ Requires arrays of very narrowband, temperature-tuned interference filters
$\rightarrow$ Many challenges: efficiency, maintenance etc
Coherence imaging polarimetry

Features:

- Spatial encoding (no modulation, single snapshot)
- Analyze polarization of full multiplet: wideband filter, tolerant of contamination and background

Applications:

- Tokamak internal current imaging (sawteeth, MHD, ECCD, shaped plasmas etc)
- Zeeman-tagged divertor Doppler imaging
- Solar spectroscopy, etc
Calibration setup for polarimeter head

Polarimeter head inserted into re-entrant port. Views plasma via turning prism.
Optical cable coupling to camera

CCD camera: Sensicam 12 bit, cooled 1376x1040 8.9mm x 6.7mm

Tiltable interference filter: 662nm, 2.5nm FWHM admits full multiplet spectrum

Imaging optical fibre cable from polarimeter head

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**View through port and prism**

Field of view limited by prism

Approx tangent to magnetic axis

20 degree camera field of view

NBI 50 keV
Double spatial heterodyne snapshot image

2-d raw fringe pattern encodes polarization orientation

Input H beam 50kV, 1MW

Fibre imperfections

Field of view

Optical component distortion ➔ limited usefulness in TEXTOR campaign
Use alternative hybrid spatio-temporal multiplex imaging system …
**Hybrid system Spatial-temporal multiplex**

- Can encode polarization information in time domain
  - Replace first Savart prism with quarter wave plate and switching ferro-electric liquid crystal (FLC) half wave plate (synchronized to camera)
  - Subtract phase pattern for successive images

- Advantages
  - Simple sinusoidal fringe pattern
  - Improved spatial resolution

- Disadvantages
  - Require two frames – poorer time resolution
Polarized emission generates interference fringes

Frame 1 Frame 2

Beam on

Polarized Stark multiplet ➔ fringes

Beam off

Unpolarized ➔ no fringes
Hybrid system – data and processing

Normalized interferograms are demodulated and their phases subtracted to obtain polarization image.
Hybrid system specifications and calibration

- **Temporal resolution**
  - Small exposure time ~1-4 ms (Simple system, wide filter)

- **Spatial resolution**
  - Radial ~3mm (set by fibre cable and image binning)
  - Vertical ~15-20mm (set by fringe period)

- **Polarization angle resolution**
  - rms ~0.5 degrees along each image line (can be improved with spatial averaging)
Line of sight integration effects are important

Left: Calculated polarization angle images of vertical planes through the beam at the 3 locations shown.

Above: Measurement (same color scale -10° → 15°)

⇒ MSE good for edge regions only
Advantages over traditional approach

- Analyse full multiplet so no need for narrowband filters
  - No filter tuning issues or incidence angle sensitivities
  - Higher light throughput (~x5 – x10)
  - **2D imaging!** (sawteeth, MHD, ELMs, ECCD, shaped plasmas, E_r)

- Insensitive to unpolarized (or wideband polarized) background contamination

- Fringe phase shift gives $4\theta$ where $\theta$ is the polarization tilt angle.

- Can be applied to spectrally complex elliptically polarized multiplets (Zeeman effect)

- Static, hybrid and temporal heterodyne options, single channel or imaging

- Simple robust optics, inexpensive
Conclusion and next steps

- Polarization interferometers have some advantages for spectro-polarimetric imaging:
  - High throughput, simple passive optics, easy alignment, inexpensive
  - In Doppler case, there is a "natural" linkage to tomographic projections
  - Zeeman Stokes vector imaging can yield line-of-sight resolved information for divertor Doppler tomography

- Future MSE imaging on TEXTOR:
  - Crosschecks: beam into gas, reverse field direction etc.
  - High speed MSE imaging (CMOS camera) for MHD, ECCD etc.
  - Attempt to model/unfold path integration effects
  - Measurement of Hβ multiplet polarization ("I-mixing").

- Zeeman weighted flow and temperature imaging on DIII-D (2009)
8th Japan – Australia Plasma Diagnostics Workshop

8th Japan-Australia
Plasma Diagnostics Workshop
2-5 February 2009, Australia

Murraramarang Resort

The Murraramarang Resort has been selected for the conference venue because of the tranquil, ocean setting offered to guests.

During the conference all delegates will be provided with breakfast, morning tea, lunch, afternoon tea and dinner. Please advise of any special dietary requirements when completing your registration form.

**MSE imaging: comments and observations**

- Results obtained on TEXTOR tokamak. Both double spatial heterodyne and hybrid systems
  - Fast imaging ➔ best use double heterodyne snapshot system

- Line-of-sight integration must be handled carefully: Good polarization angle resolution is unimportant if measurement is effectively non-local.

- Imaging a narrow fan or multiple diagnostic beams in a poloidal cross-section can give detailed information on MHD and equilibrium.

- New system is well suited for imaging Hβ.
  - Close to statistical distribution among n=4 upper levels (“l-mixing”) ➔ no polarization distortion
Spatial Heterodyne Polarization Spectroscopy
Motional Stark and Zeeman Effect

- **MSE**: H or D atoms in a heating beam experience an induced electric field $\mathbf{E} = \mathbf{v} \times \mathbf{B}$ that generates a complex spectrum. Viewed transverse to $\mathbf{E}$ the Stark split $\sigma$ and $\pi$ components are polarized perpendicular and parallel to $\mathbf{E}$ respectively.

- **Usual approach**: Isolate polarized component using narrow-band filter (e.g. Fabry-Perot or temperature-tuned filter for each spatial channel)
  - Multiple single channel measurements

- **Interferometry**: An interferometric filter allows time resolved *imaging* of the magnetic field orientation using a 2-D detector array.
MSE coherence imaging polarimetry on TEXTOR

- 2.25T on axis
- 350 kA
- H or D beams, 50keV/amu
- 3% energy noise
- 1.2 degrees divergence

Spectrum is red-shifted

Polarization tilt angle captures the poloidal field
Optical design ensures filter passband tracks Doppler shift of full energy multiplet

Measured pre-filter response
Nett contrast decreases as broadening increases

Variation of fringe contrast with ratio Doppler width/Stark splitting
2-d interference pattern carries coherence and polarization

\[ S = 1 + \zeta (1 + \sin\phi_y) \cos(\phi_x + 2\theta) + \zeta (1 - \sin\phi_y) \cos(\phi_x - 2\theta) \]

\( \theta \) is the polarization orientation

\( \phi_y \) is carrier phase in y direction
\( \phi_x \) is carrier phase in x direction (spectrum)
\( \zeta \) is effective contrast: high contrast implies good fringe visibility
**Measurements of Zeeman triplet**  
(Zn I 481nm)

Observe transverse effect  
B~0.4T

Use waveplate to rotate the multiplet to simulate MSE effect
Calibration of polarimeter head at TEXTOR

Polarimeter head inserted into re-entrant tube. Views plasma via turning prism.

- Fibre cable
- FLC cable +/-10V
- Hα lamp
- Rotatable polarizer
- Optical head (covered with protecting teflon tape). Includes polarization optics and wide-angle C-mount lens
- Fibre cable support element
1-D (poloidal plane) Doppler imaging on the H-1 heliac
(Sinusoidal electro-optic time delay modulation)

Profiles during power ramp experiments

Brightness
Centrally peaked

Temperature
Hollow profile

Flow speed
Sheared rigid rotation
CCD system for 2-D Doppler imaging
(electro-optic step delay modulation)

The IPP camera:
• LabVIEW/MDSplus
• 12 bit CCD camera,
• max 70Hz frame rate

Ion temperature animation
(WEGA ECH power step, HeII 468nm)

Comparison with high resolution echelle spectrometer (dots)
**H-1 heliac accommodates imaging diagnostic systems**

- **H-1NF:** 3 period helical axis stellarator
  - R=1m, a=0.2m
  - *Flexible* magnetic configuration, rotational transform 1.1-1.5, B 0-1T
  - 7MHz, 80kW rf
  - 28GHz 200kW ECH (2nd harmonic @0.5T)

- **Operations:**
  - Low field 0.1T Ar, helicon type discharges
  - Moderate field 0.5T ECH H/D/He

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