Imaging spectro-polarimetry of plasmas

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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 utilises polarization interferometers

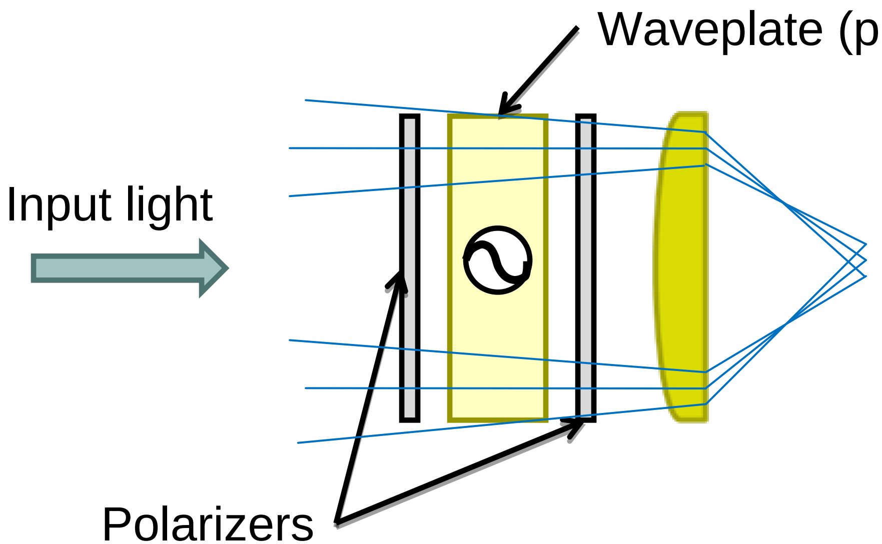


Image plane

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

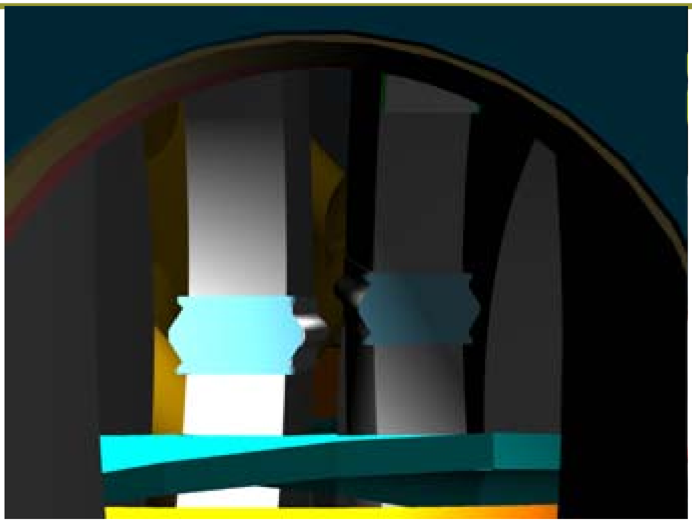
$\zeta(\tau)$ = Fringe contrast ➔ temperature

ϕ= Fringe phase ➔ flow

- Produce multiple interferometric images ➔ 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

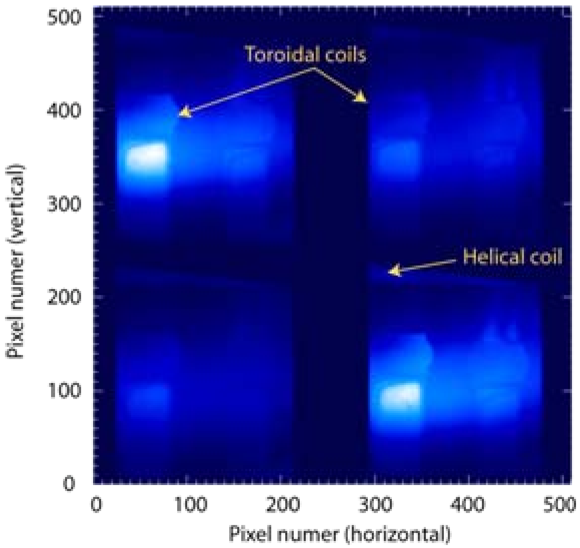
Quadrature Doppler imaging on H-1

(Angular multiplex)

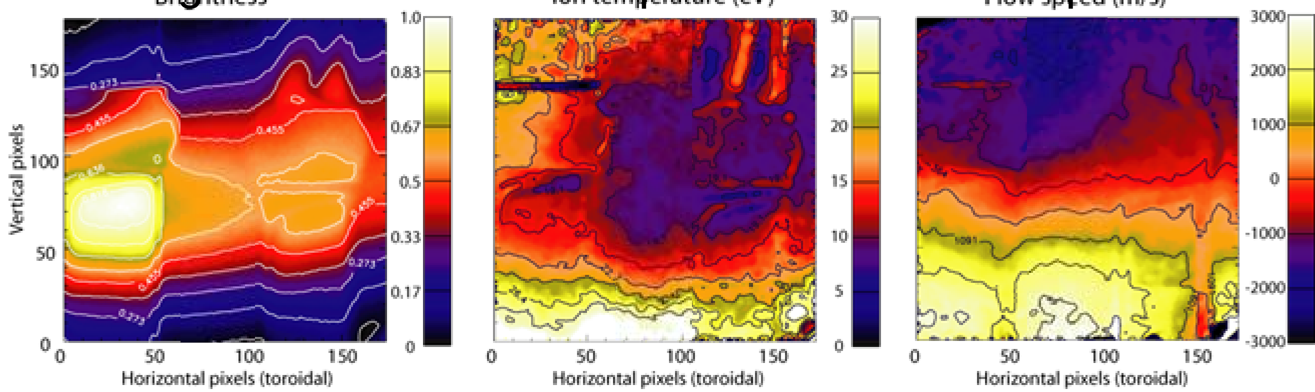


Angle multiplexing through a polarization interferometer produces quadrature images of the interferogram at the 4 corners of a CCD camera

CAD view of coil set and viewport opening

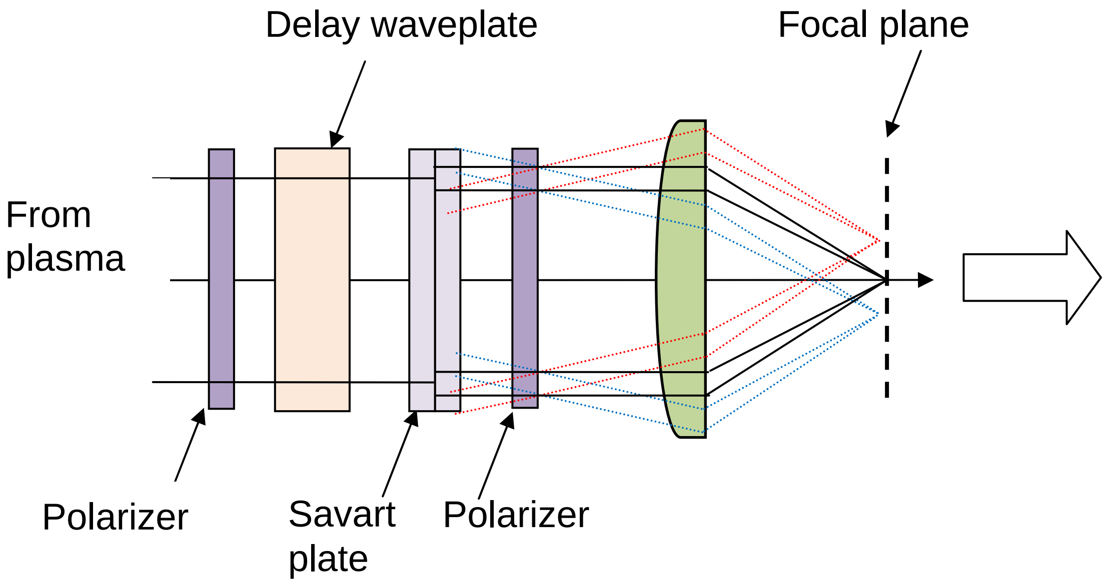


Brightness Ion temperature Flow profile

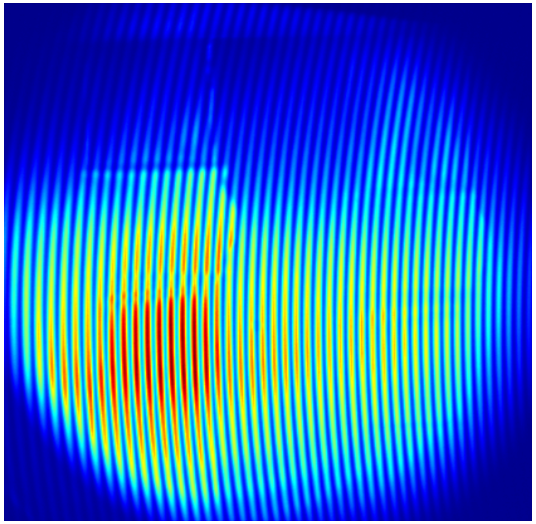


2-D, quadrature Doppler imaging

Spatial Heterodyne Coherence Imaging

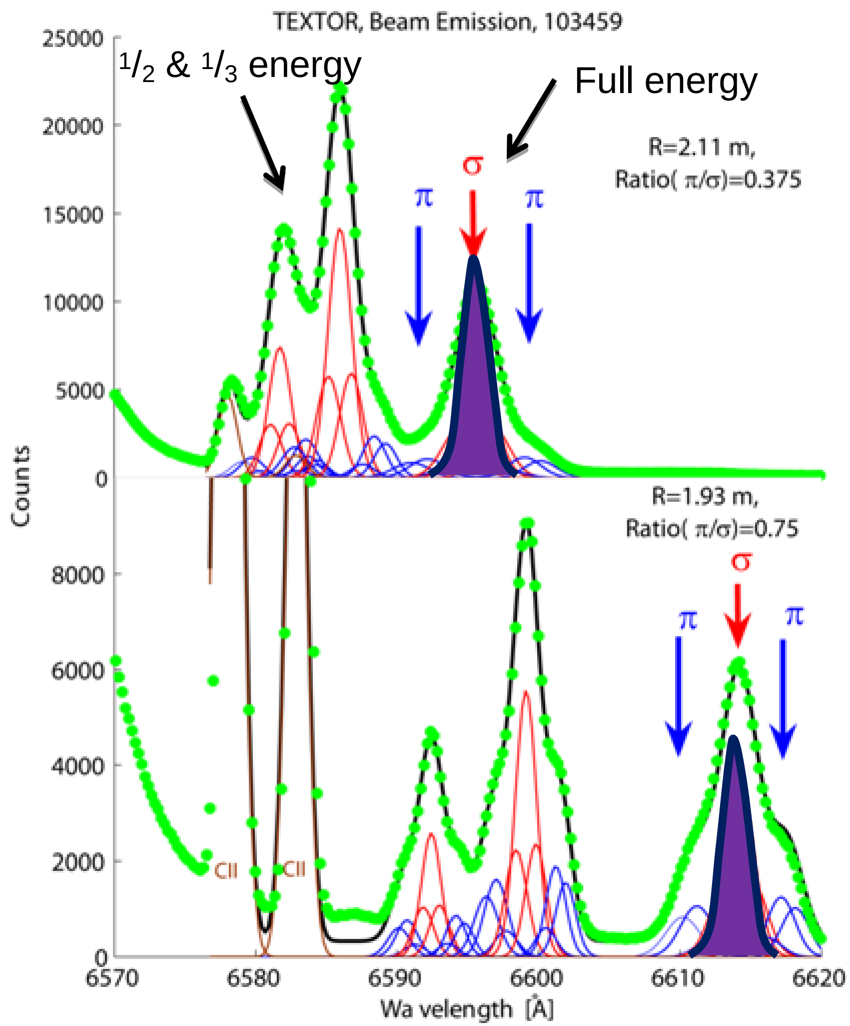


Interferogram is imprinted spatially on the plasma image



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

Introduction to MSE polarimetry



Injected beam atoms feel Induced electric field in frame of the beam ***E*** = ***v*** *x* ***B***

➔Splitting of H_α and Doppler shift

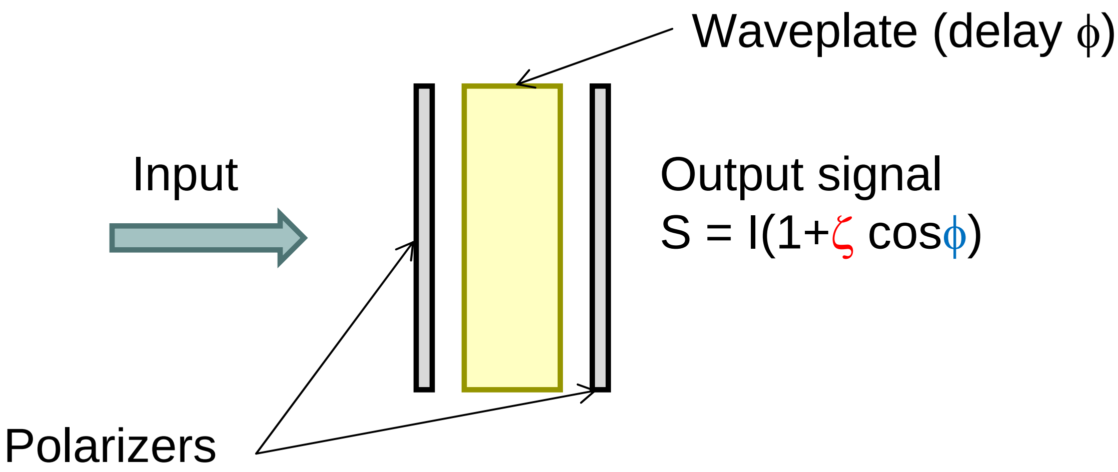
➔ π and σ components are orthogonally polarized. σ is parallel to (***v*** *x* ***B)*** so orientation gives pitch angle of B

➔ 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:



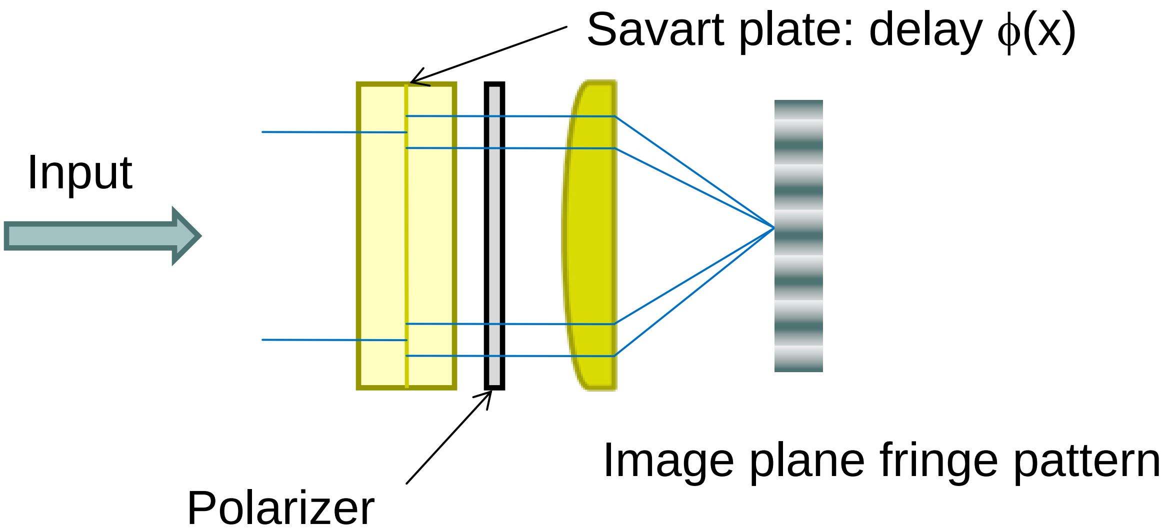
If input is polarized already, remove the first polarizer

Resulting interferogram fringe contrast depends on polarization orientation:

$S = I(1+\zeta \cos 2\theta \cos\phi)$

Shearing polarization interferometer

Replace simple waveplate with shearing (Savart) waveplate



$$S = I\ [1 - \zeta \cos 2\theta \cos\phi(x)\ ]$$

Polarization imaging of closely spaced polarized multiplet (MSE, Zeeman)

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 $\zeta_1 - \zeta_2$.

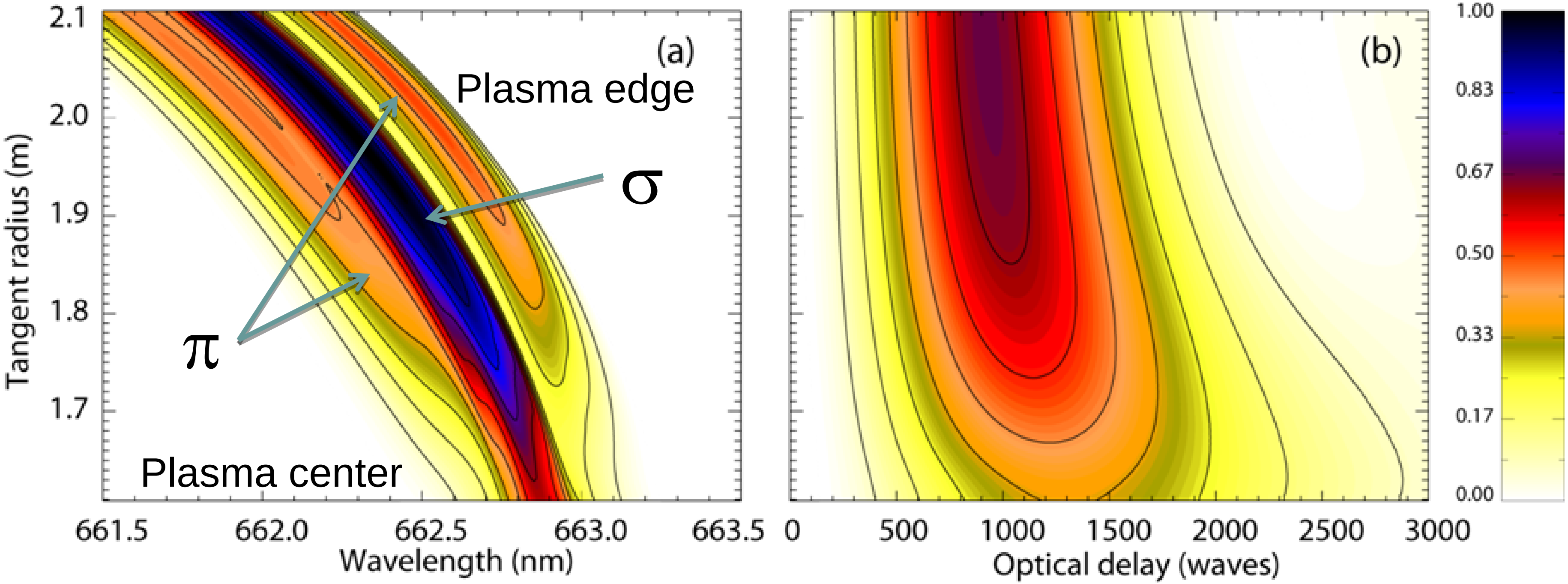
Choose optical delay τ (plate thickness - equivalent to spectrometer dispersion) to maximize the contrast difference $\zeta_1 - \zeta_2$

i.e. interferometric filter period matches multiplet component spacing

Model of TEXTOR isolated full energy Stark multiplet and associated nett contrast

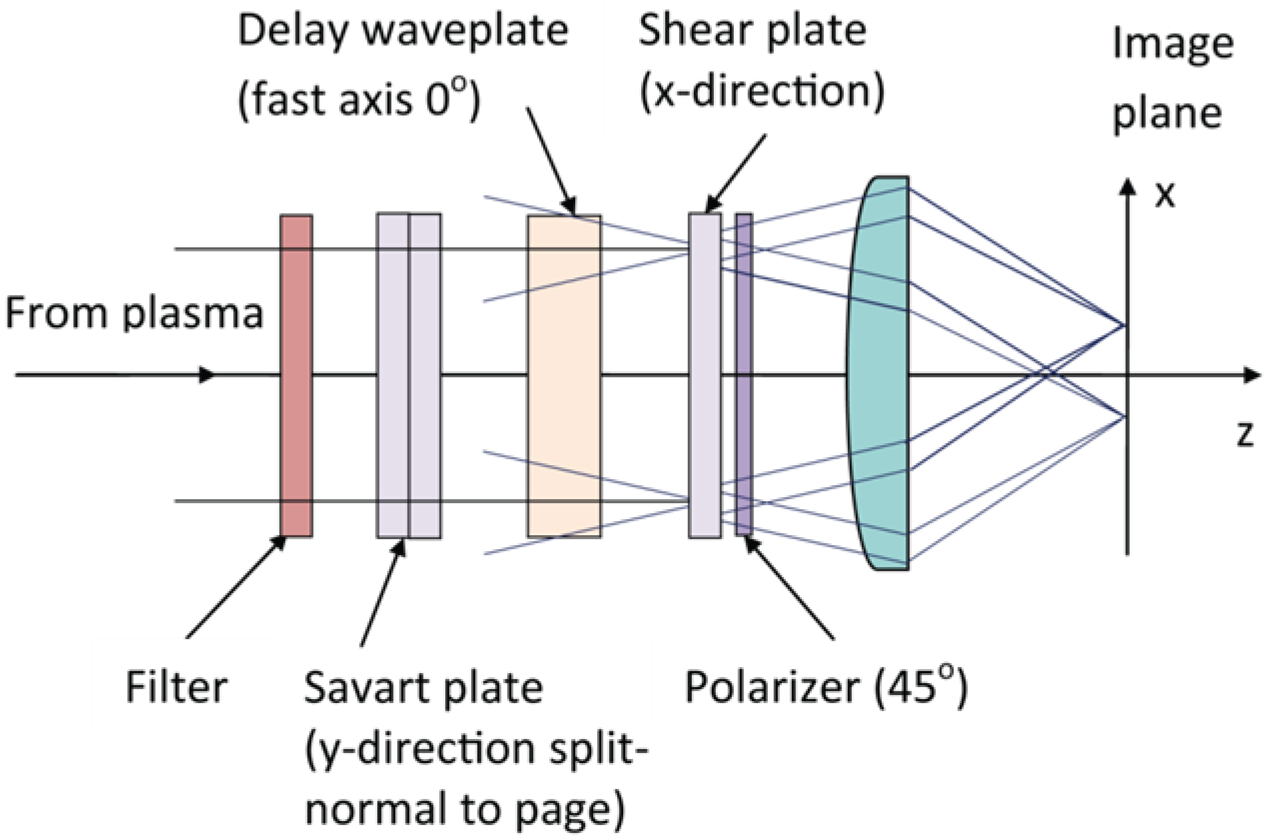
Full energy MSE spectrum

Fringe contrast versus delay



Nett contrast decreases as the splitting decreases
But good contrast across full field of view (edge to center)

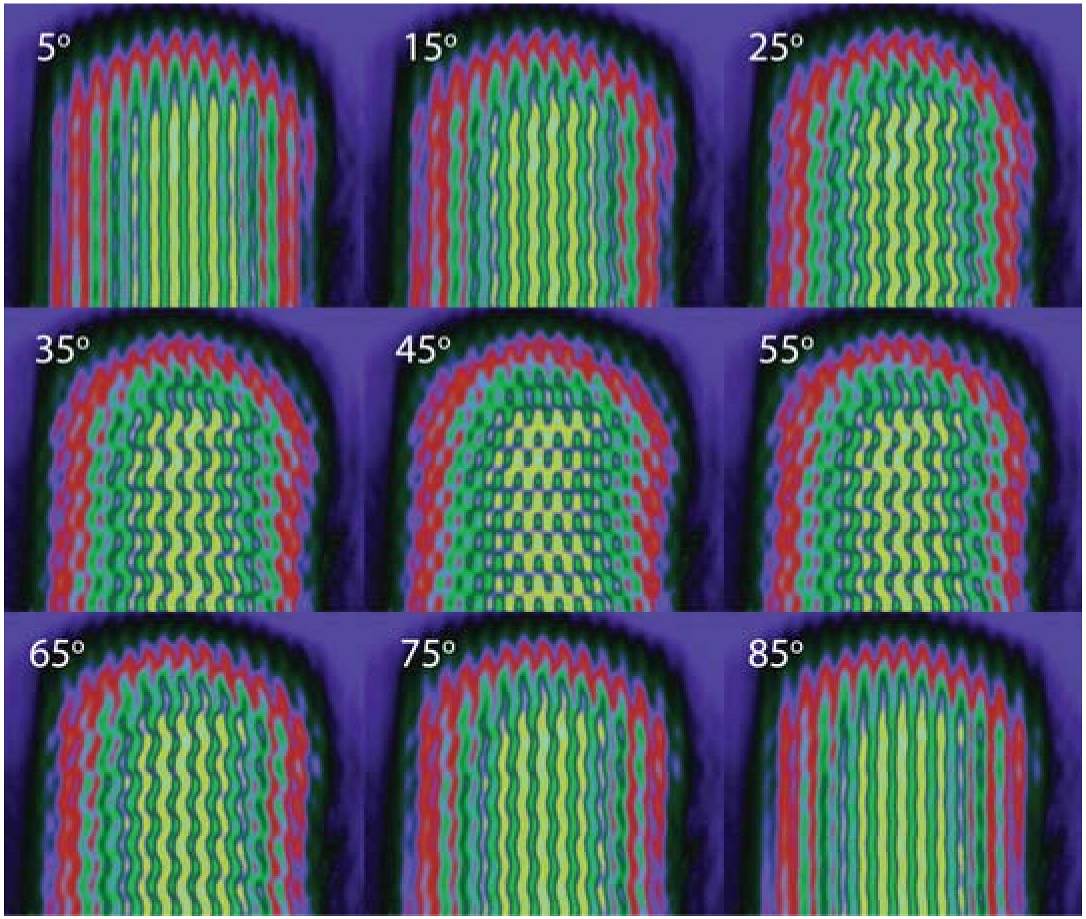
Static double heterodyne polarimeter

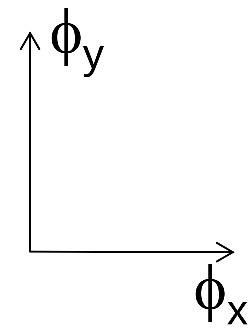


Compact optics attached as filter to coherent imaging fibre cable

Impose orthogonal carriers in x (coherence ϕ) and y (polarimetric θ) directions

Imaging measurements of polarization angle based on Zeeman effect in a magnetized Zn lamp



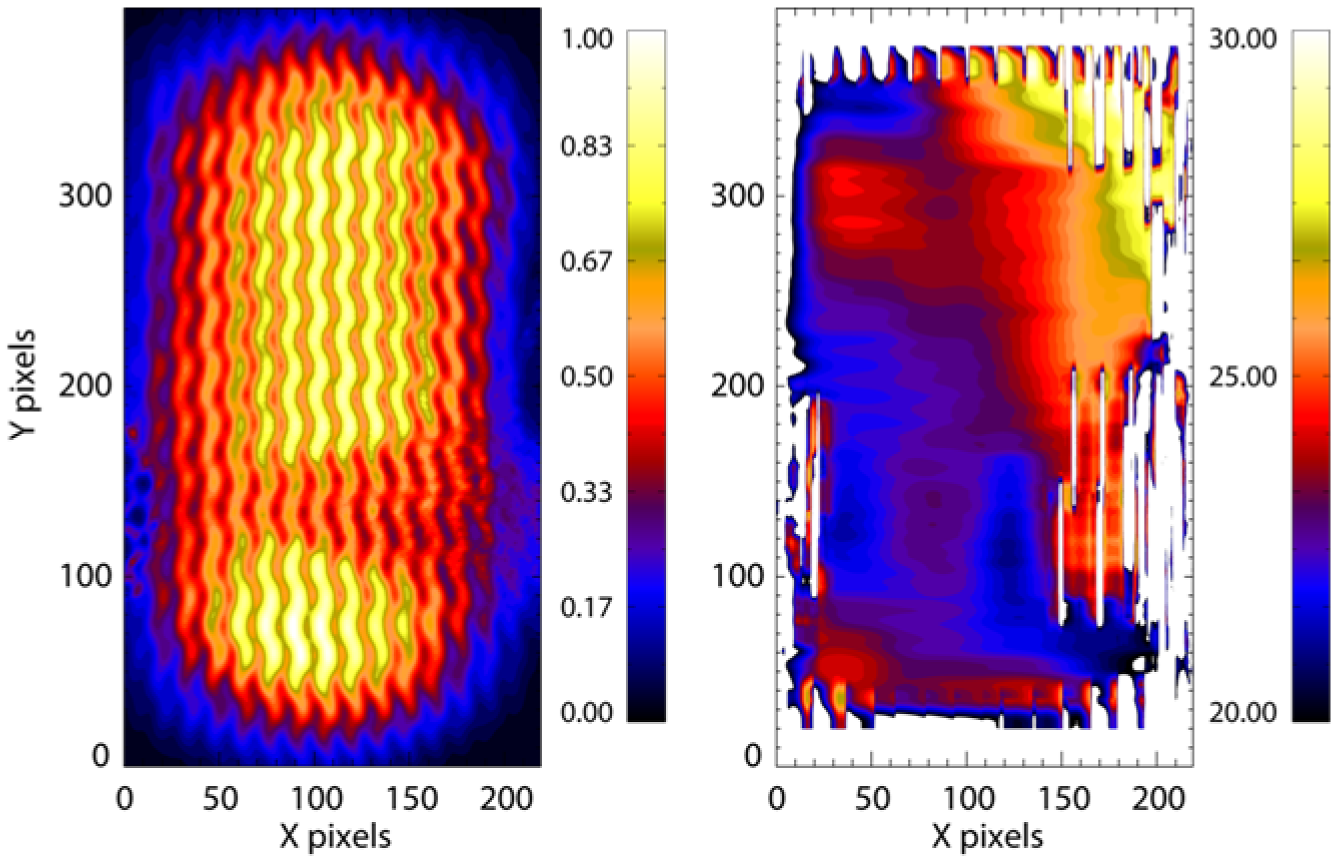


Step vary the polarization angle θ (i.e. magnetic field tilt angle)

Demodulate pattern ➔ θ

$$S = 1 + \zeta\,(1 + \sin\phi_y)\cos(\phi_x + 2\theta) + \zeta\,(1 - \sin\phi_y)\cos(\phi_x - 2\theta)$$

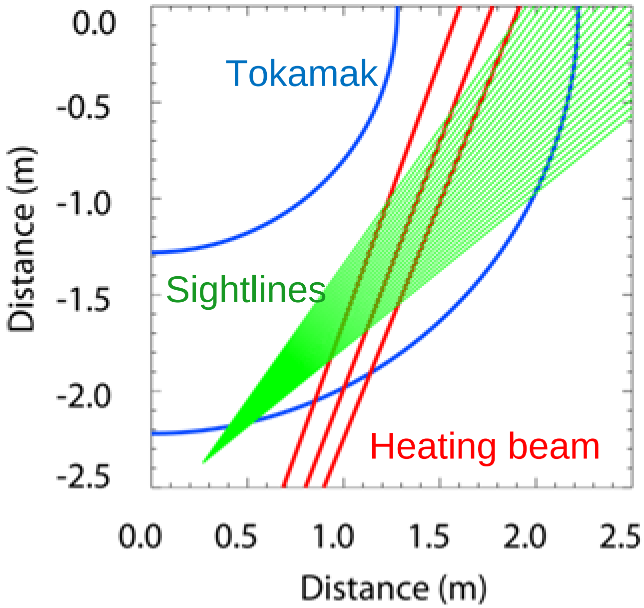
Demodulated polarization angle image

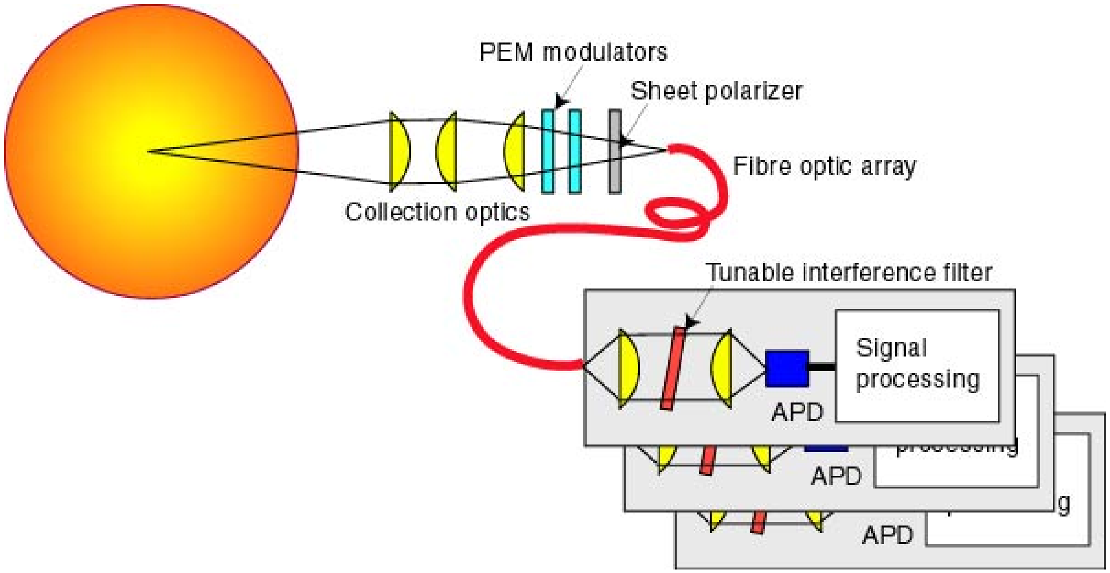


Nett contrast ~0.25

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

Standard MSE arrangement





Spectrally isolate the central σ component

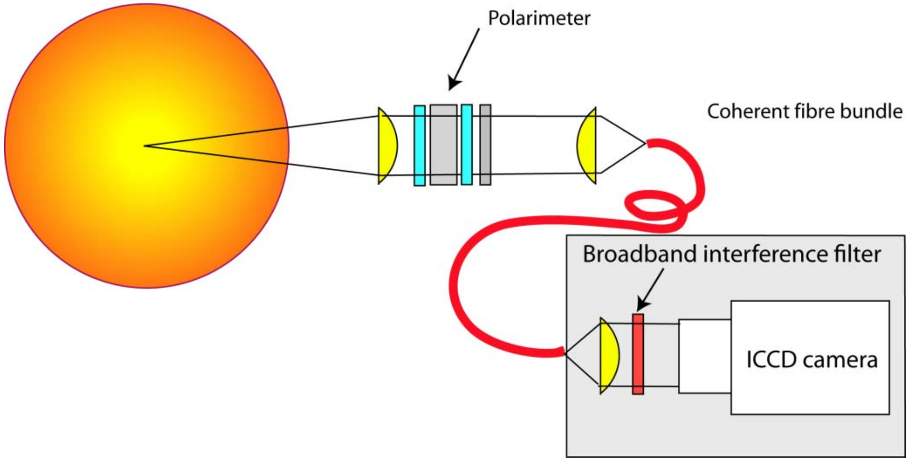
Measure its polarization orientation ➔ B orientation. Know Btor, extract Bpol

➔of order 20 discrete channels is typical.

➔Requires arrays of very narrowband, temperature-tuned interference filters

➔Many challenges: efficiency, maintenance etc

Coherence imaging polarimetry



Features:

➢Spatial encoding (no modulation, single snapshot)

➢Analyze polarization of full mutliplet: wideband filter, tolerant of contamination and background

Applications:

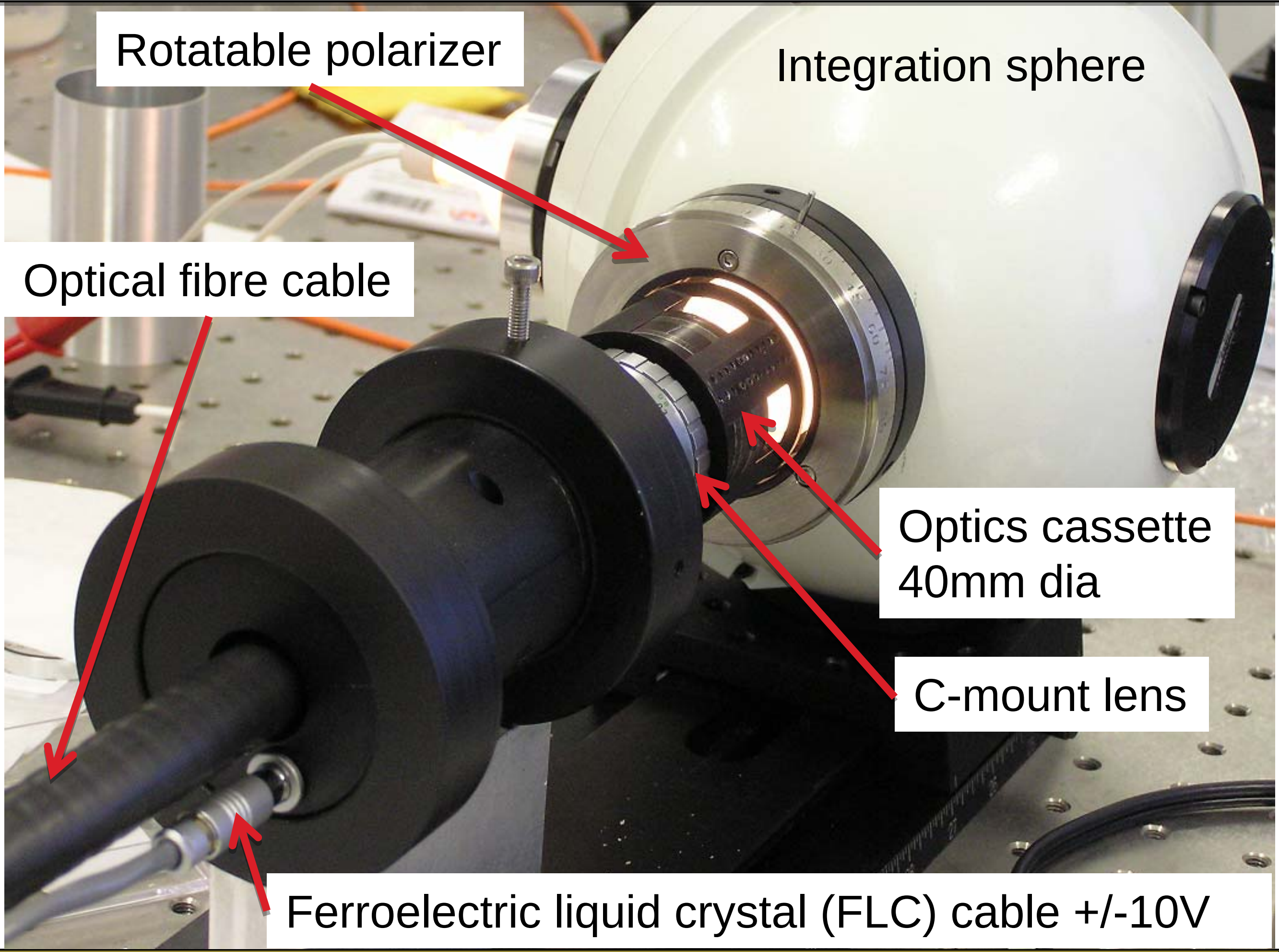
➢Tokamak internal current imaging (sawteeth, MHD, ECCD, shaped plasmas etc)

➢Zeeman-tagged divertor Doppler imaging

➢Solar spectroscopy, etc

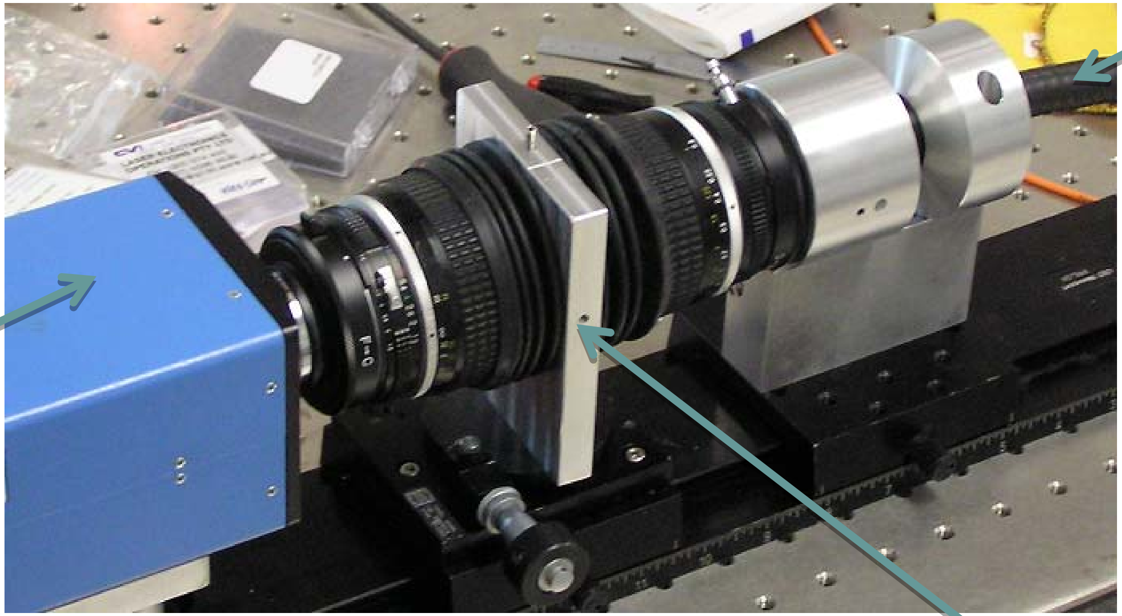
Calibration setup for polarimeter head

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



Optical cable coupling to camera

Imaging optical fibre cable from polarimeter head

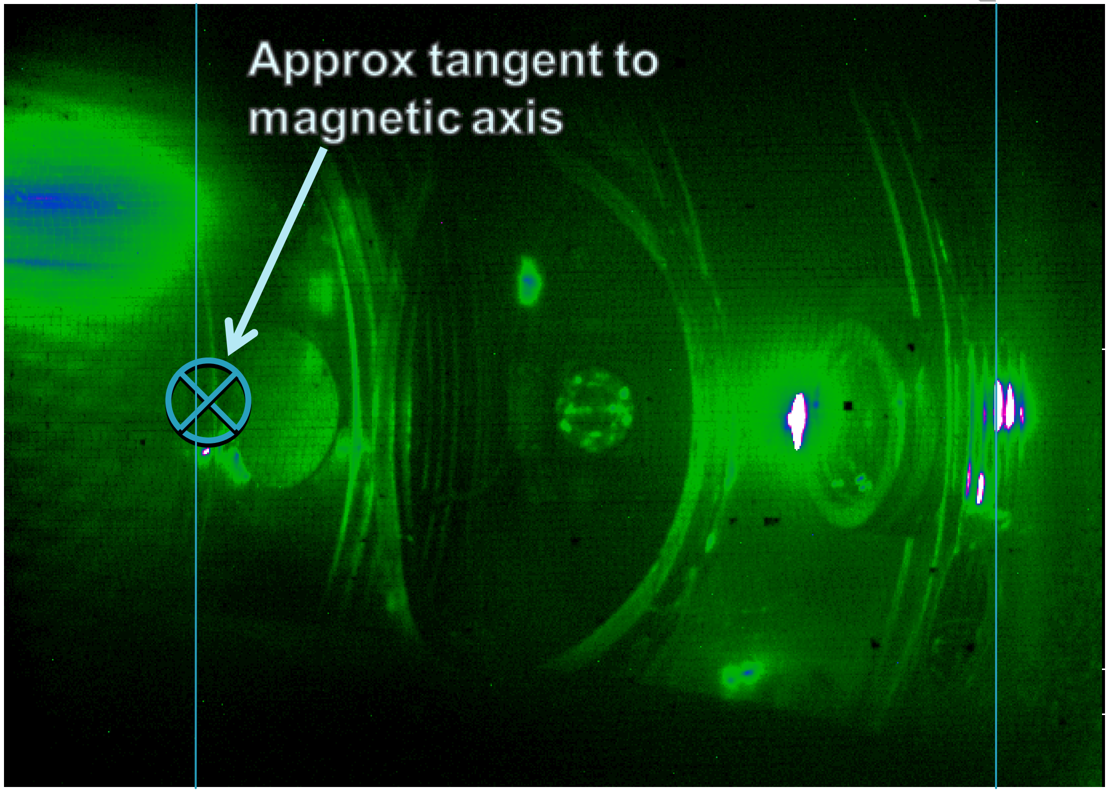


CCD camera:
Sensicam
12 bit, cooled
1376x1040
8.9mm x 6.7mm

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

View through port and prism

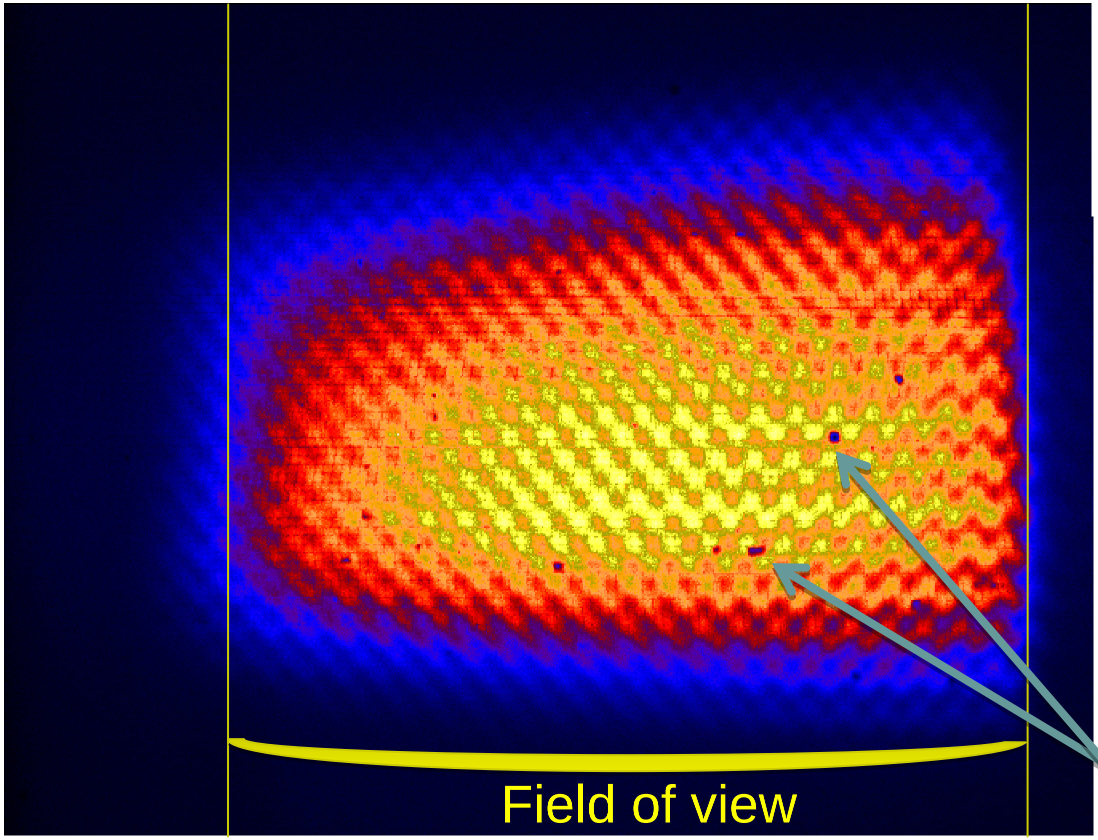
Field of view limited by prism



NBI
50 keV

20 degree camera field of view

Double spatial heterodyne snapshot image



2-d raw fringe pattern encodes polarization orientation

Input H beam
50kV, 1MW

Fibre imperfections

Optical component distortion ➔ limited usefulness in TEXTOR campaign

Use alternative *hybrid spatio-temporal mutliplex* imaging system …

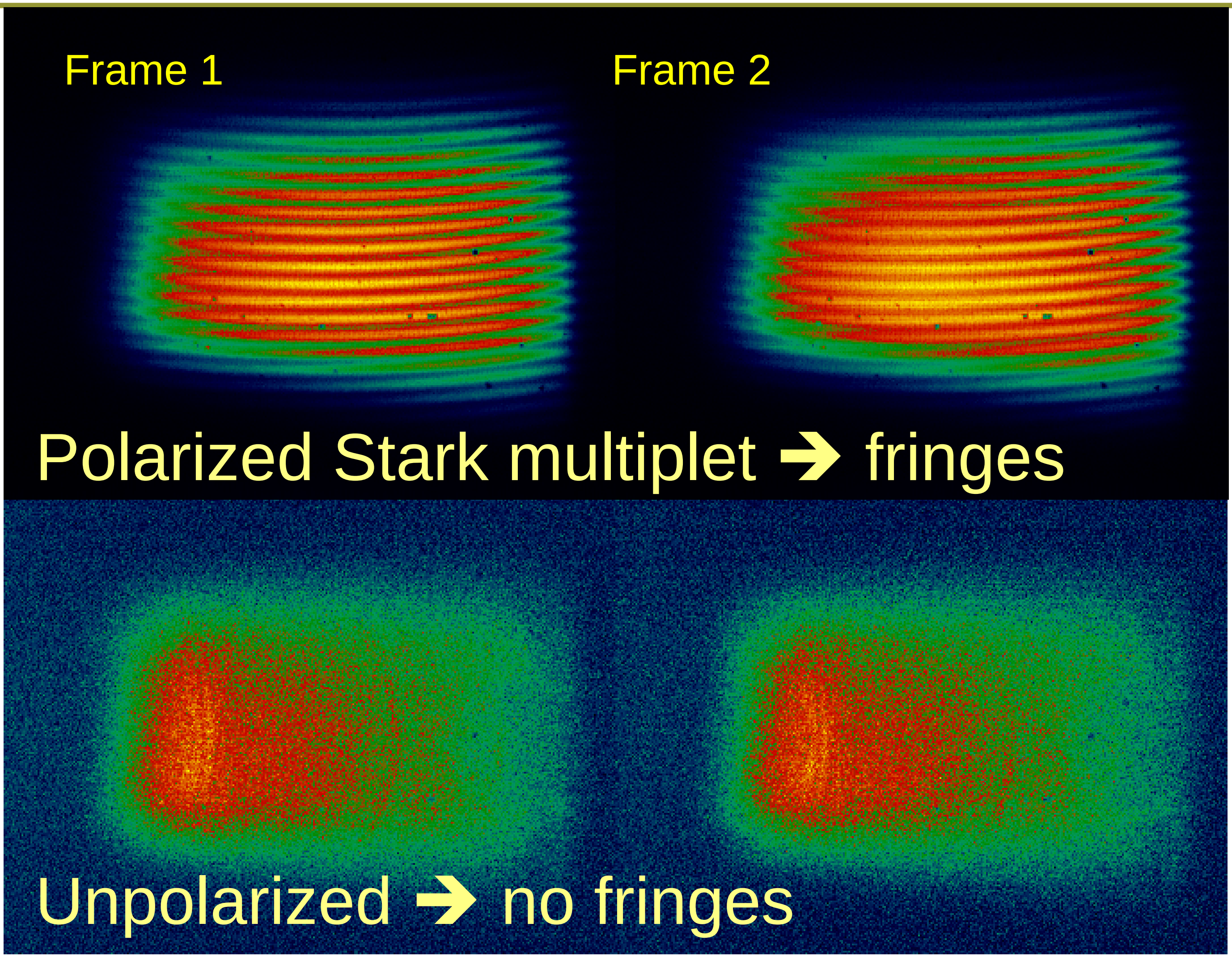
Hybrid system Spatial-temporal multiplex

- 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 ➔ 4θ

- Advantages
  - Simple sinusoidal fringe pattern
  - Improved spatial resolution

- Disadvantages
  - Require two frames – poorer time resolution

Polarized emission generates interference fringes

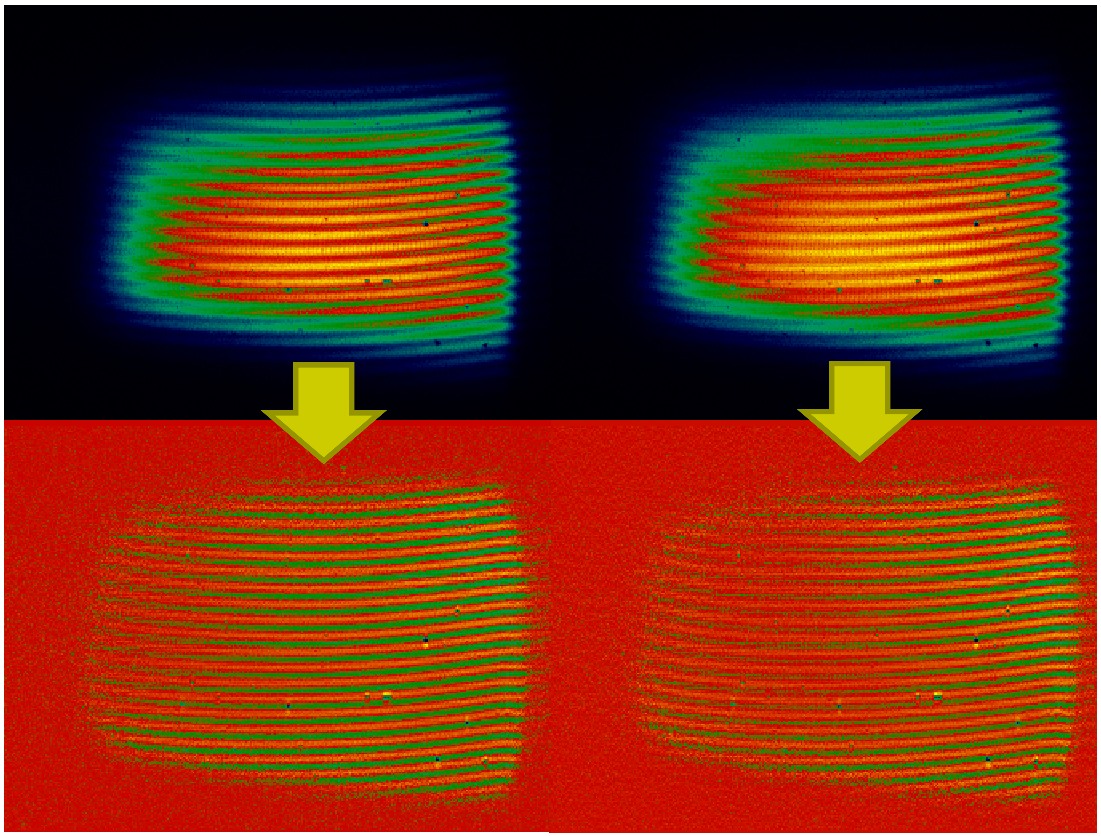


Beam on

Beam off

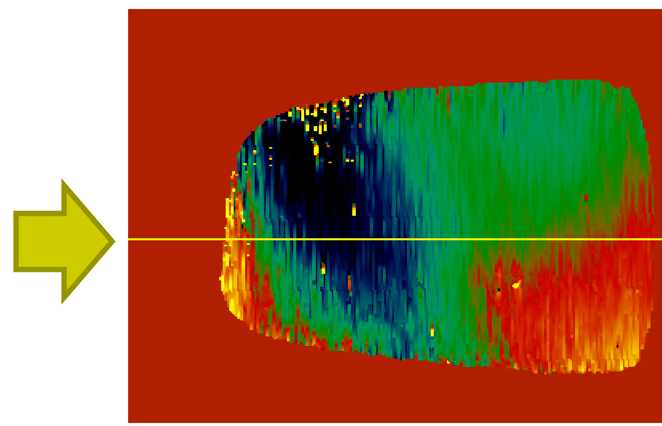
Hybrid system – data and processing

Raw image 1 Raw image 2



Normalized interferogram 1 Normalized interferogram 2

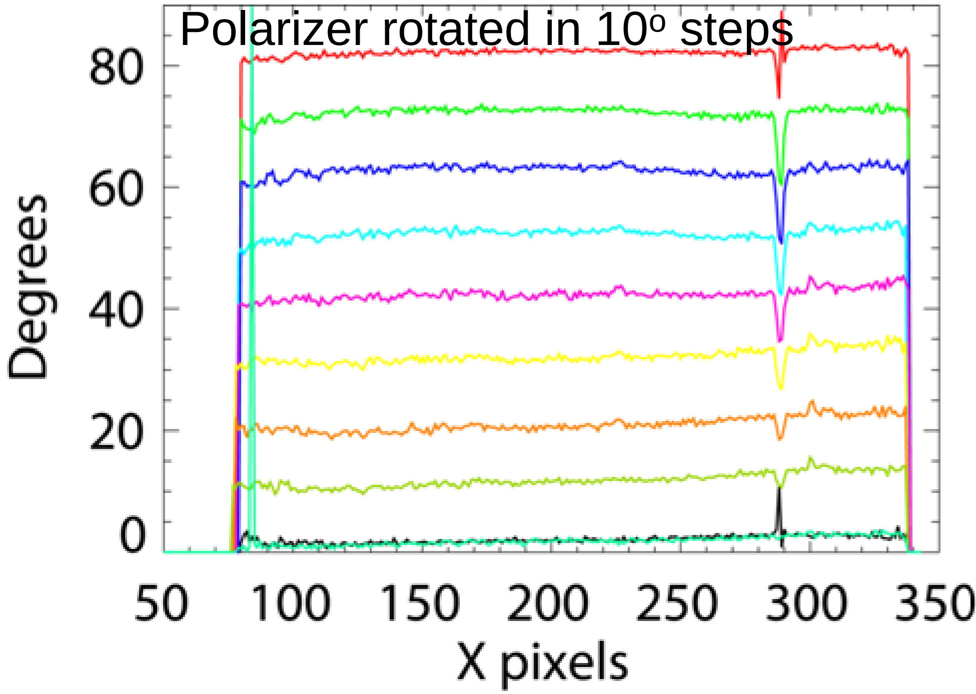
Normalized interferograms are demodulated and their phases subtracted to obtain polarization image



Stark polarization image

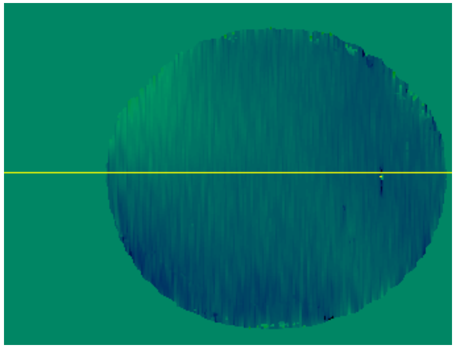
Hybrid system specifications and calibration

- 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)

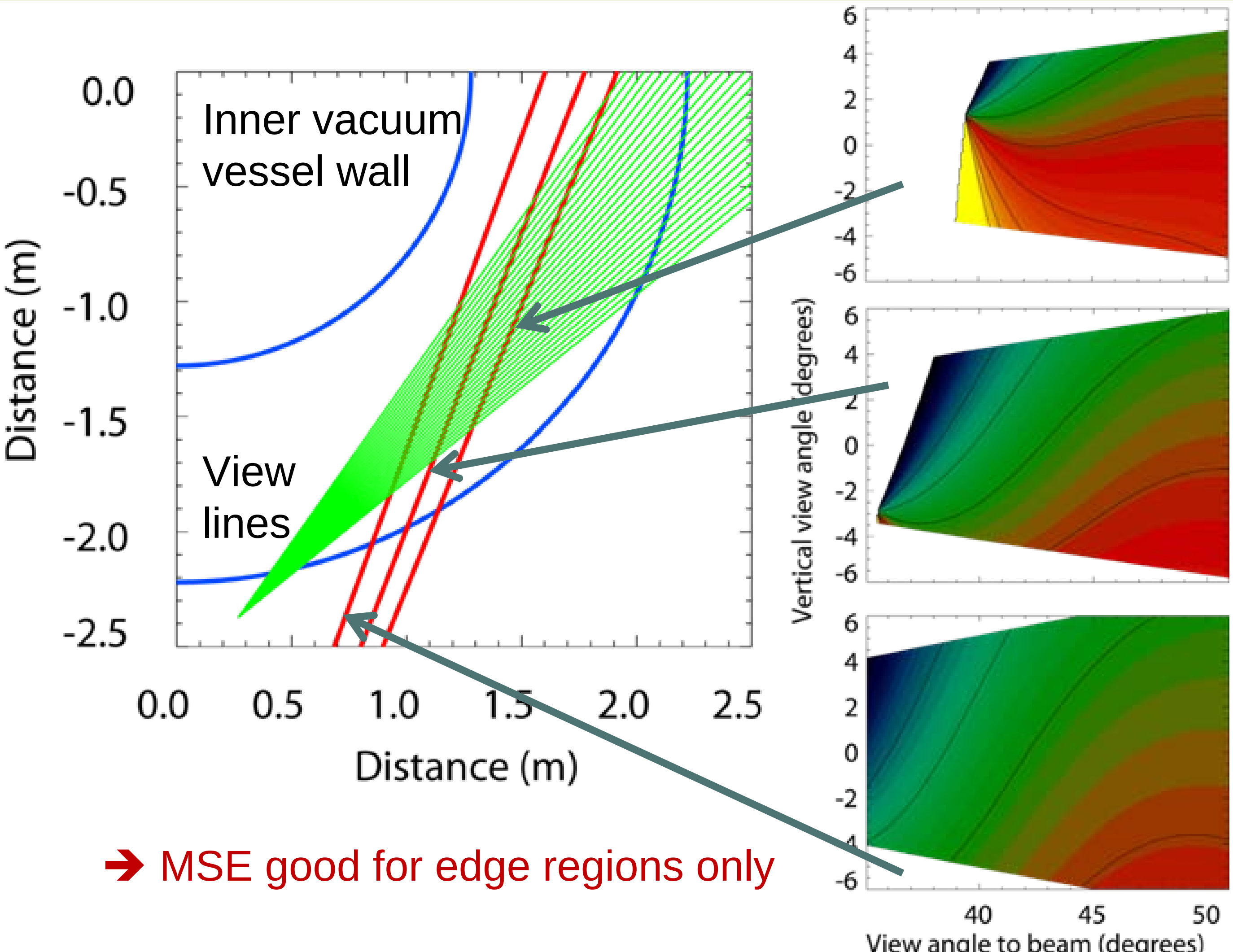


Right: Typical calibration image

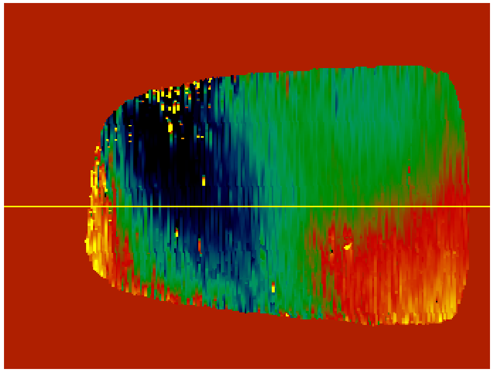
Above: Central line profiles for cal sequence



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^{o}→ 15^{o})

➔ 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 4θ where θ 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 (“l-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

Home

Workshop Information

Technical Program

Registration and Fees

Abstract Submission

Booking Accommodation in Canberra

Murramarang Resort

The Murramarang 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.

http://www.rsphysse.anu.edu.au/jaw09/index.html

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

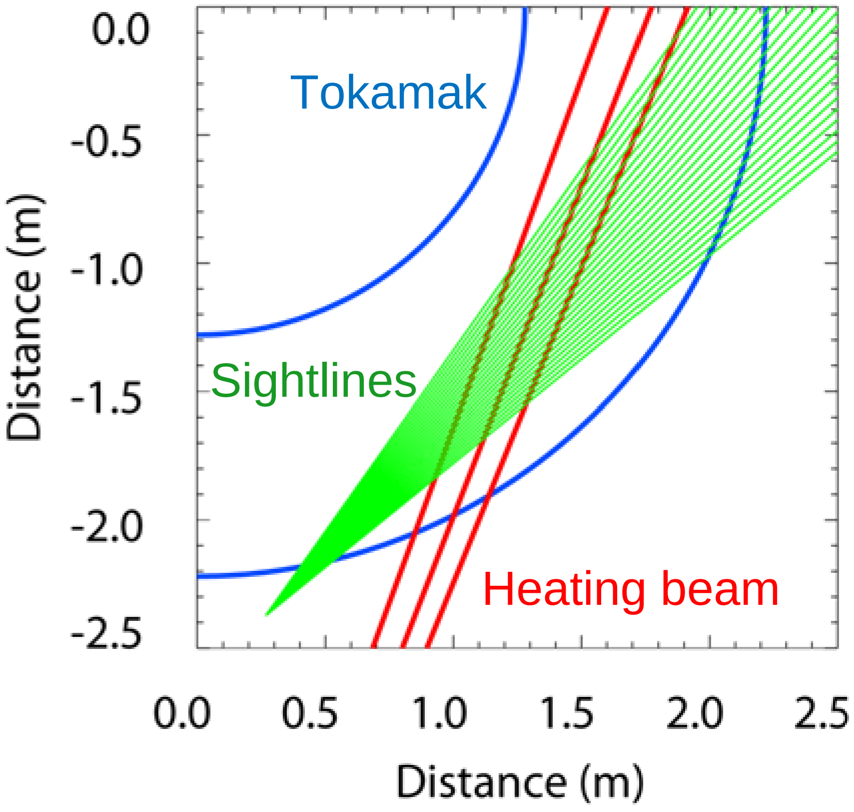
- **MSE:** H or D atoms in a heating beam experience an induced electric field **E=v x B** that generates a complex spectrum. Viewed transverse to **E** the Stark split σ and π components are polarized perpendicular and parallel to **E** respectively

- **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

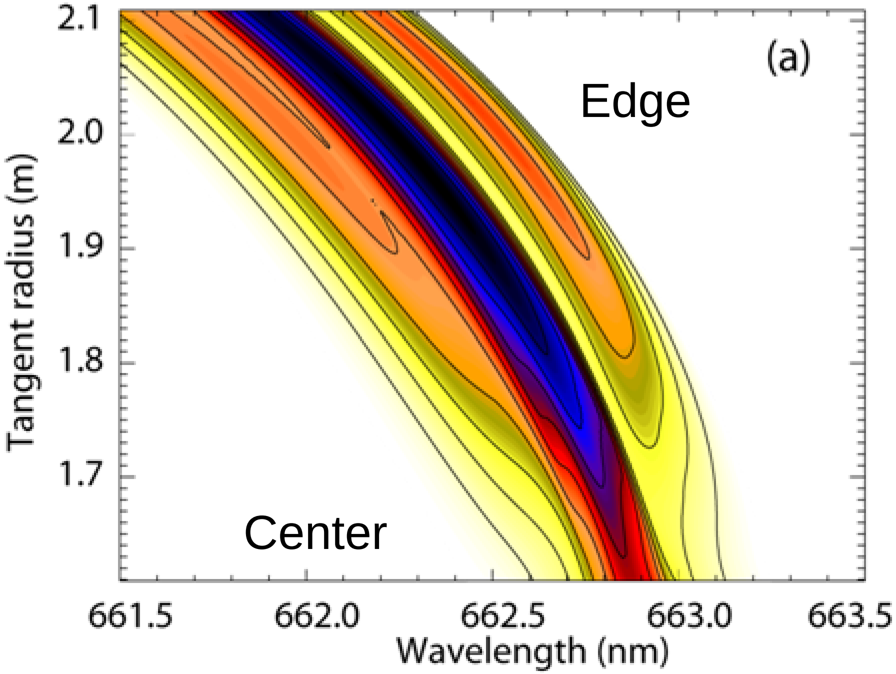


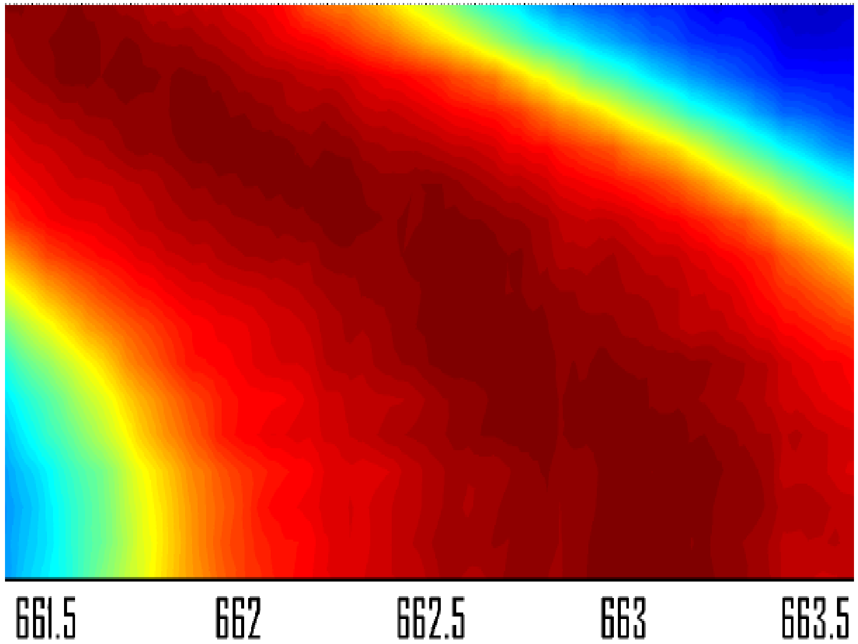
2.25T on axis
350 kA
H or D beams, 50keV/amu
3% energy noise
1.2 degrees divergence

Spectrum is red-shifted

Polarization tilt angle captures the poloidal field

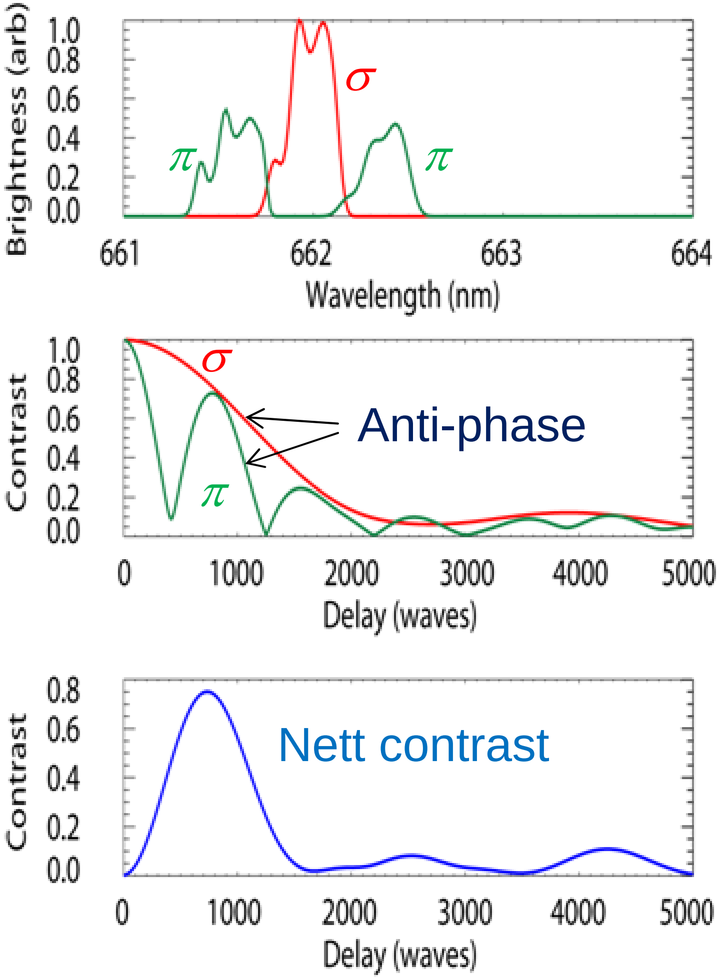
Optical design ensures filter passband tracks Doppler shift of full energy multiplet

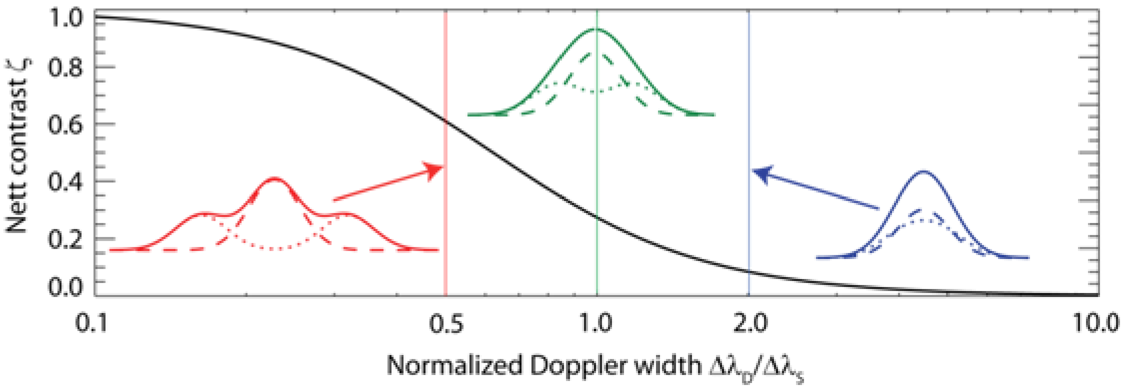




Measured pre-filter response

Nett contrast decreases as broadening increases





Variation of fringe contrast with ratio Doppler width/Stark splitting

Instrument response

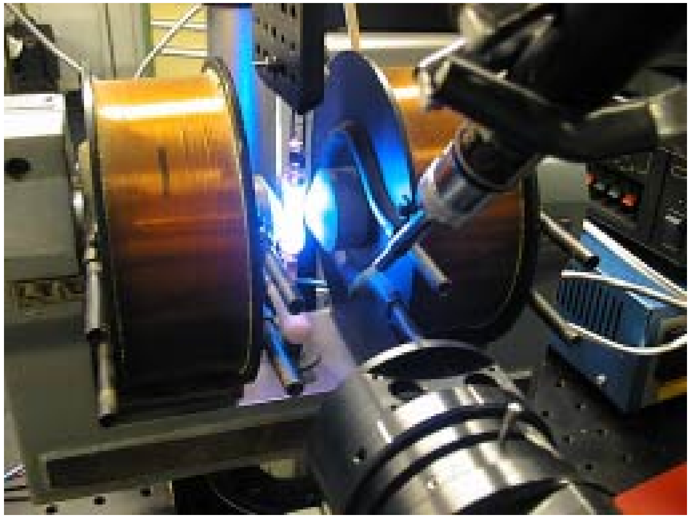
2-d interference pattern carries coherence and polarization

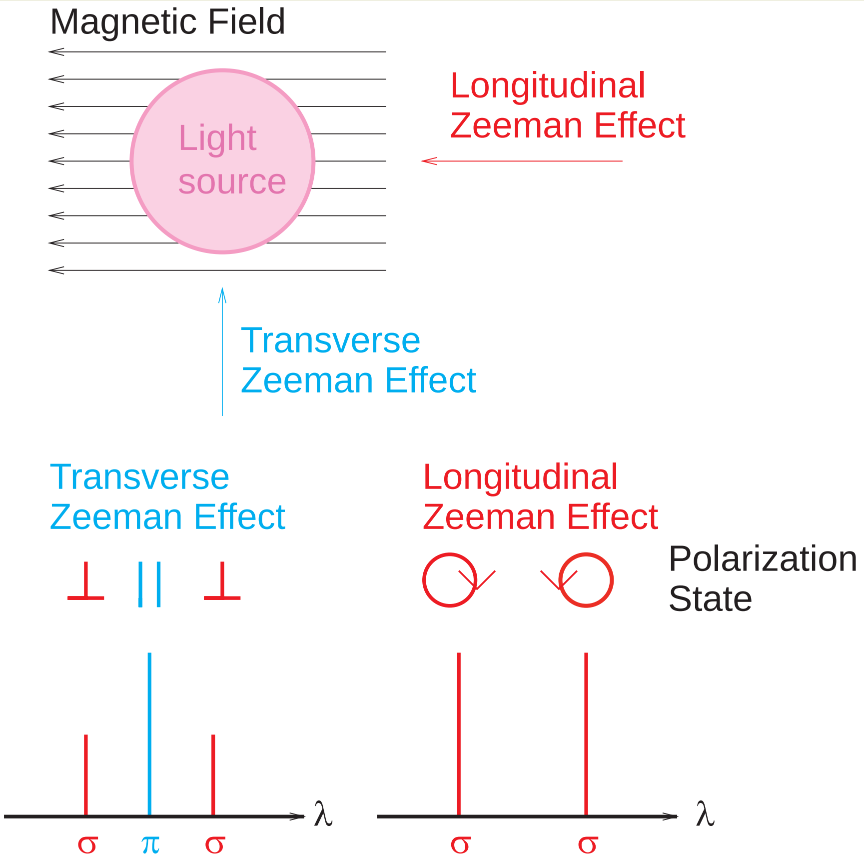
$$S = 1 + \zeta\,(1 + \sin\phi_y)\cos(\phi_x + 2\theta) + \zeta\,(1 - \sin\phi_y)\cos(\phi_x - 2\theta)$$

θ is the polarization orientation

ϕ_y is carrier phase in y direction
ϕ_x is carrier phase in x direction (spectrum)
ζ is effective contrast: high contrast implies good fringe visibility

Measurements of Zeeman triplet (Zn I 481nm)





Observe transverse effect
B~0.4T

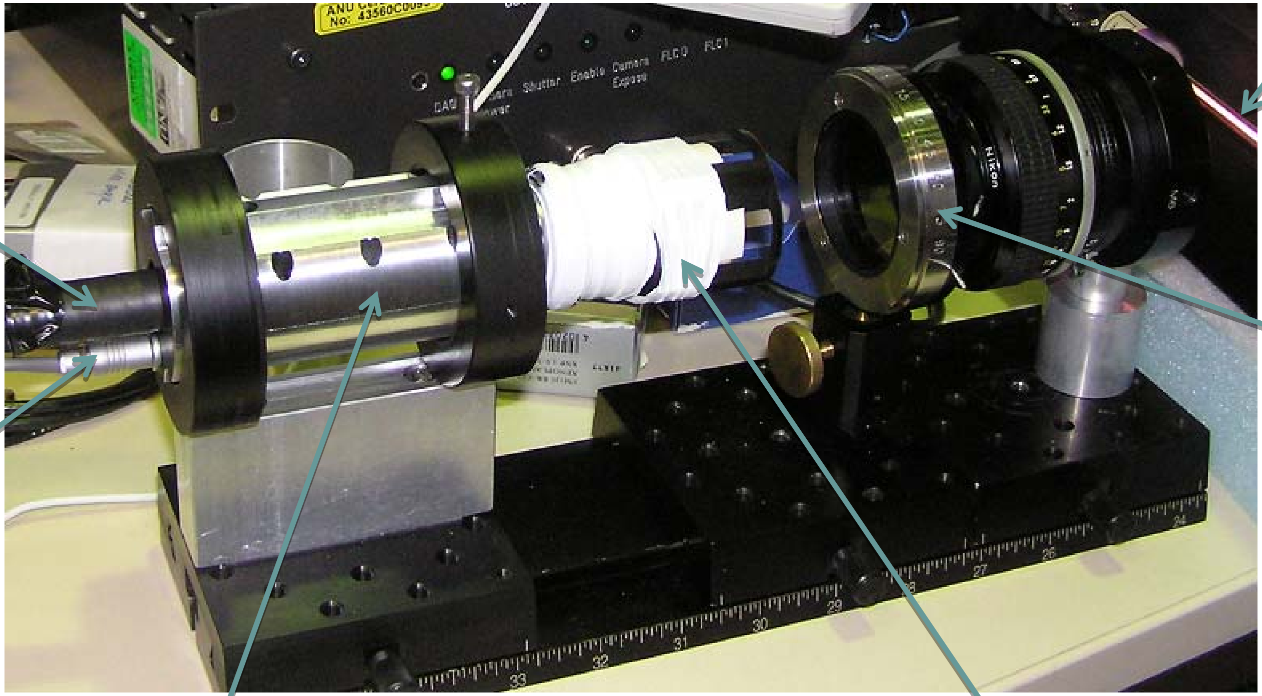
Use waveplate to rotate the multiplet to simulate MSE effect

Calibration of polarimeter head at TEXTOR

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

Fibre cable

$H\alpha$ lamp



Rotatable polarizer

FLC cable +/-10V

Fibre cable support element

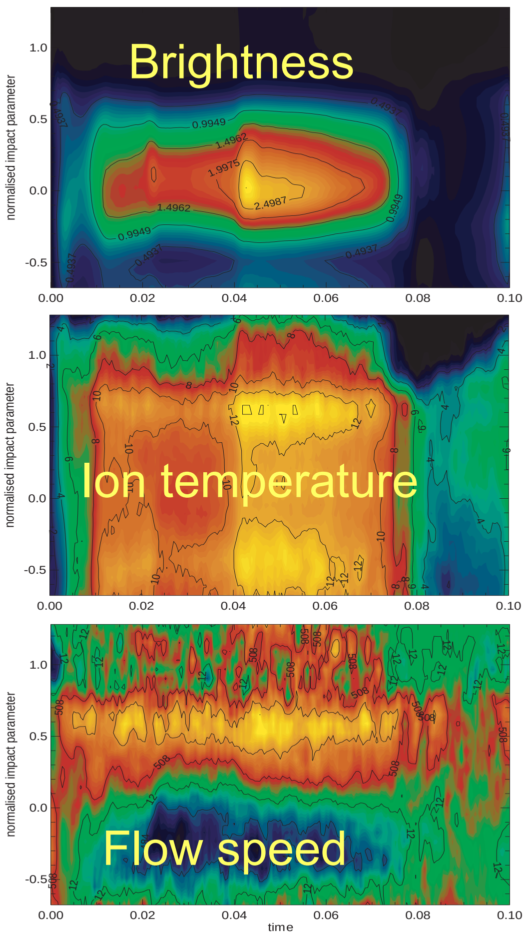
Optical head (covered with protecting teflon tape). Includes polarization optics and wide-angle C-mount lens

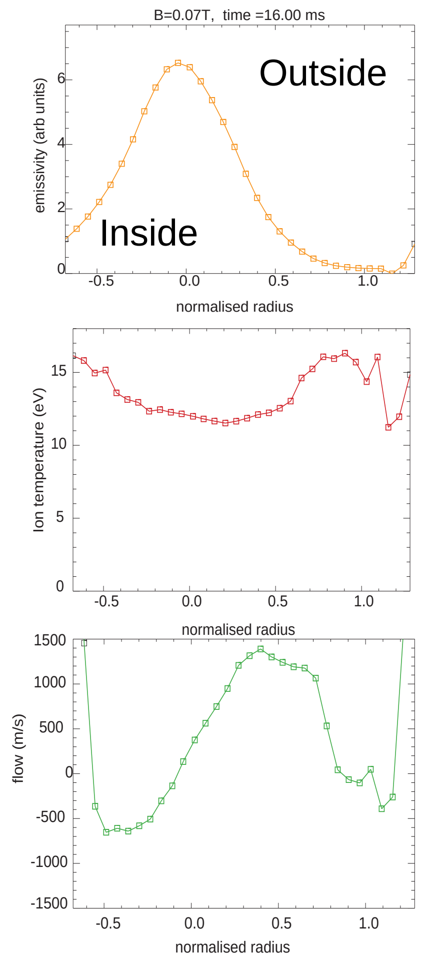
1-D (poloidal plane) Doppler imaging on the H-1 heliac

(Sinusoidal electro-optic time delay modulation)

Outside

Inside





Brightness

Centrally peaked

Temperature

Hollow profile

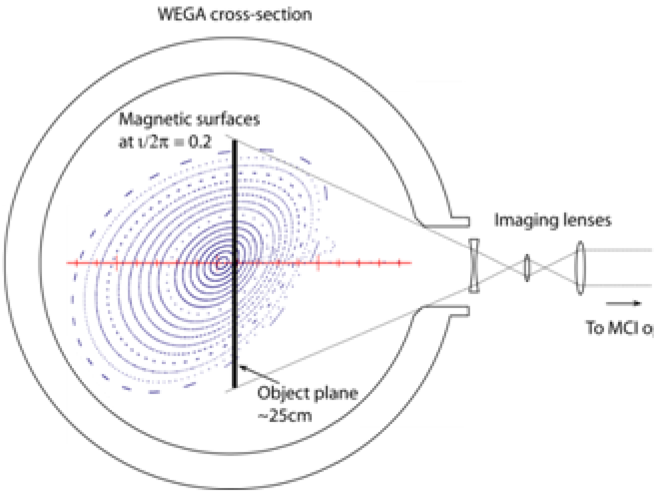
Flow speed

Sheared rigid rotation

Profiles during power ramp experiments

CCD system for 2-D Doppler imaging

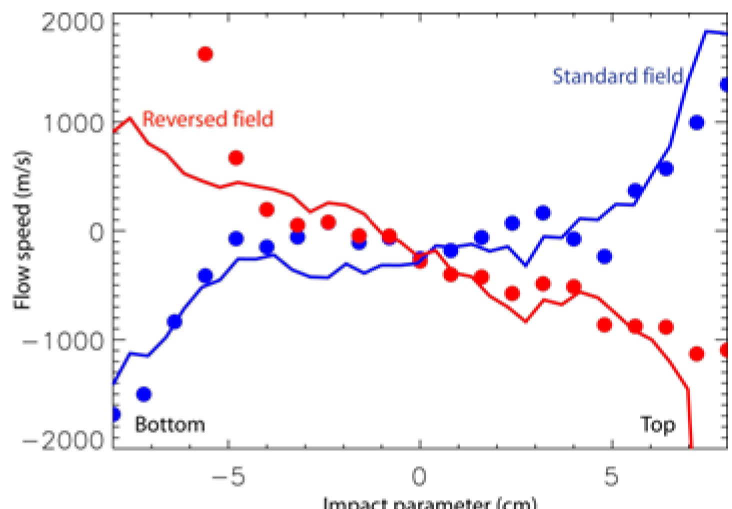
(electro-optic step delay modulation)



The IPP camera:

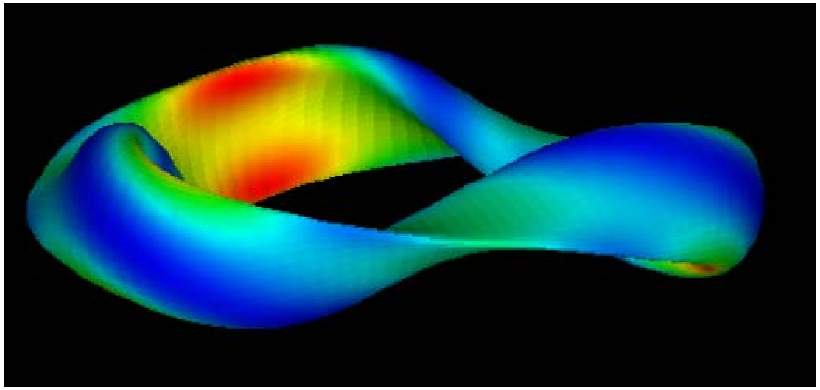
- LabVIEW/MDSplus
- 12 bit CCD camera,
- max 70Hz frame rate

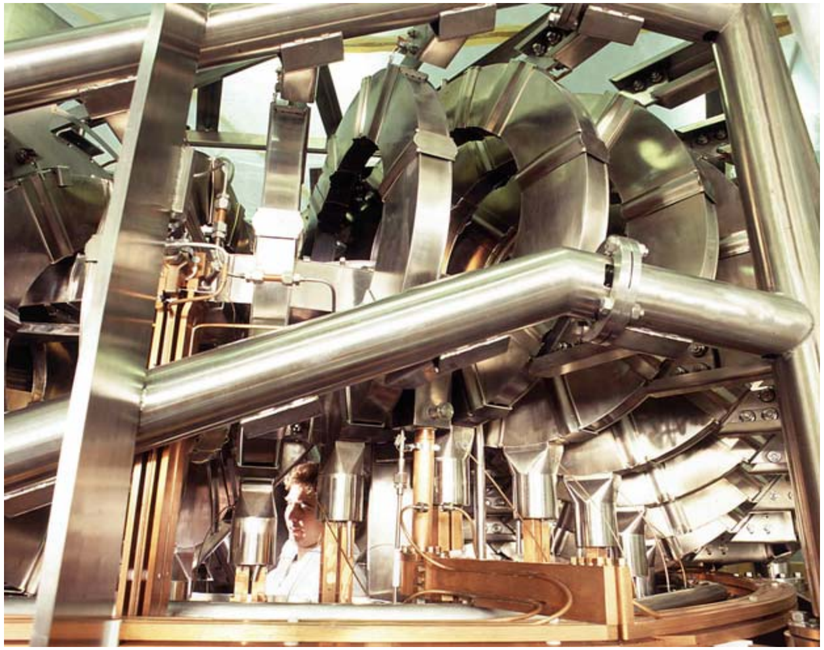
Ion temperature animation
(WEGA ECH power step, HeII 468nm)



Comparison with high resoution 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.-1.5, 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