Coherence imaging spectroscopy:
A new method for measuring plasma dynamics.

Deutsche Physikalische Gesellschaft, Berlin, March 2014

O. P. Ford,[1] J. Howard,[2] M. Reich,[1] J. Hobirk,[1]
J. Svensson,[1] R. Wolf,[1] ASDEX Upgrade Team

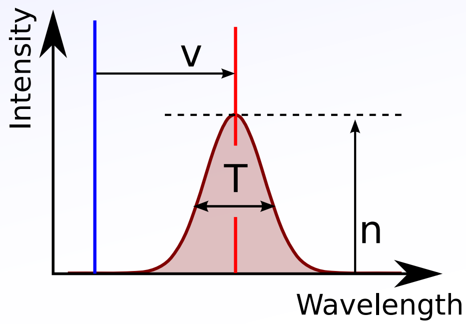
1: Max-Planck Institut für Plasmaphysik, Greifswald/Garching, Germany
2: Plasma Research Laboratory, Australian National University, Canberra

With special thanks to S. Silburn, CCFE / Durham University, UK

Doppler Spectroscopy

For fusion relevant plasmas, the high temperature means nearly all measurements are made by observation of emitted particles or radiation.

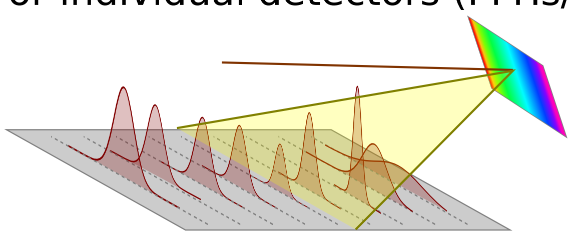
Very common is the observation of atomic line emission from neutral hydrogen, impurities or laser light scattered by plasma particles.



Doppler shift --> Bulk velocity
Doppler broadening --> Temperature
Intensity --> Particle density

Typical spectroscopy techniques:

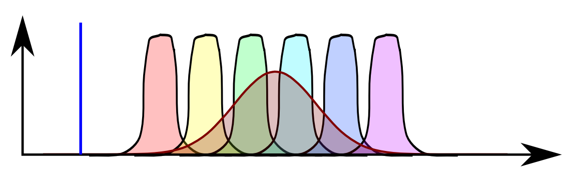
Diffraction grating and CCD camera, or individual detectors (PMTs/APDs)



Low light levels. 1D set of points.

or

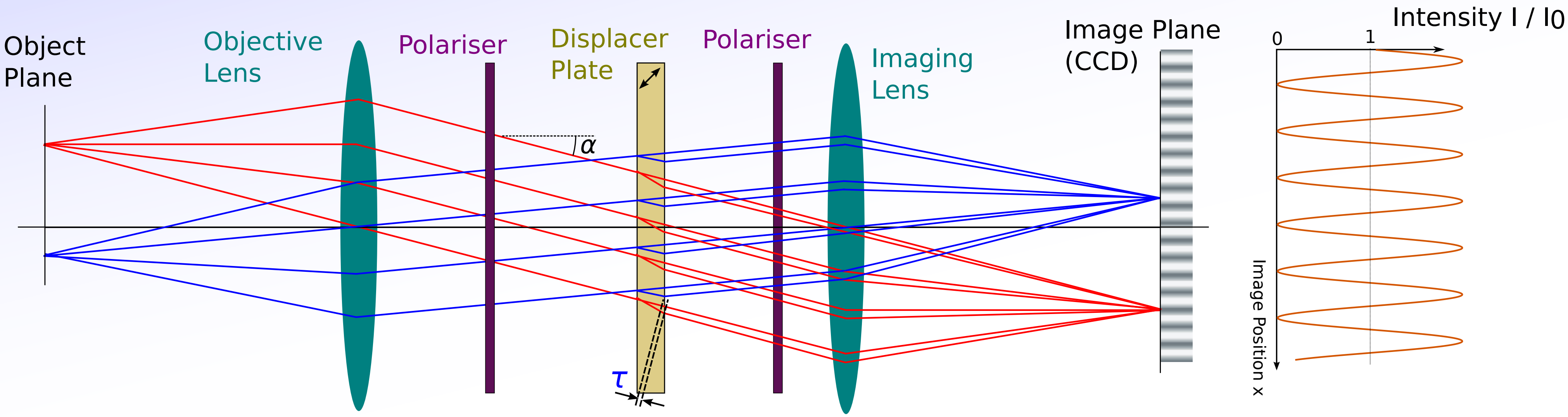
Individual spectral filters and fast sensitive detectors.

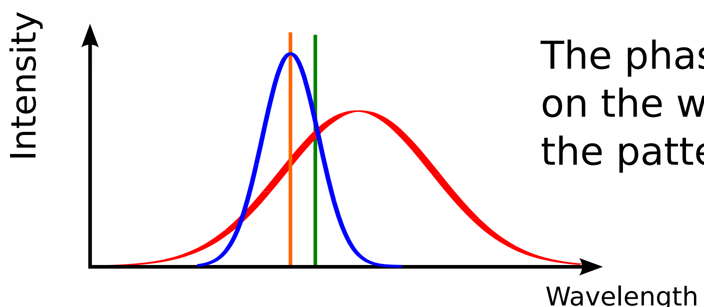


Very complex setup per channel.
Low spectral resolution.

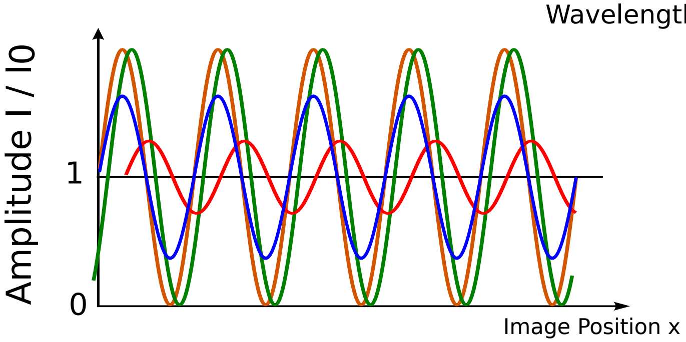
Coherence Imaging

Displacer Plate: A crystal plate with optic axis at 45° to the surface. It has an angle dependant phase shift. Imaged at infinity, it creates an interference pattern across image.

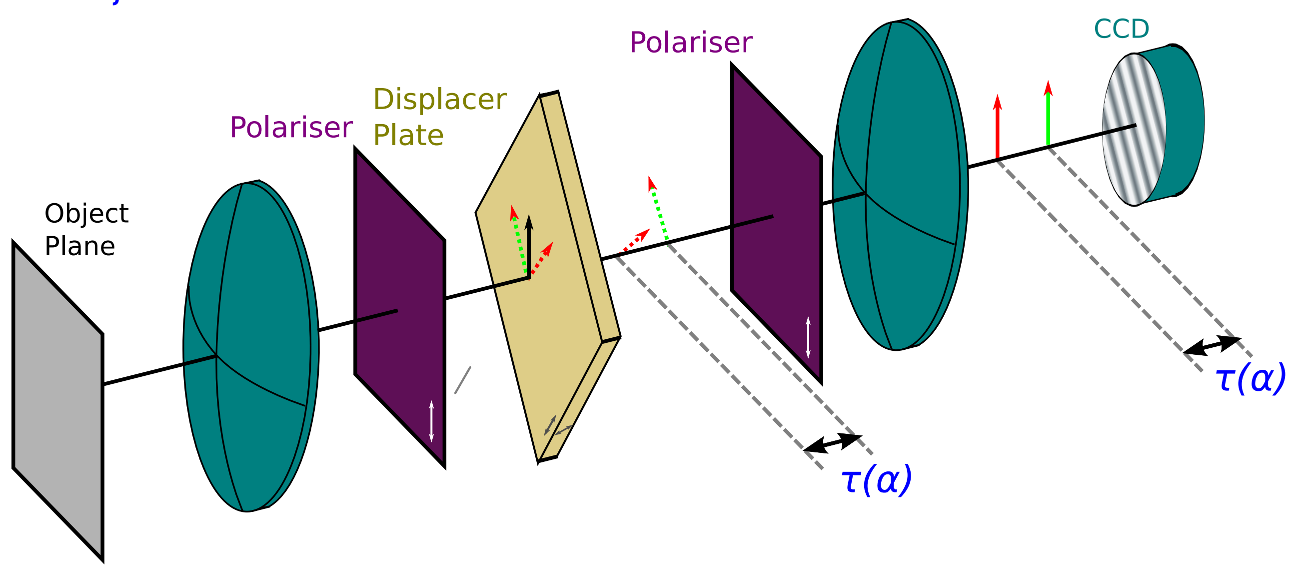




The phase of the interference pattern depends on the wavelength Δω. With multiple wavelengths, the pattern contrast ζ is reduced.



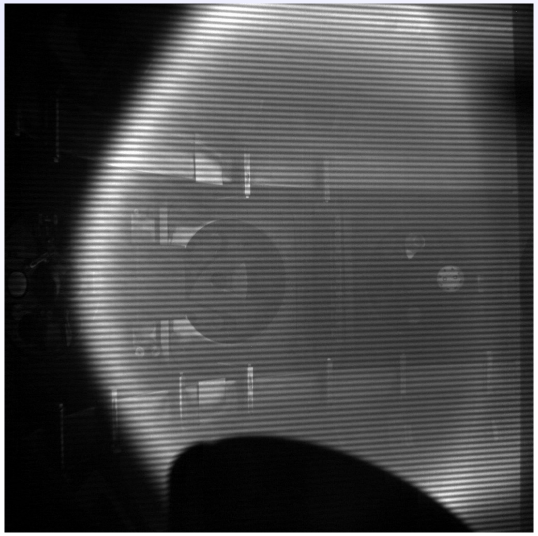
$$I \propto 1 + \zeta\, cos((\omega + \Delta\omega)x)$$



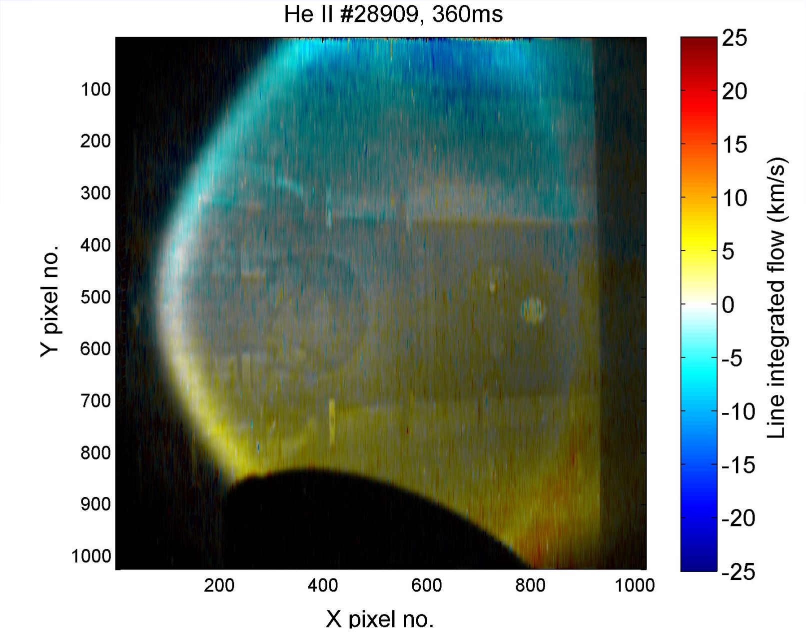
Doppler Coherence Flow Imaging - MAST

Some results of neutral Helium flow in the (relatively) cold edge of MAST:

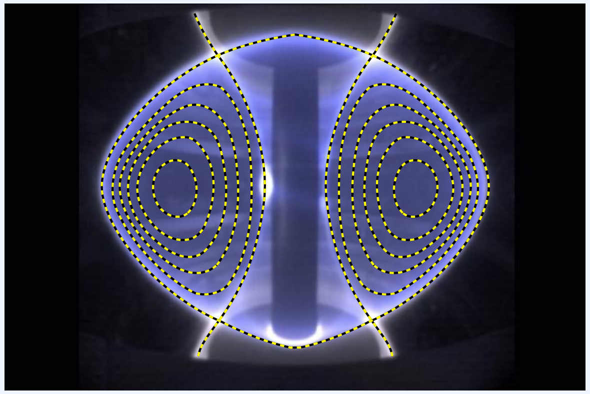
Raw Image:



Helium Flow Velocity:



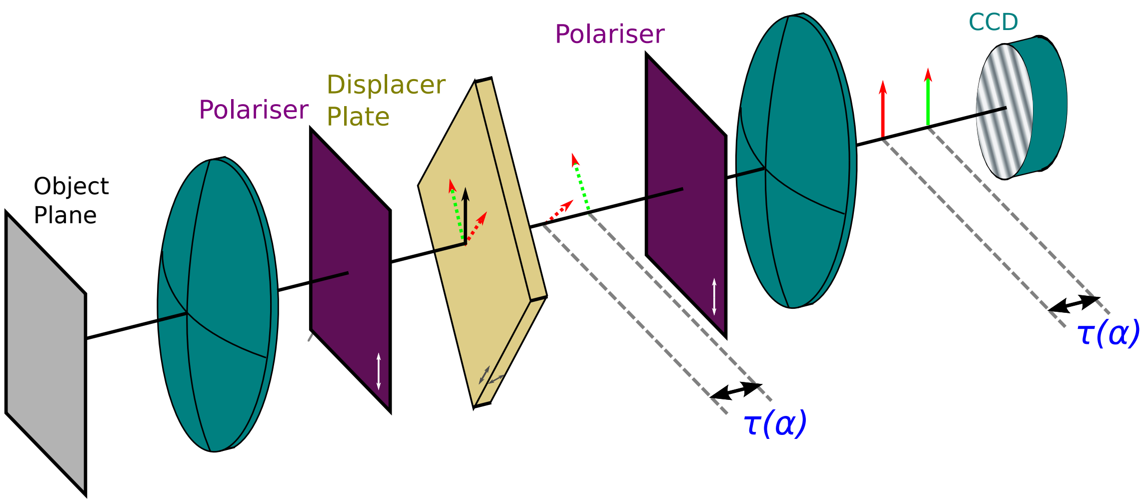
MAST
Mega Amp Spherical Tokamak, CCFE, Culham, UK



MAST is a 'spherical' Tokamak. The torus has a very small major radius compared to it's minor radius, but is still a Tokamak.

And some videos...

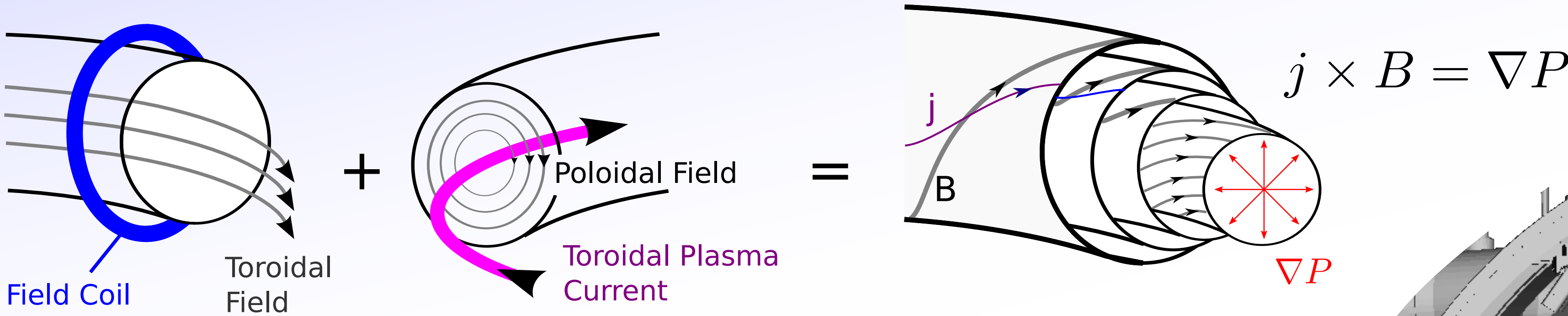
*With thanks to Scott Silburn, Durham University / CCFE
[S. Silburn et. al. 40th EPS Conf. on plasma phys. 2013]



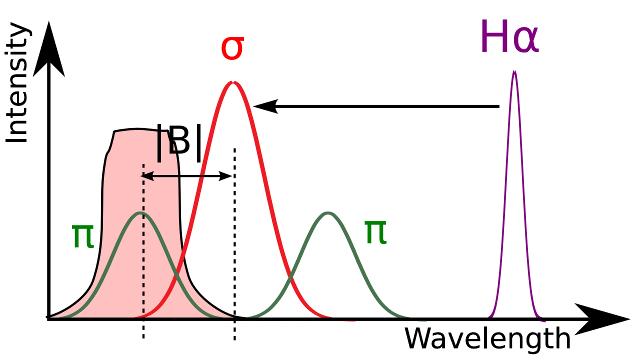
Project started to use this technique to look at flows during magnetic reconnection on the linear device VINETA.

Tokamak Magnetic Configuration

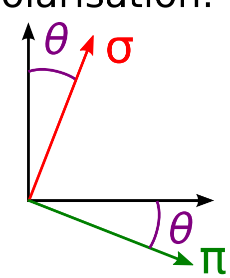
The Tokamak plasma current and magnetic configuration strongly effects the stability and confinement properties of the plasma. Measurements of the internal magnetic pitch angles highly desirable.



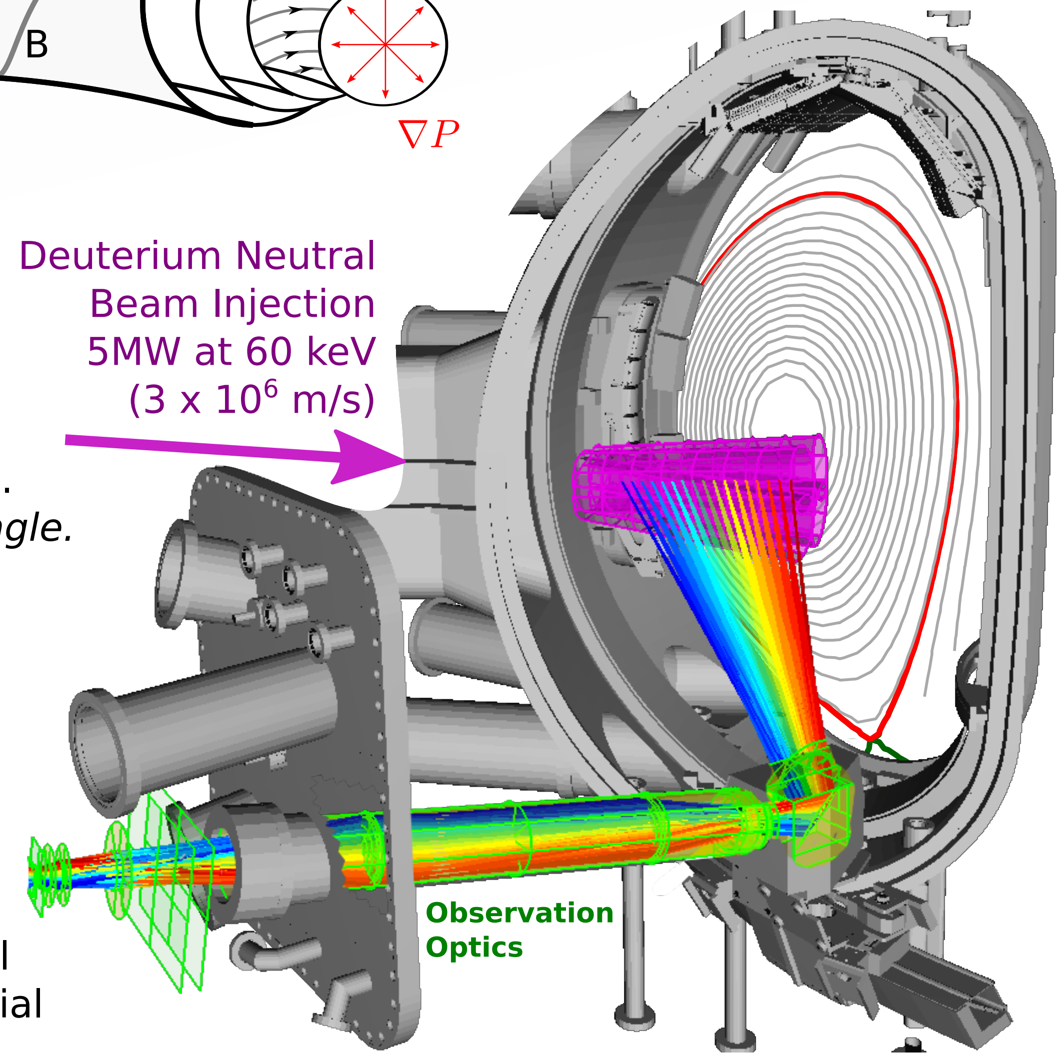
Typical is usually done with polarimetry.
Spectral lines are split and polarised by E/M fields:
  Zeeman Effect: Magnetic field.
  Stark Effect: Electric field.
  Motional Stark Effect (MSE): Stark effect from Lorentz
  transformed **E** = **v** x **B** for fast injected neutrals.
Polarisation θ gives information about the field *pitch angle*.



Polarisation:



Typically, complex hardware is required, with individual filters for each spatial position. Up to a few 10s of spatial positions usually measured.



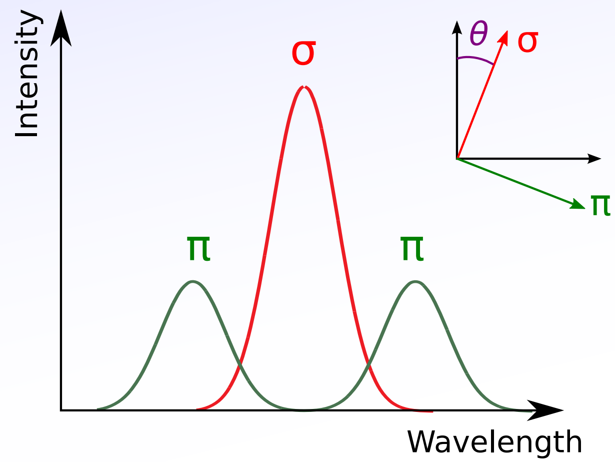
ASDEX Upgrade Vacuum Vessel

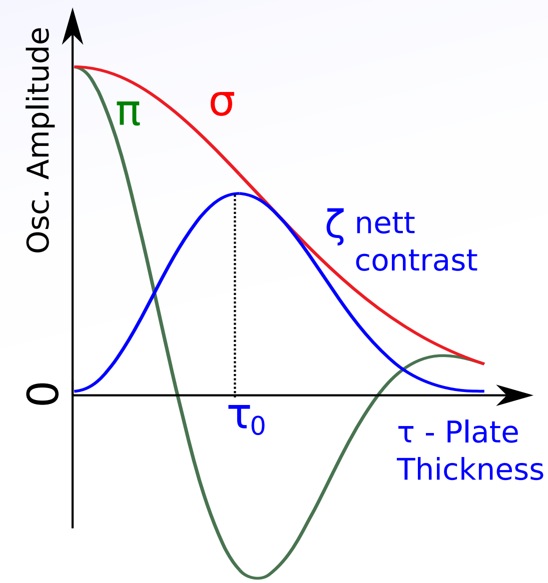
Multiplet Polarisation Coherence Imaging

Removing the first polariser gives a dependence on the initial polarisation:

$$I \propto 1 + \zeta \, cos2\theta \, cos(x)$$

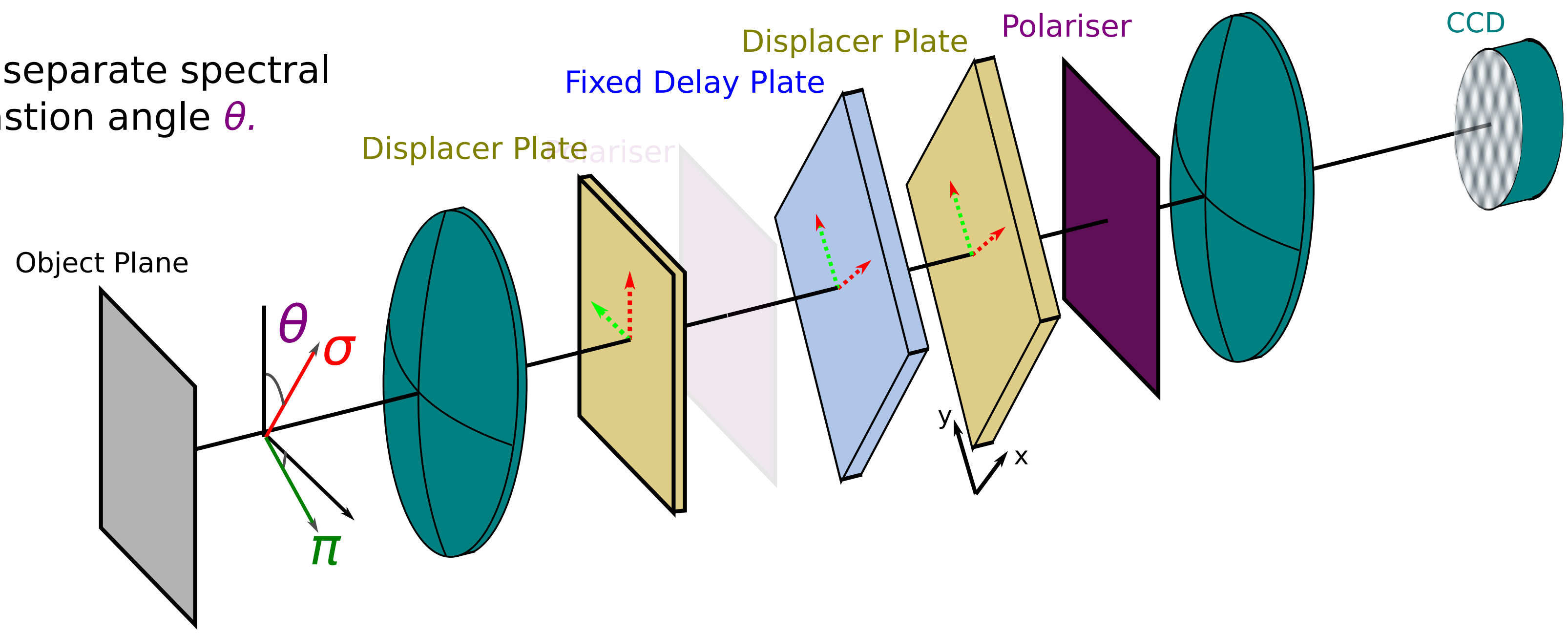
For the Stark/Zeeman spectrum, the π component is at 90° to σ, introducing a 180° phase shift, so they would cancel.





At specific phase delay τ, the phase of the π wings is 180° from σ. This cancels the 180° from the opposite polarisation, and the patterns add. We add a delay plate with the best τ_0.

However, we now need to separate spectral contrast ζ from the polariastion angle *θ*.



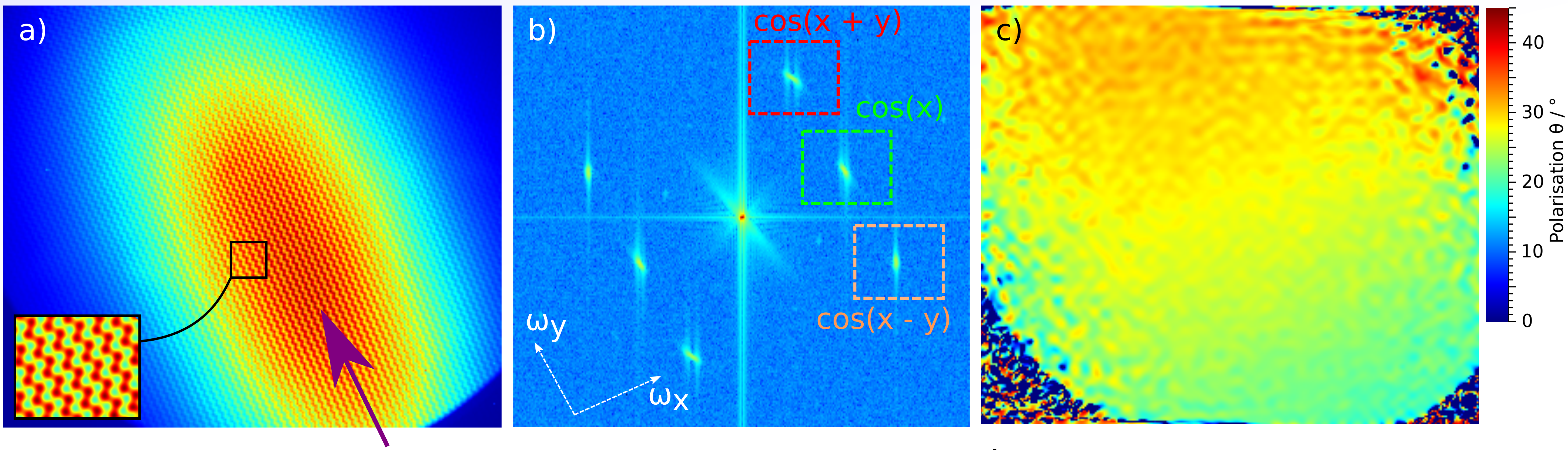
add another displacer at 45°. Combined effect adds 2 extra terms:

$$I \propto 1 + \zeta \, cos2\theta \, cos(x) + \zeta \, sin2\theta \, cos(x-y) - \zeta \, sin2\theta \, cos(x+y)$$

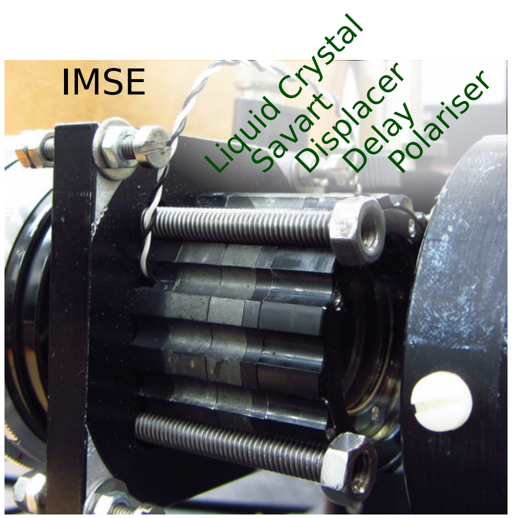
Image Demodulation

The two orthogonal interference patterns give 3 components in the Fourier transform. We can filter these from the FT and extract the polarisation angle θ:

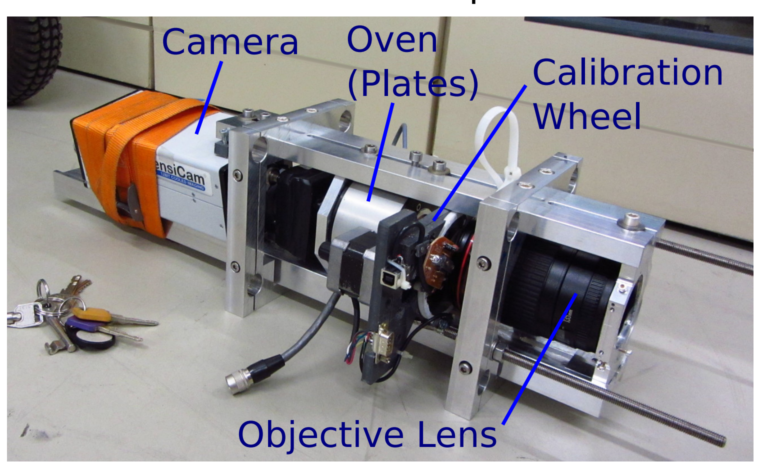
$$I \propto 1 \quad + \zeta \cos(2\theta)\cos(x) \quad + \zeta \sin(2\theta)\cos(x+y) \quad + \zeta \sin(2\theta)\cos(x-y)$$



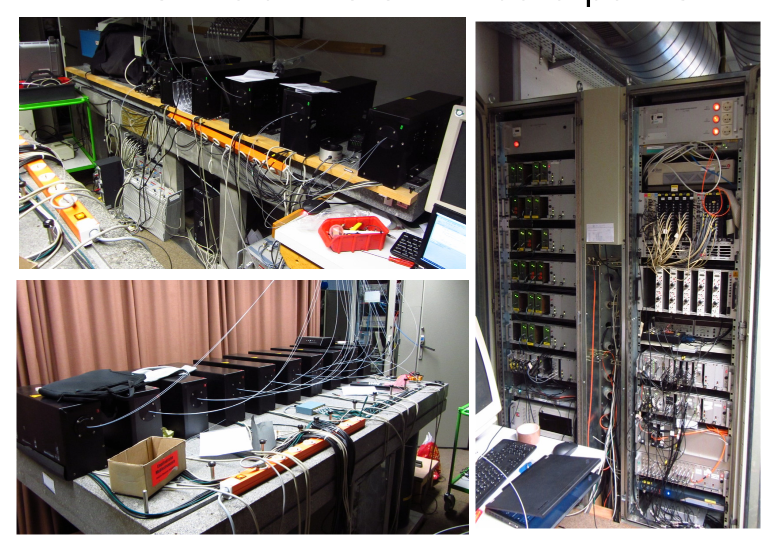
The hardware:



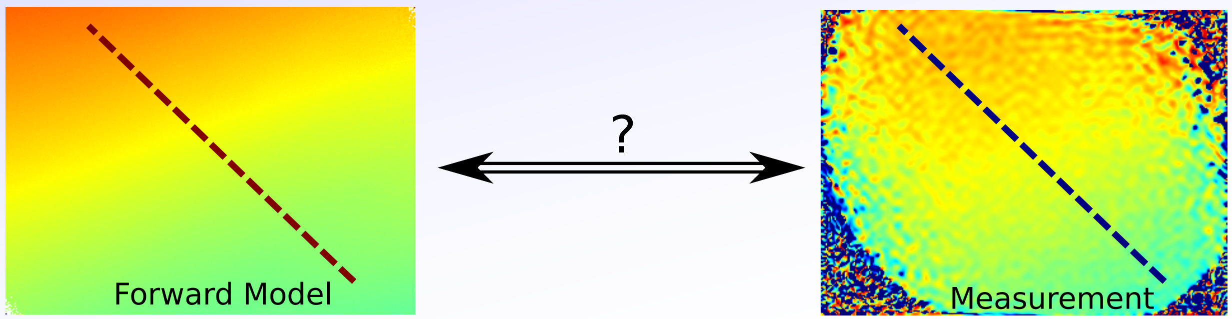
IMSE: 100x100 data points



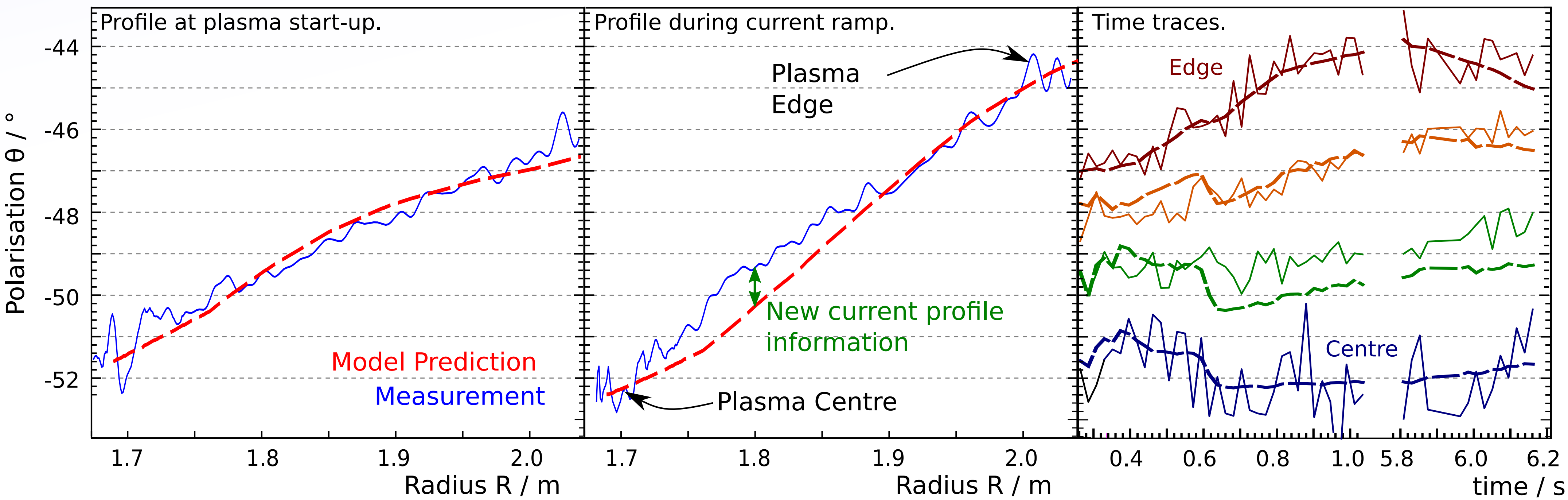
MSE Polarimeter: 12 data points



Preliminary comparison with Forward Model



Except for a 0.7° *offset*, the results agree with the modelling where what we already know from other diagnostics is excepted to be correct. The difference is the new information that the IMSE provides:



Inferring the plasma current and q-profiles from the polarisation is far from trivial and the analysis work is still on-going.

Summary

- Diagnosis of fusion plasma is challenging and usually involves passive spectroscopic analysis.
- Diagnosis of the current/magnetic configuration is particularly important, yet one of the most poorly diagnosed quantities in modern Tokamaks.
- ✓ Coherence imaging allows spectroscopic and polarimetric measurements to be made on complete images of the plasma, with considerably simpler hardware.
- ✓ An new Imaging Motional Stark Effect diagnostic has been designed, constructed and operated on ASDEX Upgrade.
  It has many advantages, including:
  - Simpler hardware.
  - Over 100x more data.
  - Automatic positional calibration.
  - Relatively insensitive to the spectrum (no finely tuned filters)
- ✓ Initial analysis shows agreement with modelled polarisation, within expected uncertainty.
- ••• Next stage is to calculate safety factor profiles and plasma current image from the observed polarisation images.
- ••• Further experiments in May 2014 including better camera for improved Signal/Noise.

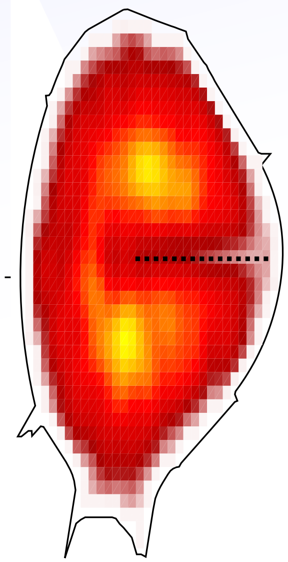
(Additional)

Motivation: Effect on Current Tomography

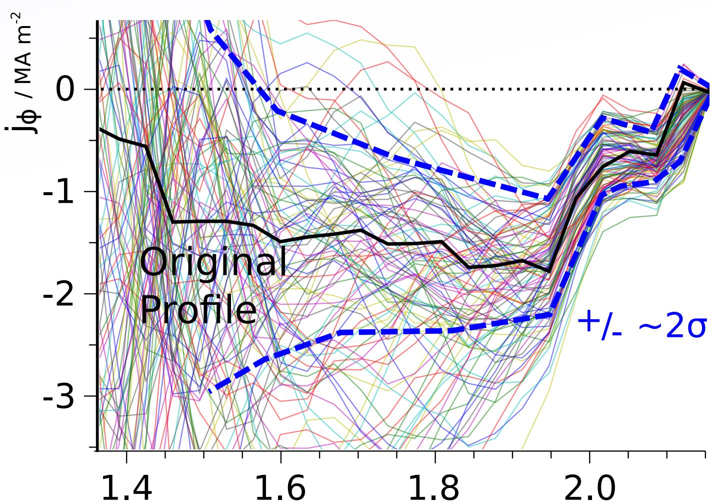
Magnetic configuration and current distribution are very important for many aspects of Tokamak physics.

Tomographic reconstruction of ASDEX Upgrade current from simulated external magnetic sensors and magnetic pitch angle measurements reveal that the current profile is more constrained by a distributed 2D grid of data points than than the same amount of data on the conventional 1D line.

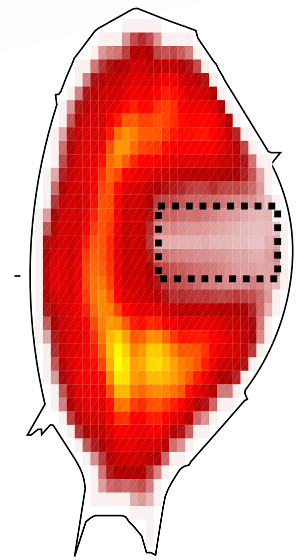
$j\phi$ Uncertainty



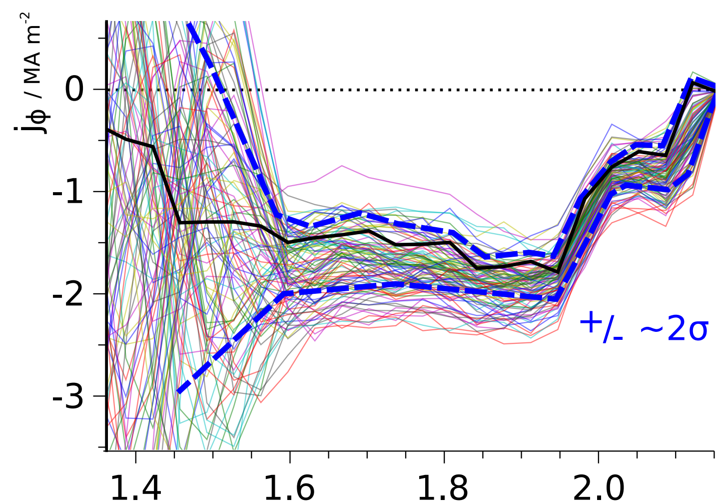
Magnetics + MSE system:
30 x Bz at 30 positions along NBI centre.



$j\phi$ Uncertainty



Magnetics + IMSE System:
30x30 grid of Bz measurements.



Each case has 900 measurements at $\sigma = 10mT$. So difference is only in the ***type*** of information.

Conclusion: 2D information greatly improves current inference ability,
even *excluding* increase in data quantity.