Max-Planck Institut
für Plasmaphysik

ASDEX Upgrade

Videos and images of fusion plasma properties with coherence imaging spectroscopy and polarimetry.

Technische Universität Berlin, November 2013

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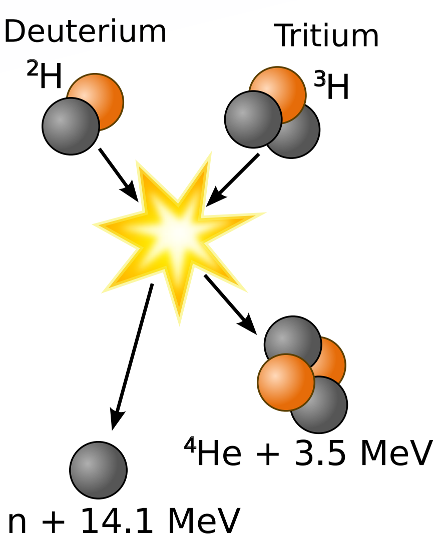
Fusion

The aim is to produce energy by fusing Deuterium and Tritium nuclei, which produces Helium, a neutron and **lots** of energy.

Why?

+ Clean - no radioactive waste products. (Only reactor parts).
+ Carbon free - No carbon output from the actual energy production.
+ Abundant Fuel - requires only Lithium and sea water, enough for millions of years.
+ Safe - Only enough fuel in reactor to sustain reaction - we can just turn off the tap.
+ On demand - Can turn it up/down as required.
- Very centralised - Requires very large, expensive, high-technology machines.

So, it's almost perfect? Unfortunately, it's ***really*** hard to do.



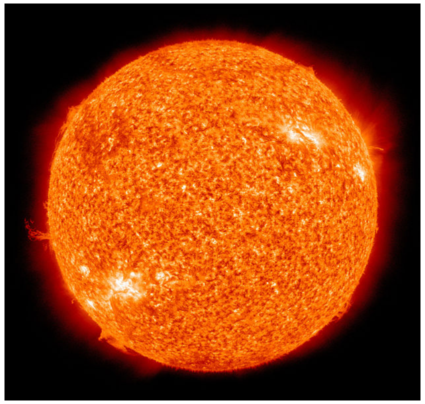
For sustained thermonuclear fusion, we need enough high-energy collisions of the fuel, that more heat is generated than is lost.

The Deuterium-Tritium reaction has the lowest energy peak in cross-section, but still requires T ~ 10keV (more than 100,000,000 K).

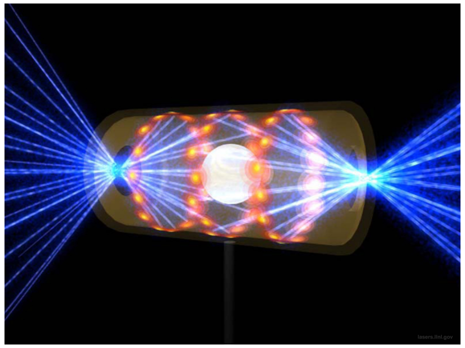
We need to keep the plasma really clean - any impurities radiate away all the energy, so no contact with solid materials is possible.

How can you hold 1 x 10^8 K without solid materials?

Gravity?



Inertia?



Magnetic Fields...

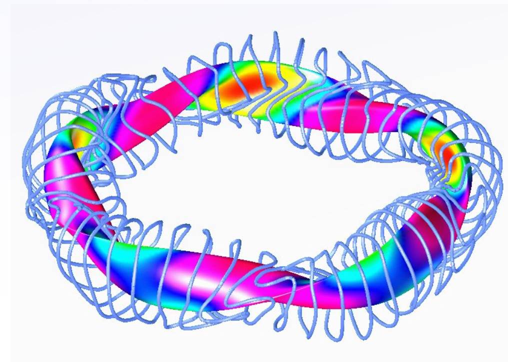
Magnetic Confinement

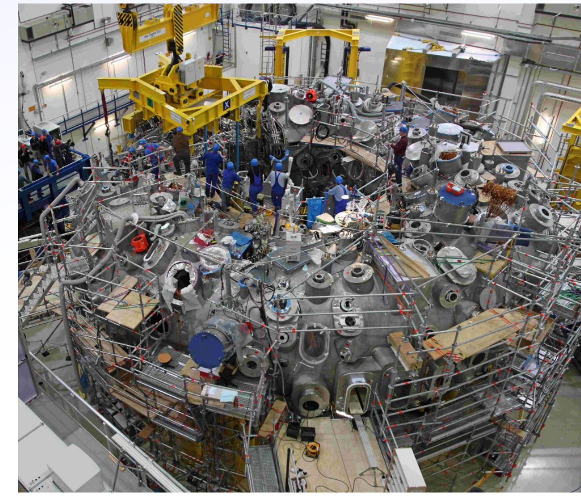
At this temperature, the fuels will be a fully ionised plasma, so we can use magnetic fields to confine them.

The electrons and plasma ions move freely along the magnetic field - so the field must be closed and never contact the walls.
It must be a torus and the magnetic field must be helical.

Currently two main approaches to do this:

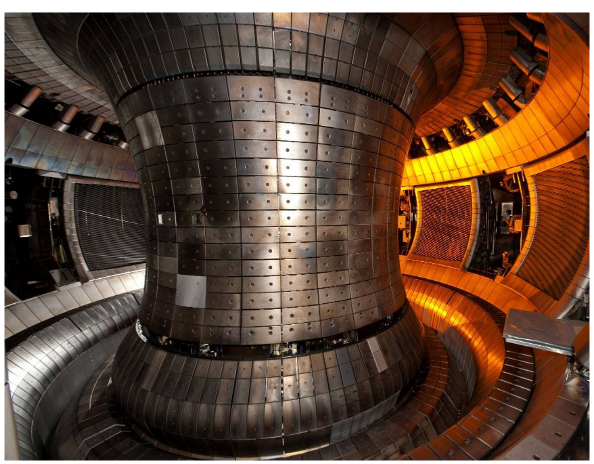
1) Stellarator:
External coils are complex twisted shapes to twist the plasma.



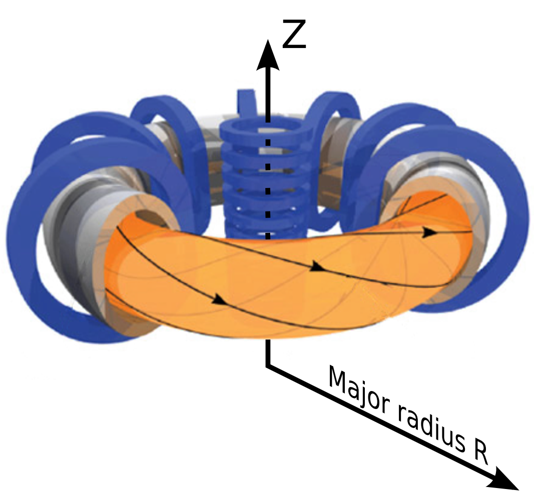


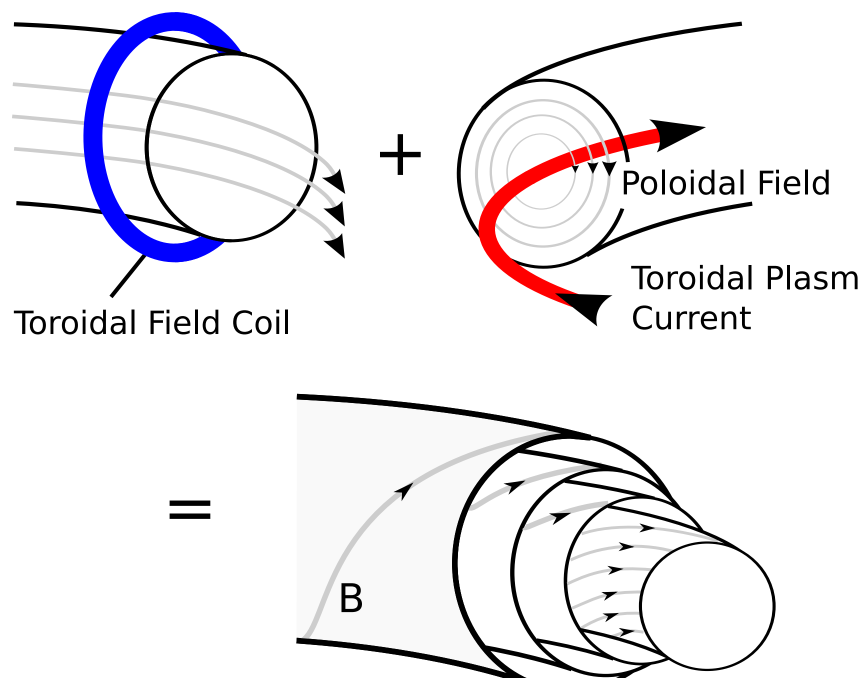
Wendelstein-7X (IPP Greifswald)

2) Tokamak:
External coils create a toroidal field and current is driven in the plasma itself (~ Mega amps), to make the poloidal field.

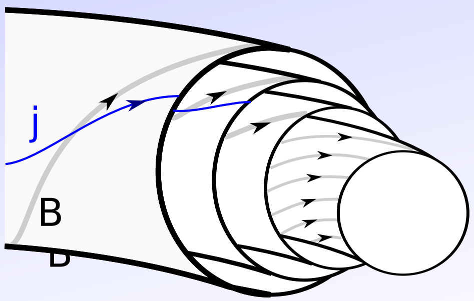


ASDEX Upgrade (IPP Garching)



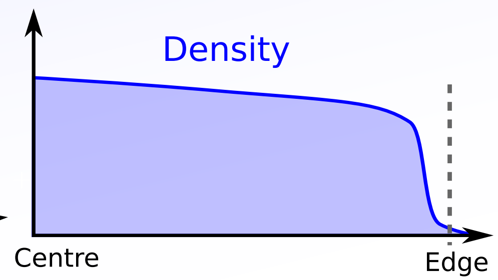


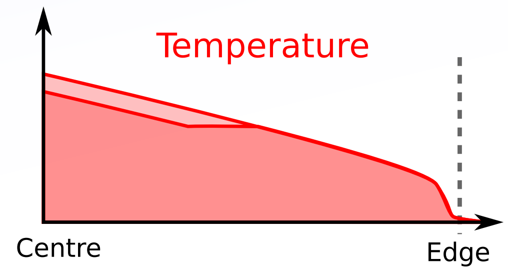
Magnetic Configuration

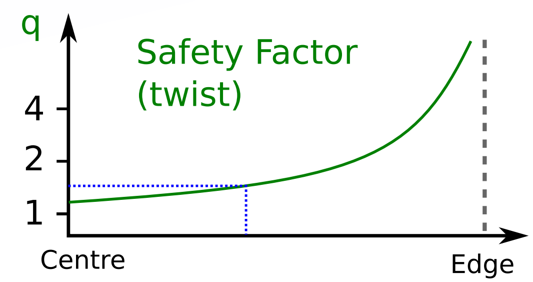


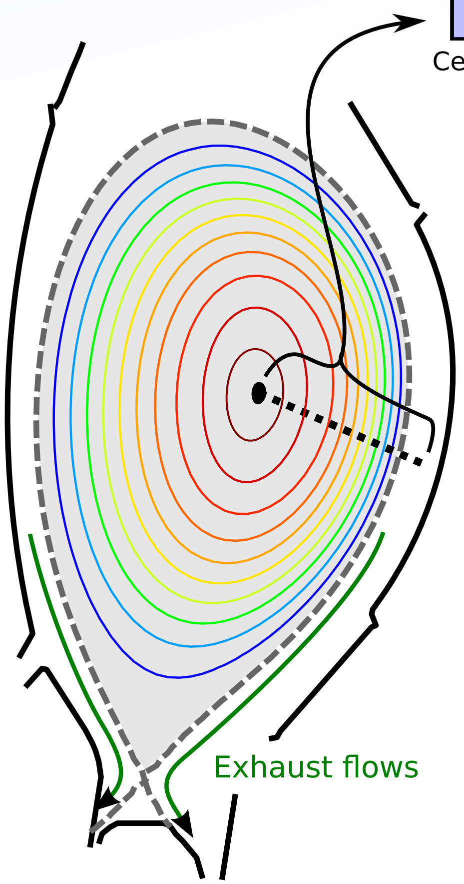
The current in the plasma is flowing through this field, and the Lorenz force must balance the pressure from the high temperature we are trying to confine, in a (hopefully stable) equilibrium.

$$j \times B = \nabla P$$



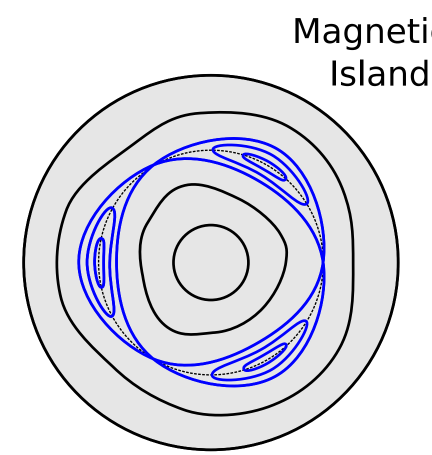






Temperature, density, current* etc are approximately equal around the magnetic surfaces, so knowing the magnetic configuration is vital for interpeting other diagnostics, in order to study the plasma confinement.

The twist of the surfaces is so important for the stability, that we call it the 'safety factor' q. Where q is rational, e.g. 3/2, the surface can break up into islands. This increases the transport, so lowers the core temperature, reducing the Fusion reaction rate. Large islands can also disrupt the plasma completely.



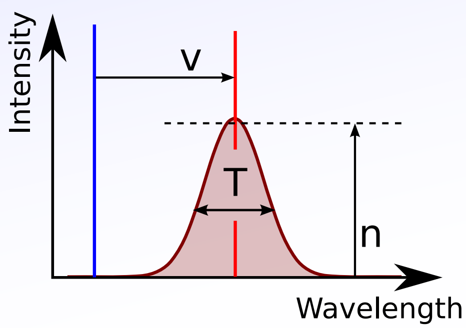
Recently, control systems have been developed that can drive current to remove the islands, but this requires knowing q accurately, in real-time.

* Toroidal current follows ~ f(1/R) + f(R) within each surface.

Fusion Diagnostics

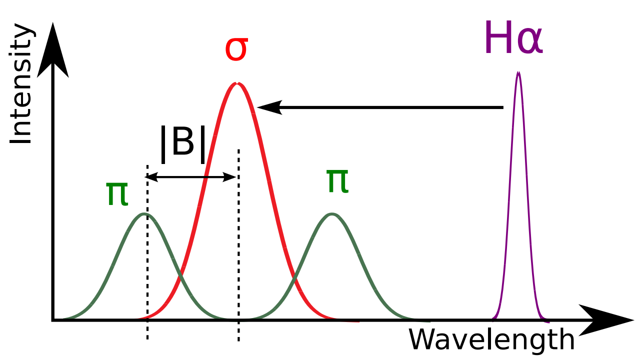
To measure the hot plasma core, we have to examine the emitted radiation and/or particles and use the plasma physics we learn to infer quantities of interest. For example:

Doppler Spectroscopy: Observe atomic line emission from neutral hydrogen, impurities or laser light scattered by plasma particles.

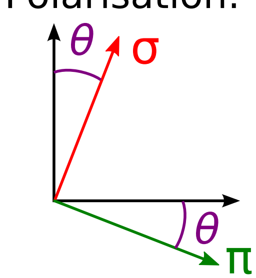


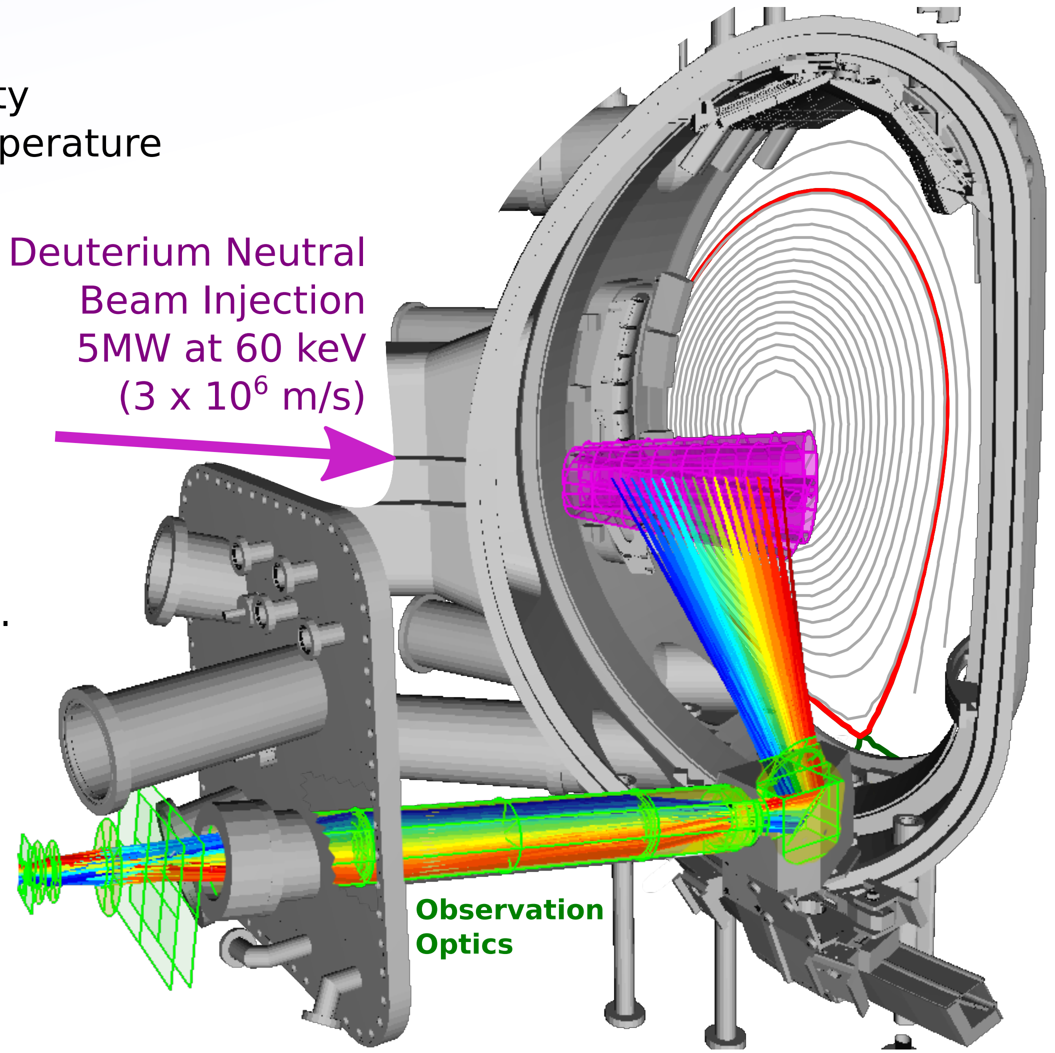
Intensity --> Particle density
Doppler shift --> Bulk velocity
Doppler broadening --> Temperature

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:



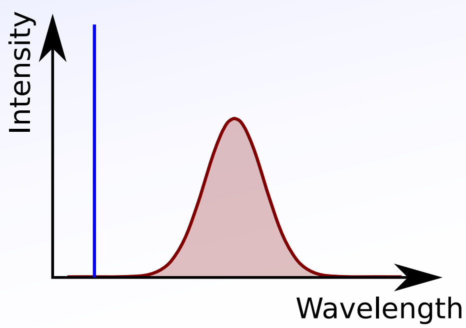


ASDEX Upgrade Vacuum Vessel

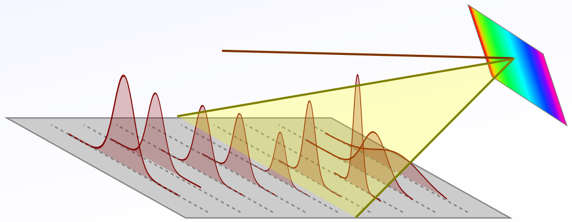
Traditional Systems

Existing systems typically have lots of complex hardware per spatial point:

Doppler Spectroscopy:



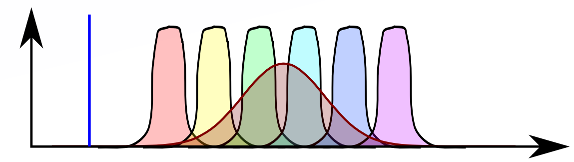
Diffraction grating and CCD camera, or individual detectors (PMTs/APDs)



Low light levels. 1D set of points.

or

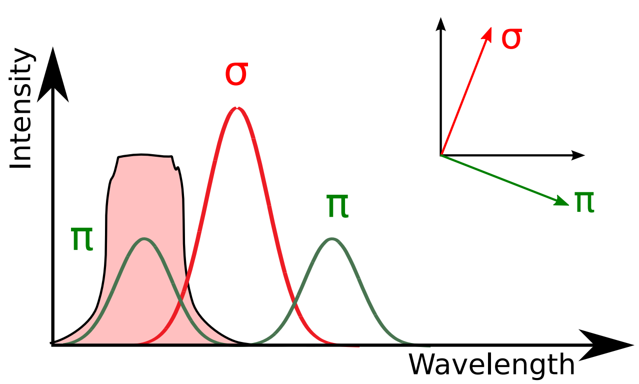
Individual spectral filters and fast sensitive detectors.

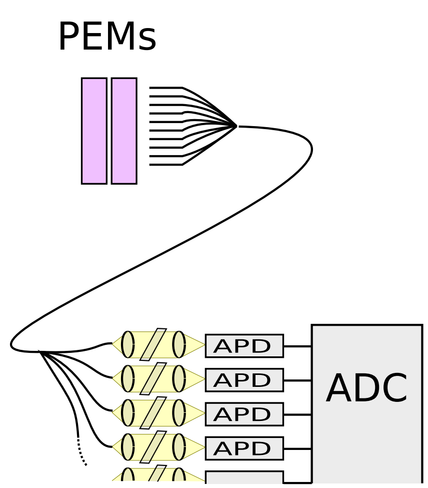


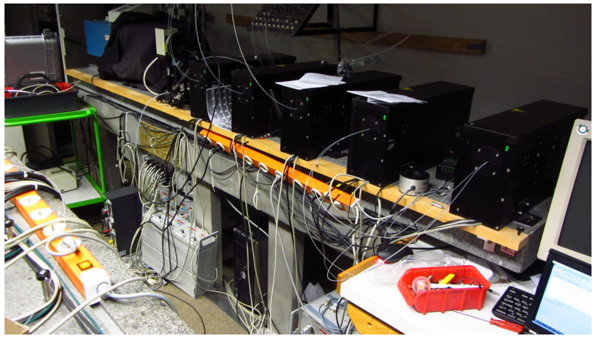
Very complex setup per channel.
Low spectral resolution.

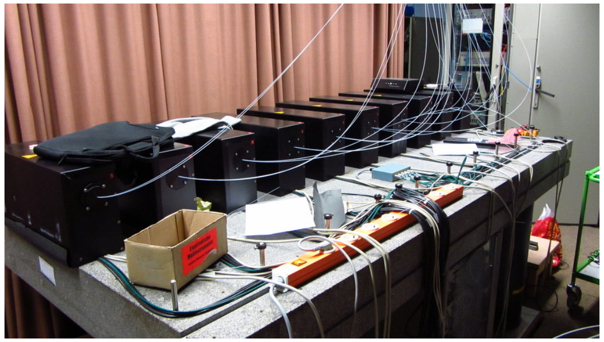
Polarimetry:

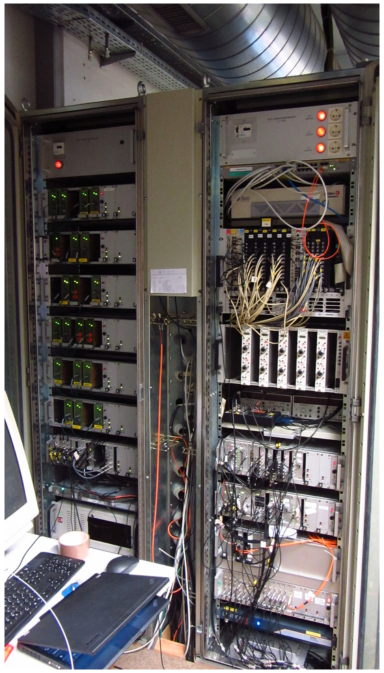
Motional Stark Effect is usually done with a Photo-elastic modulator (PEM - an acoustically excited crystal) and individually tuned inteference filters for each measurement (up to ~50).





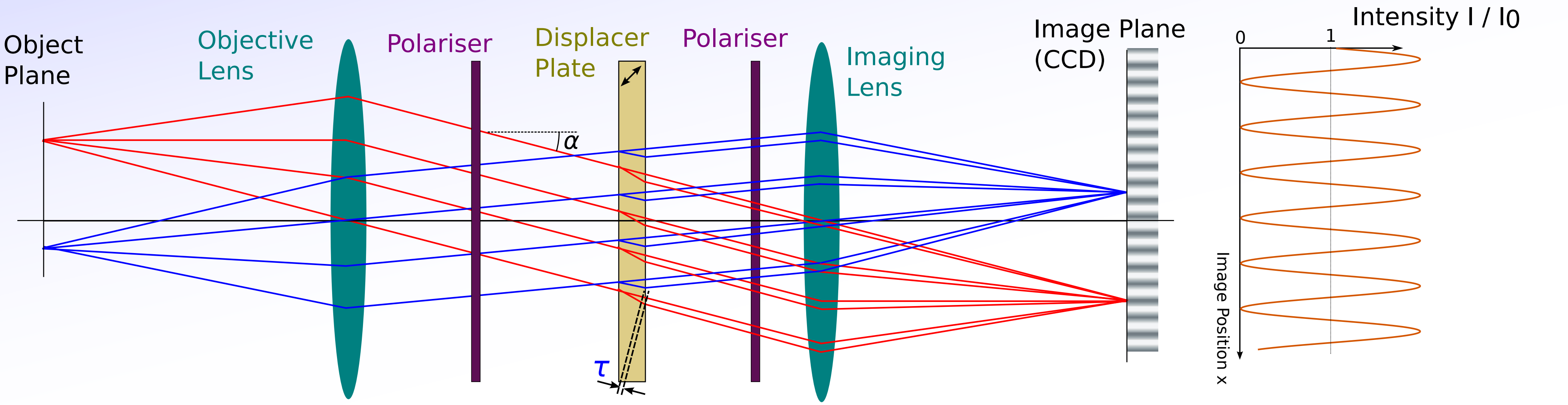


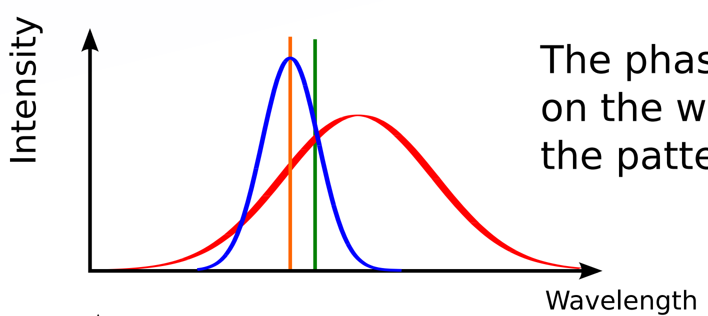




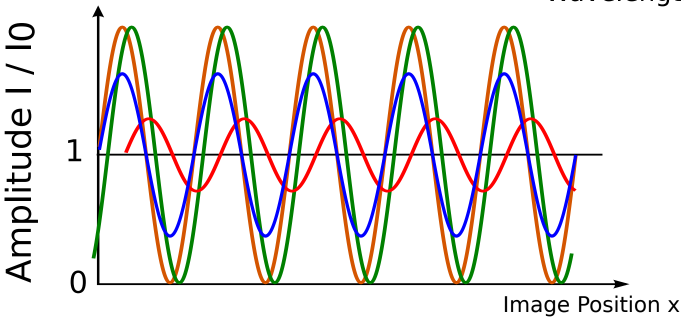
Coherence Imaging

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.

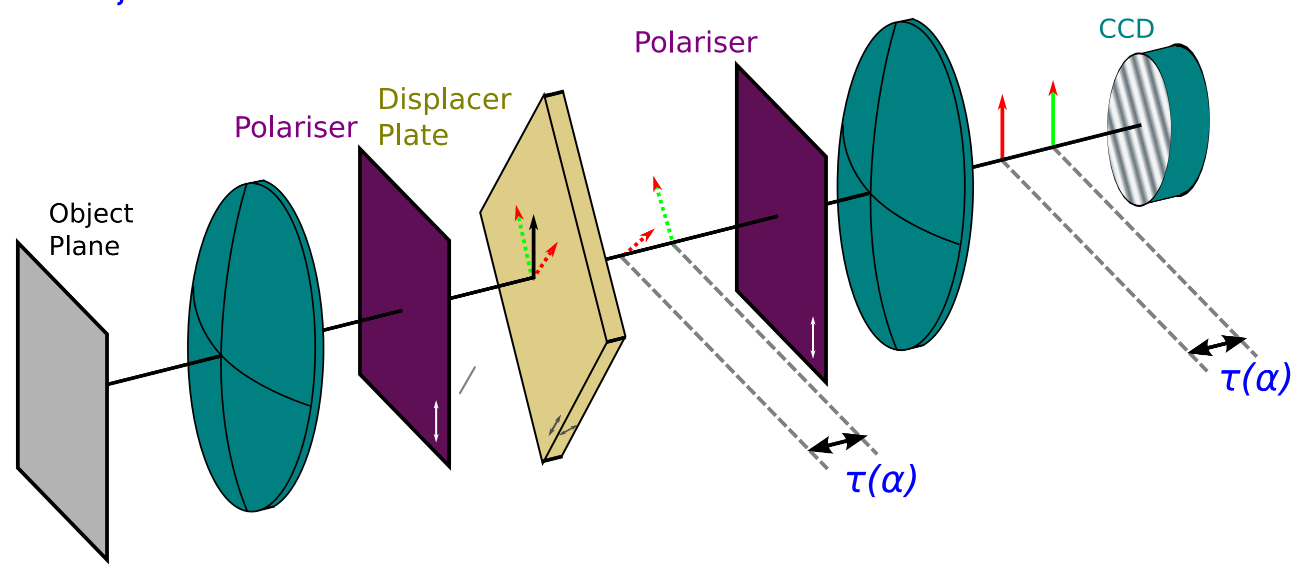




The phase of the interference pattern depends on the wavelength $\Delta\omega$. With multiple wavelengths, the pattern contrast ζ is reduced.



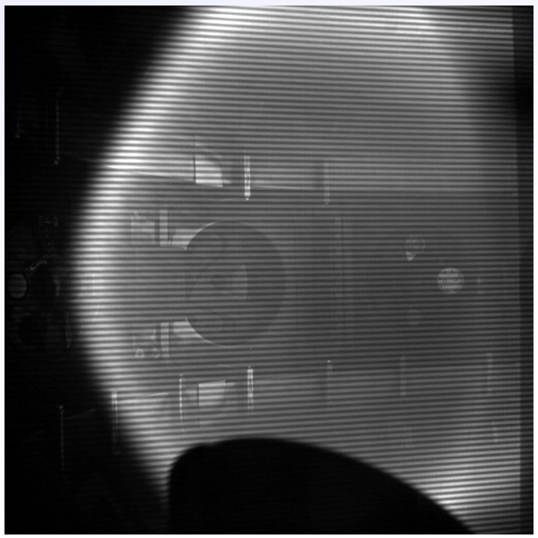
$$I \propto 1 + \zeta\, cos((\omega + \Delta\omega)x)$$



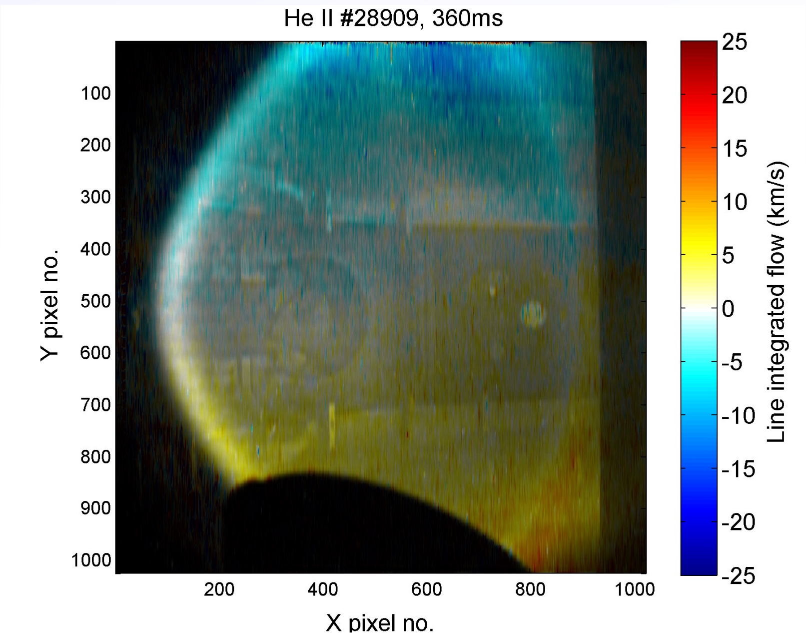
Doppler Coherence Flow Imaging - MAST

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

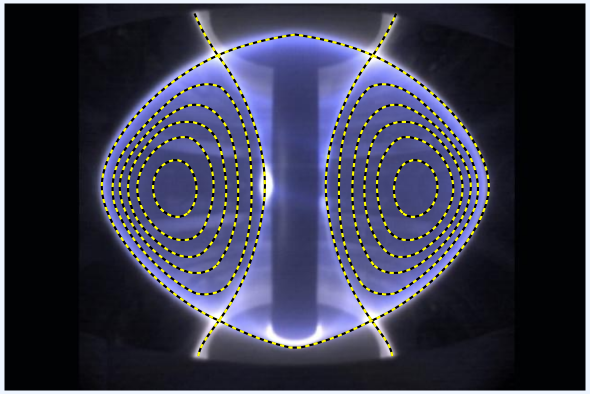
Raw Image:



Helium Flow Velocity:



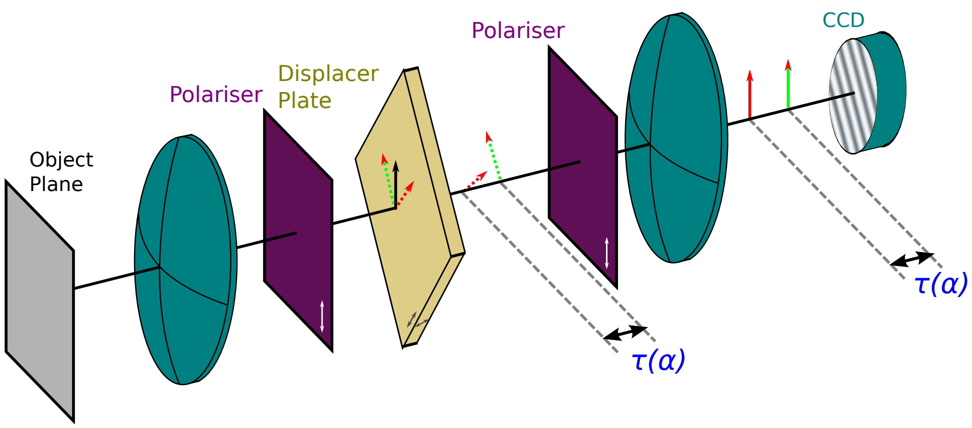
MAST
Mega Amp Spherical Tokamak,
CCFE, Culham, UK



MAST is a 'sphereical' 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]

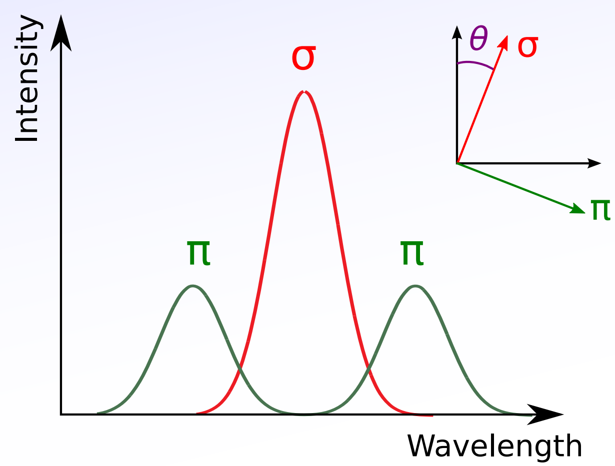


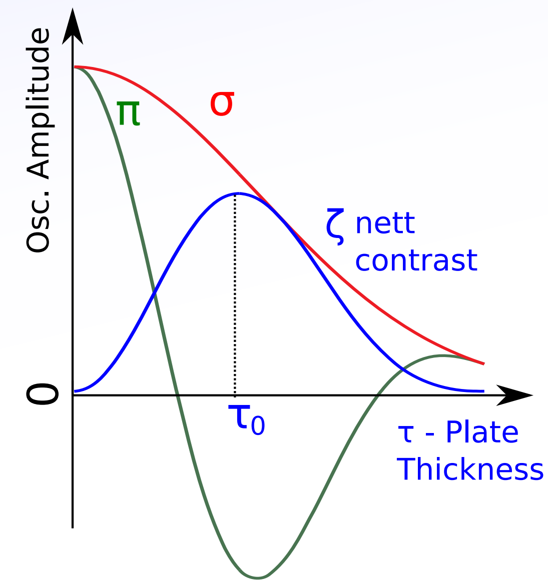
Multiplet Polarisation Coherence Imaging

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

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

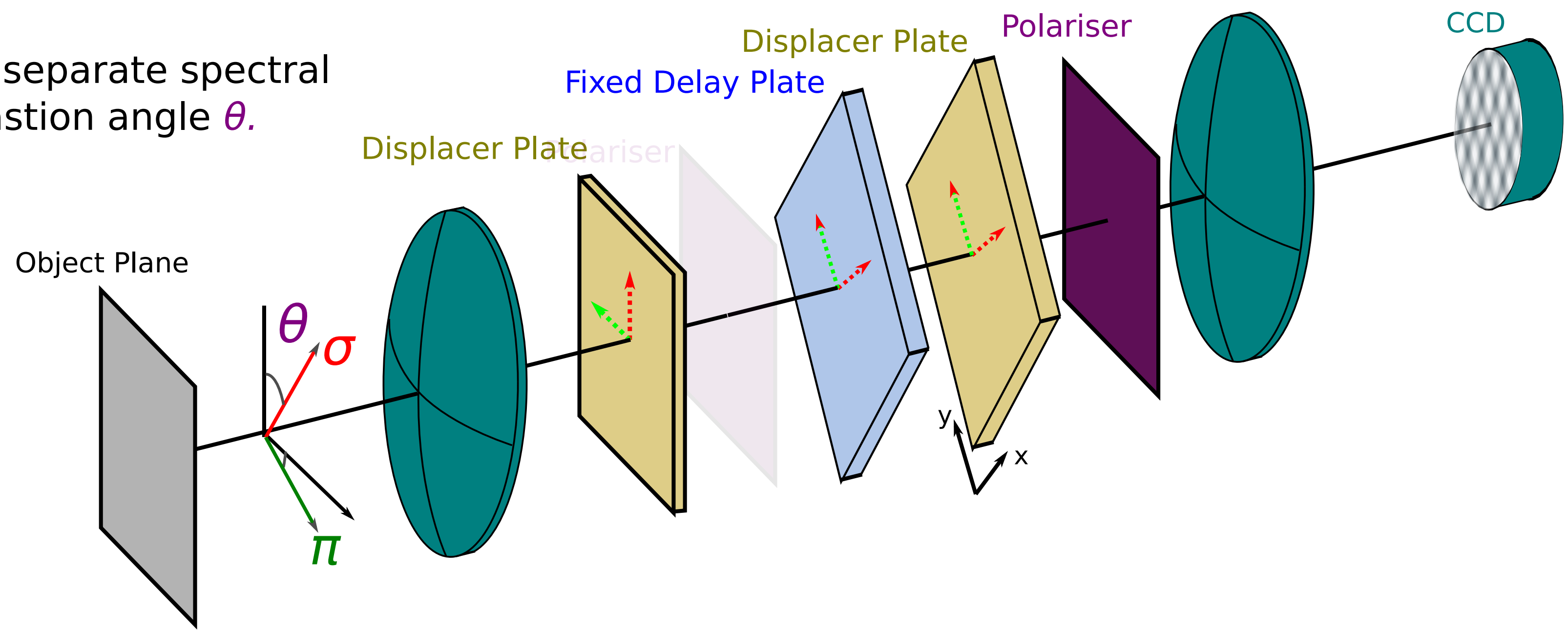
For the Stark/Zeeman spectrum, the π component is at 90° to σ, introducing a 180° phase shift, so they would cancel.





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.



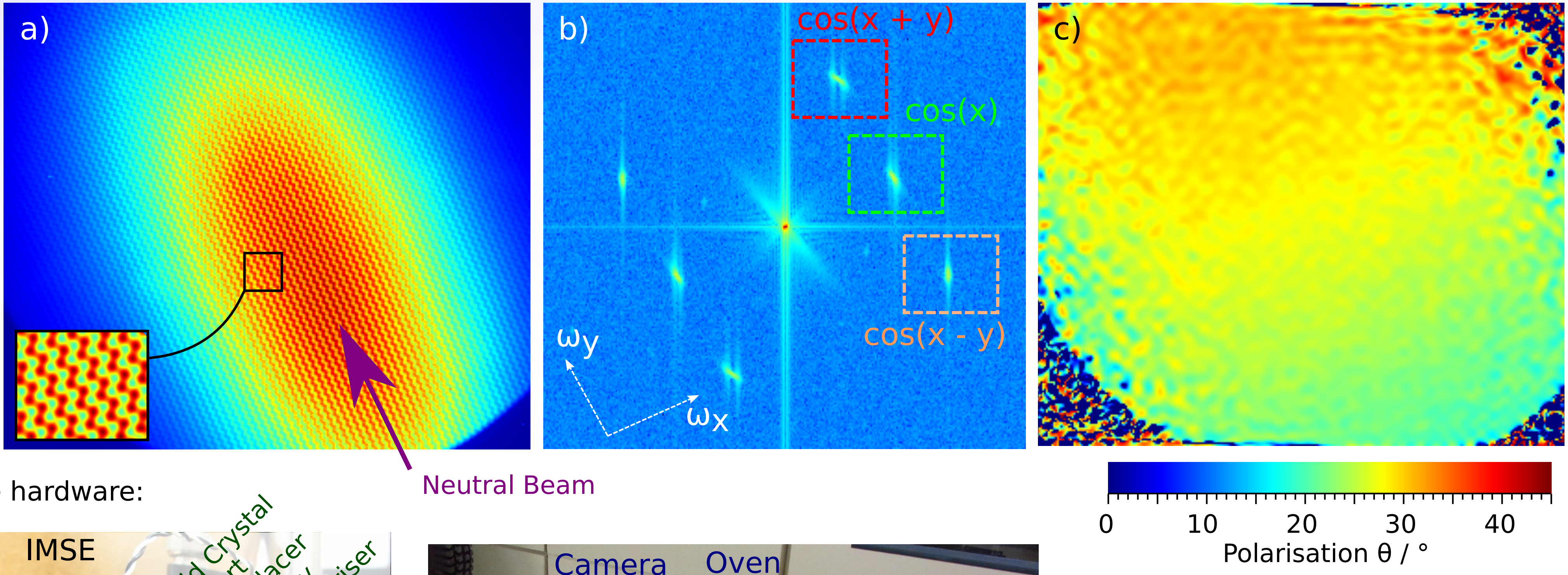
add another displacer at 45°. Combined effect adds 2 extra terms:

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

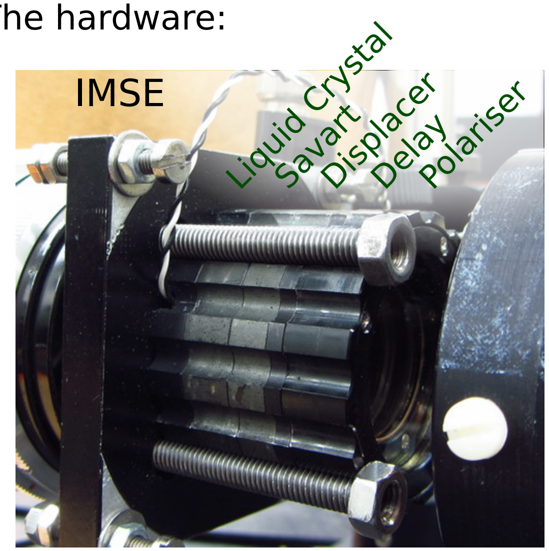
Image Demodulation

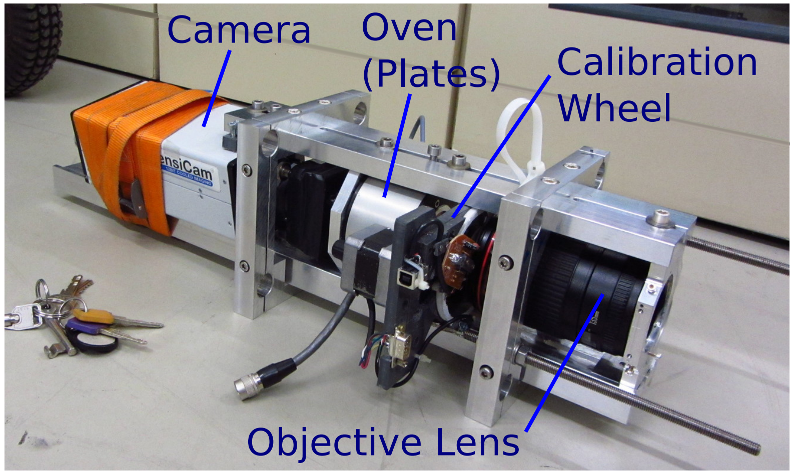
The two orthogonal interference patterns give 3 components in the Fourier transform. We can filter these from the FT and extract the polarisation angle θ:

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



The hardware:



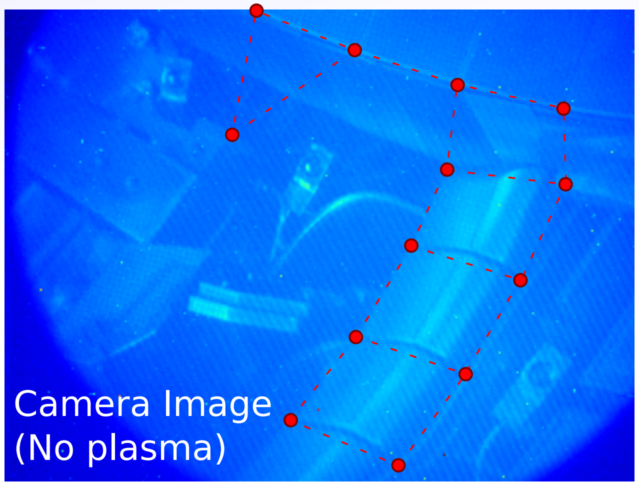


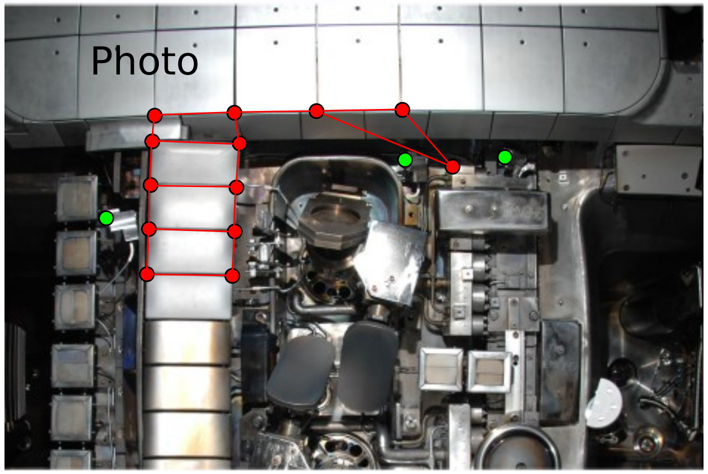
Position Calibration

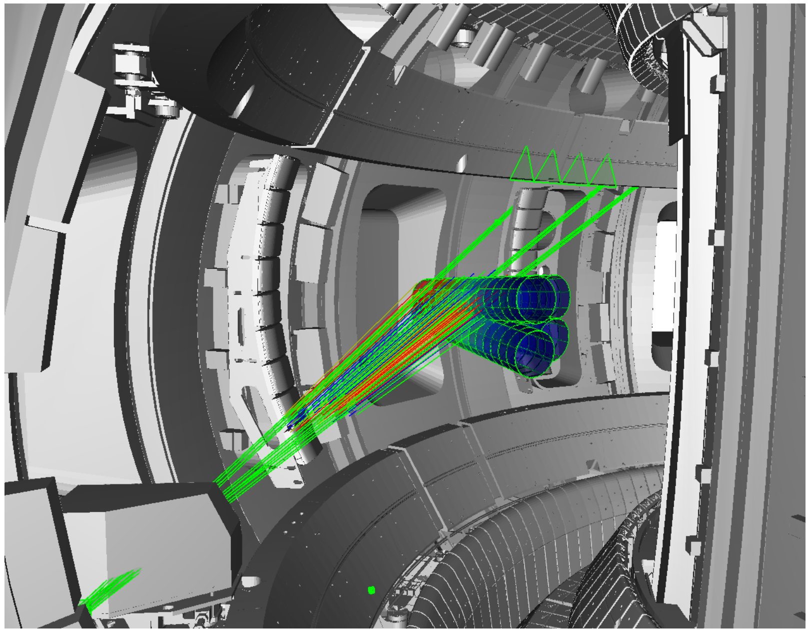
Access inside the Tokamak is rare (~once per year) so diagnostic calibrations are bet avoided.
The imaging nature of the CIS systems allow easy position calibration by identifying known features in a background image and calculating the lines of sight from them.

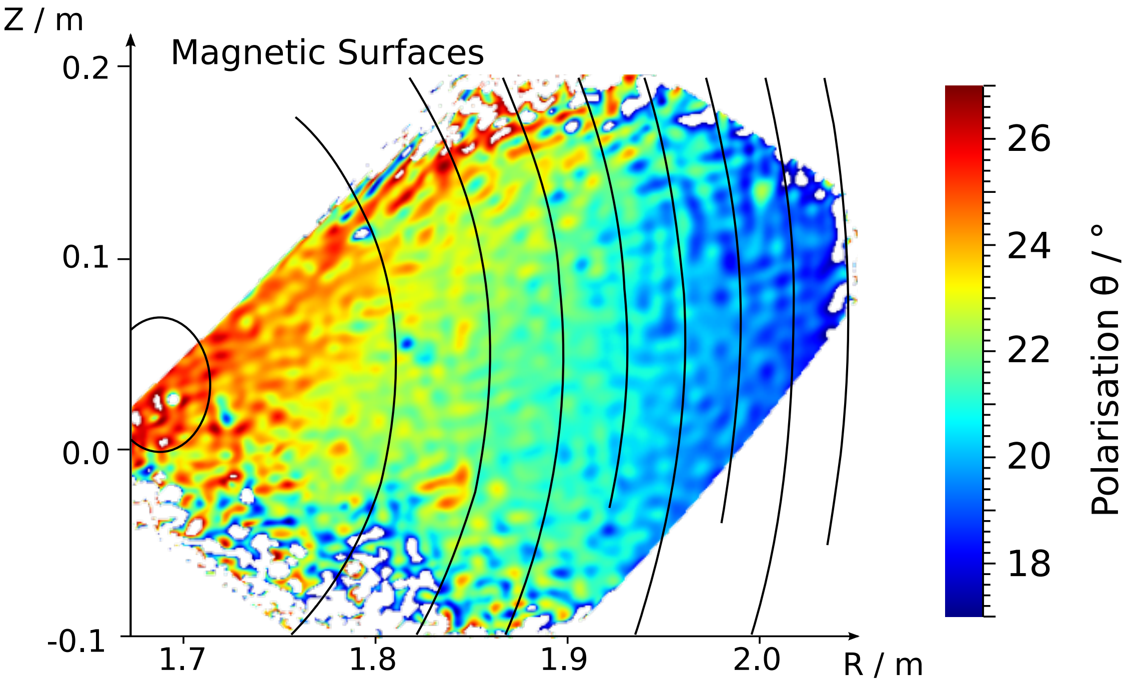
For the IMSE, we are interested where our view lines intersect the injected neutral beam:

The IMSE has required no torus access to calibrate (so far).





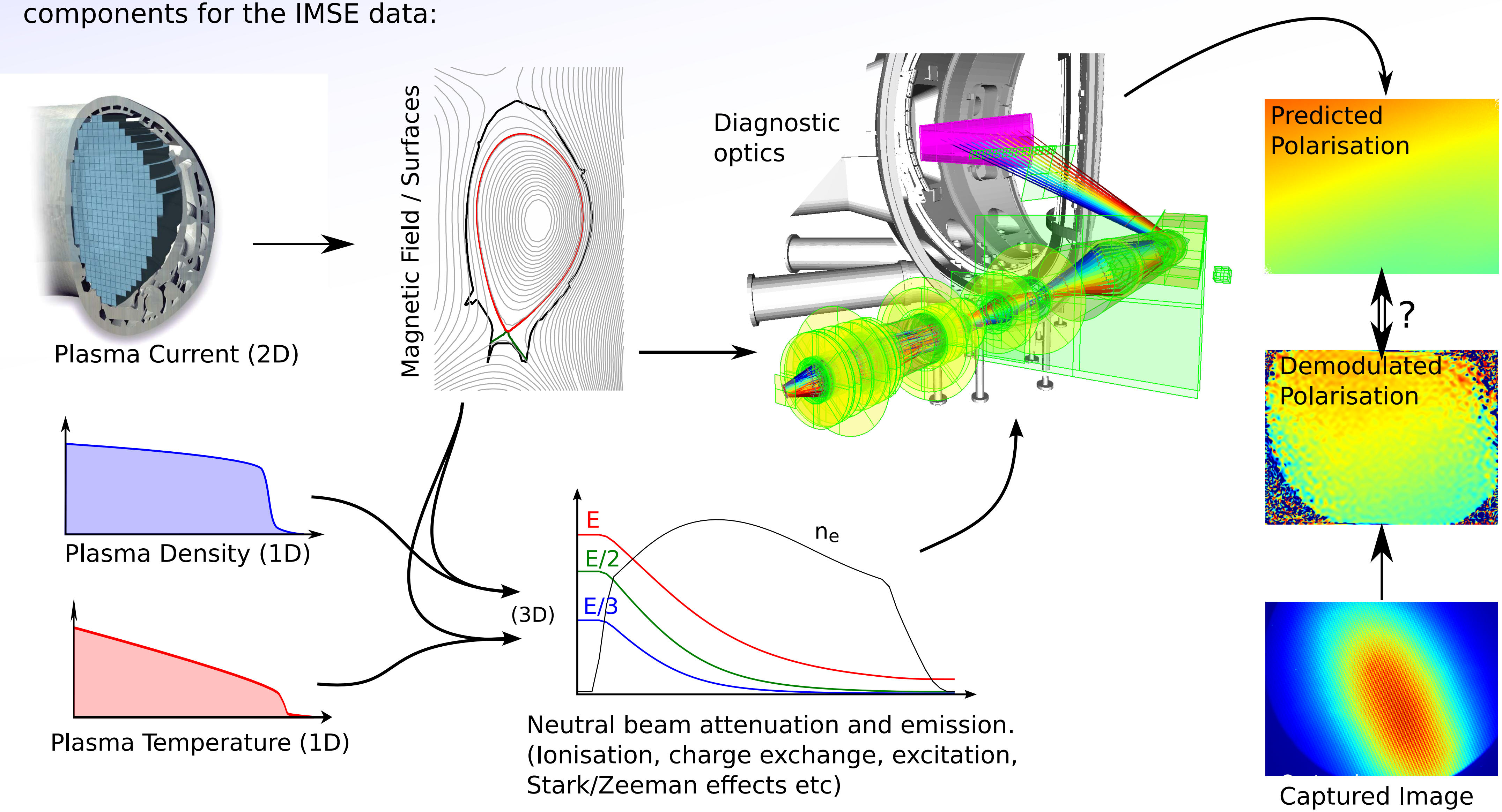




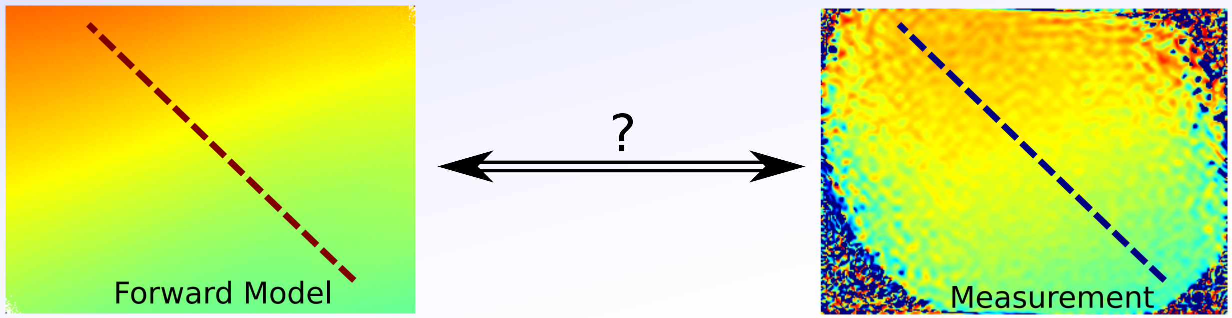
Analysis - Forward Modelling

Videos are nice, but we also need to do some quantitive analysis of the data. The observed polarisation is a very complex function of the magnetic and electric fields, the neutral beam injection, the atomic/quantum physics of the Stark emission and the diagnostic optics.

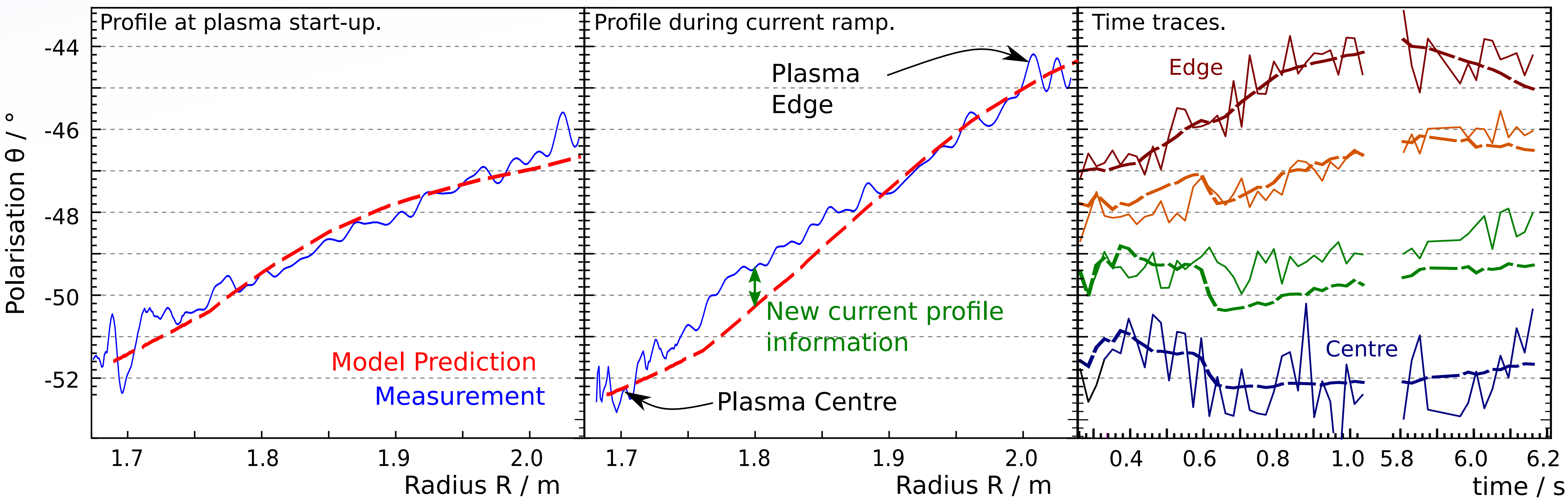
We have a highly detailed modular forward modelling system for the entire plasma, to which we added components for the IMSE data:



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.