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

Technische Universität Berlin, November 2013

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

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.

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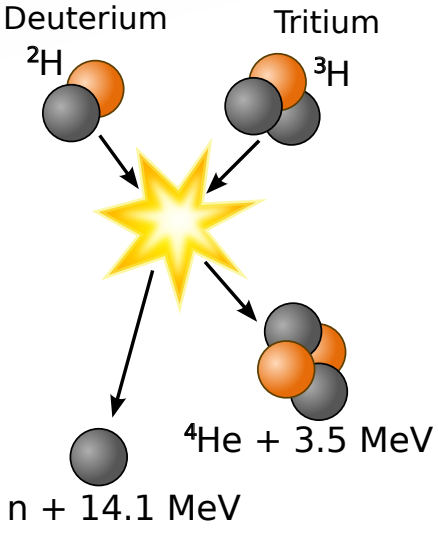

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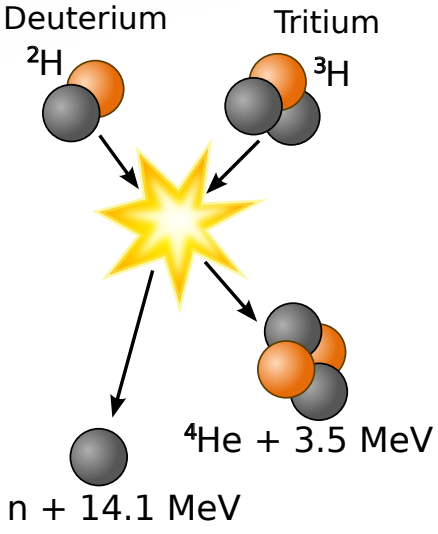

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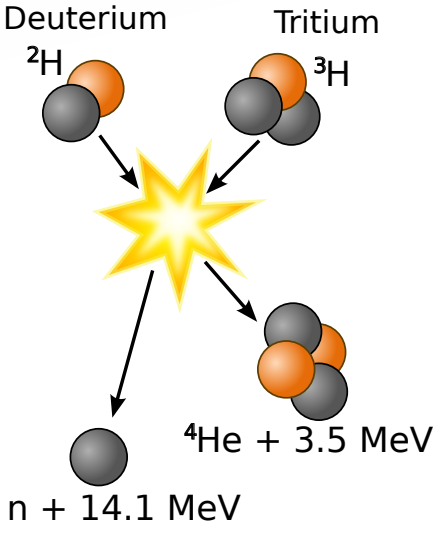

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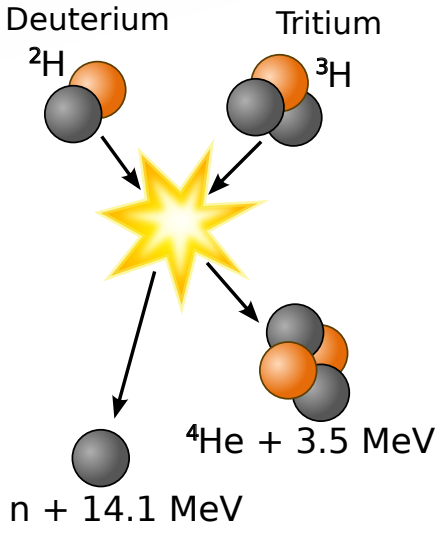

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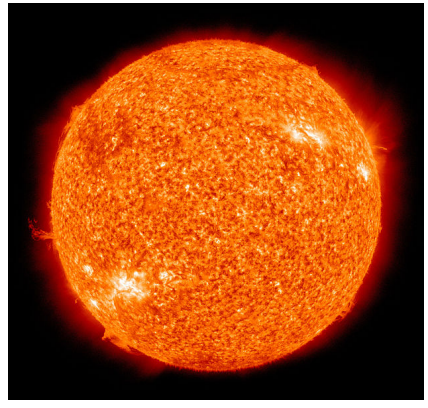
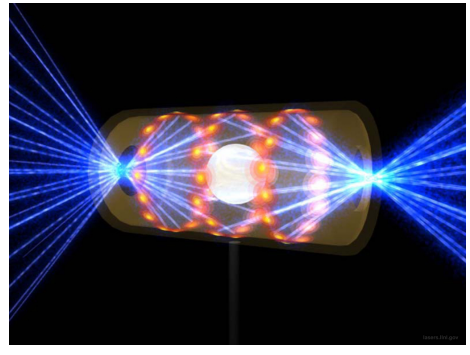


Inertia?



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.

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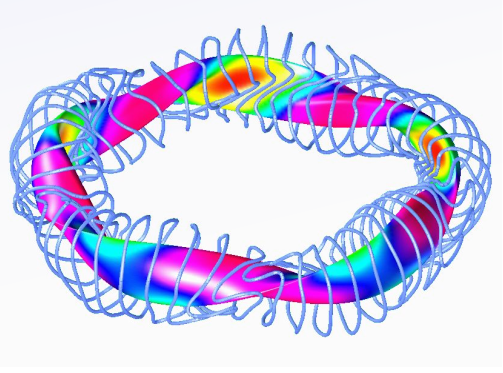

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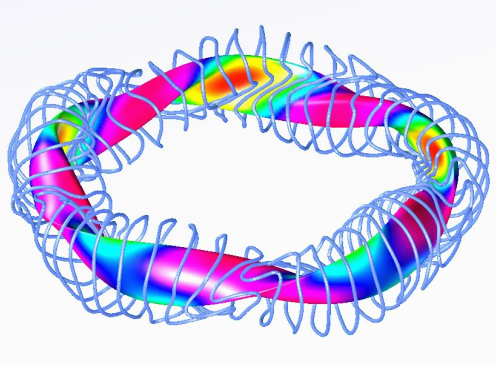

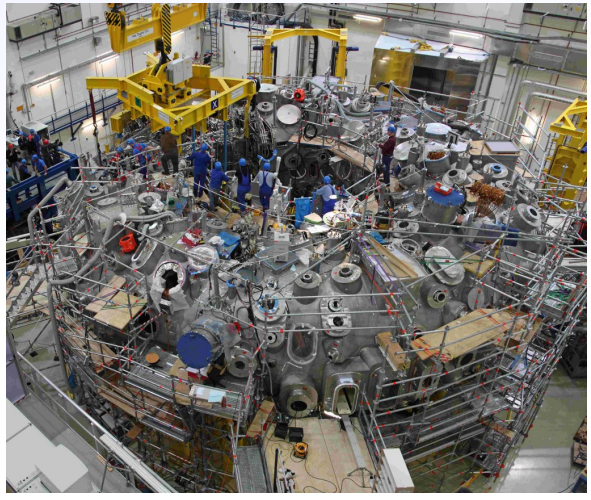

Wendelstein-7X (IPP Greifswald)

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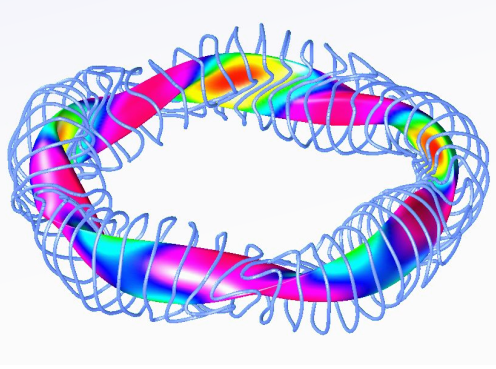

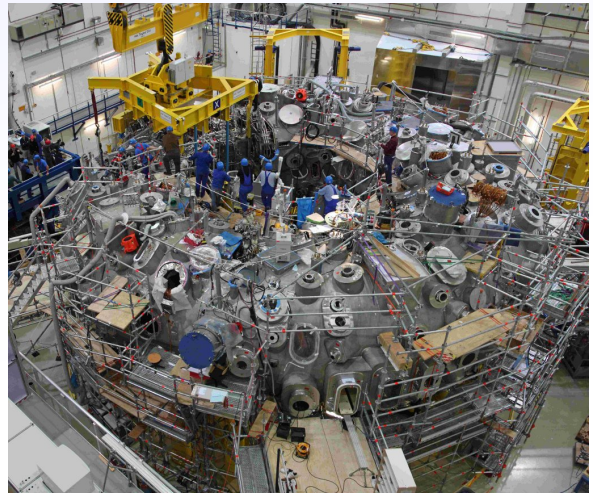

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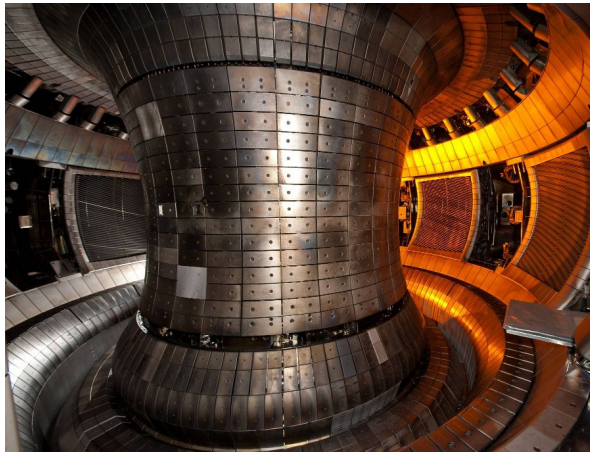

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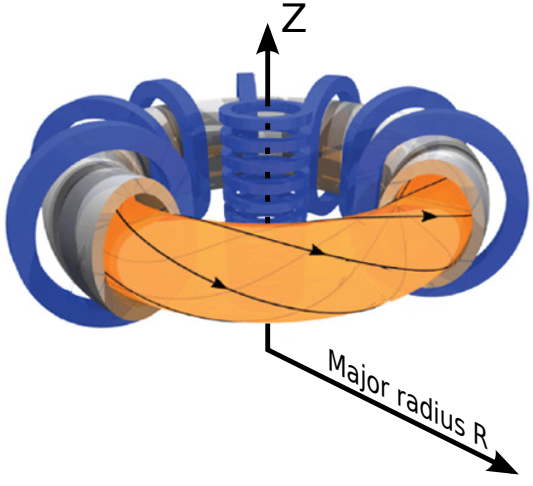

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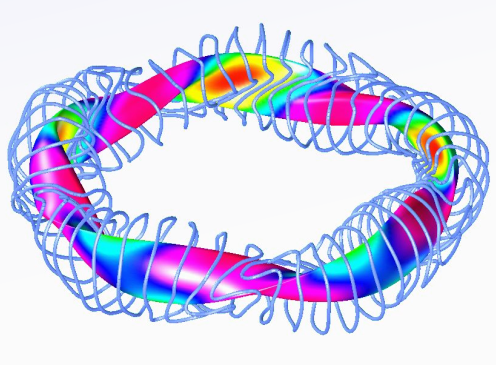

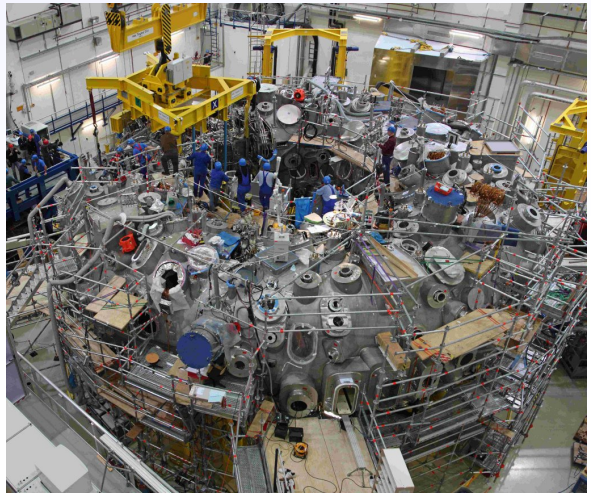

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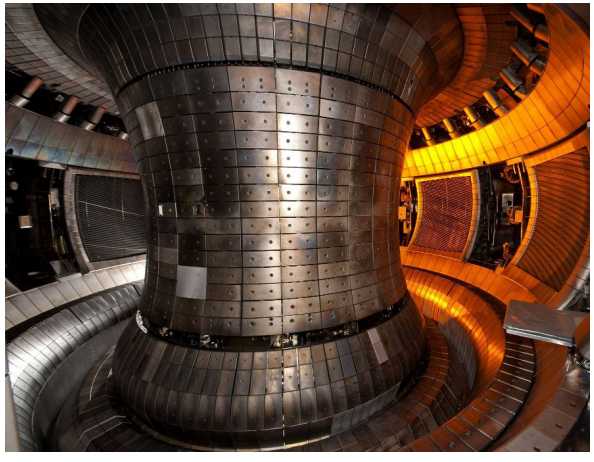

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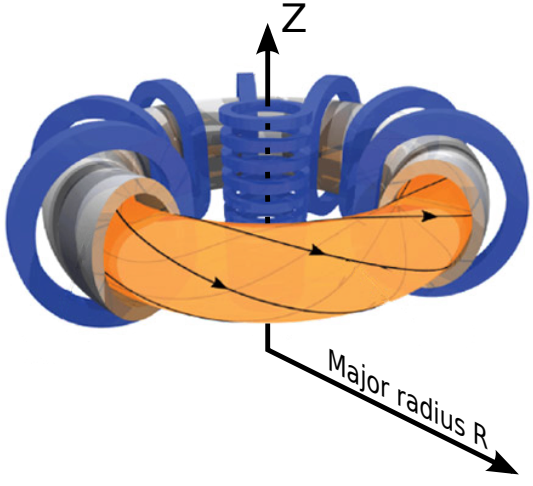

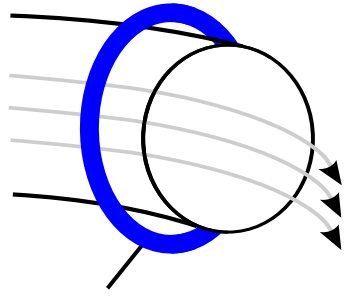

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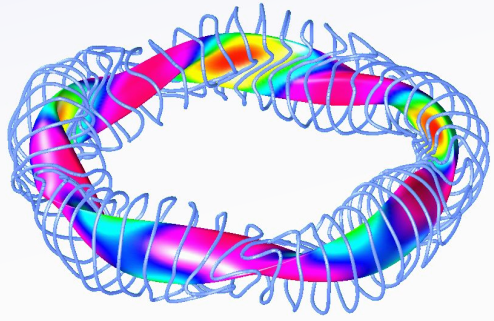

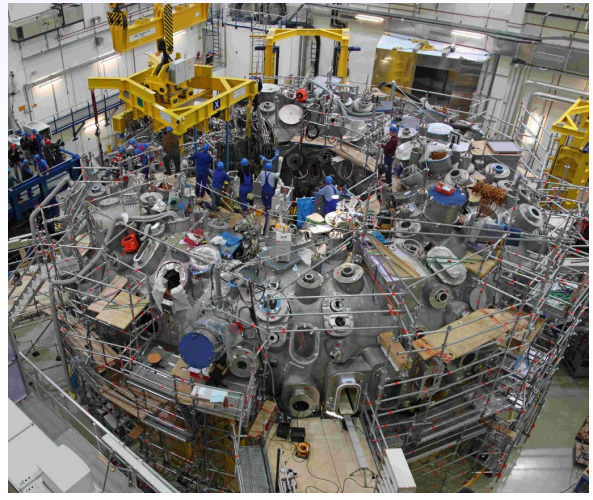

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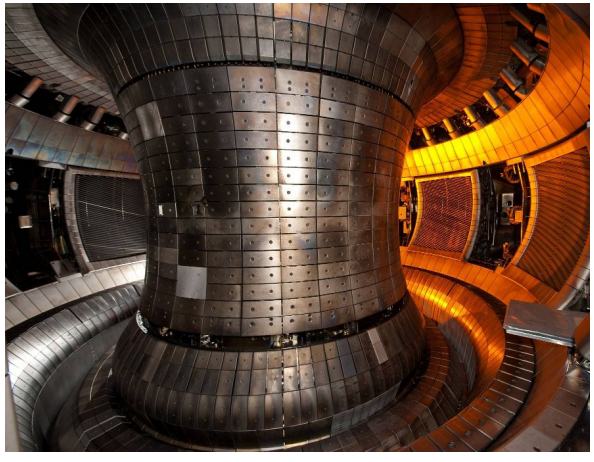

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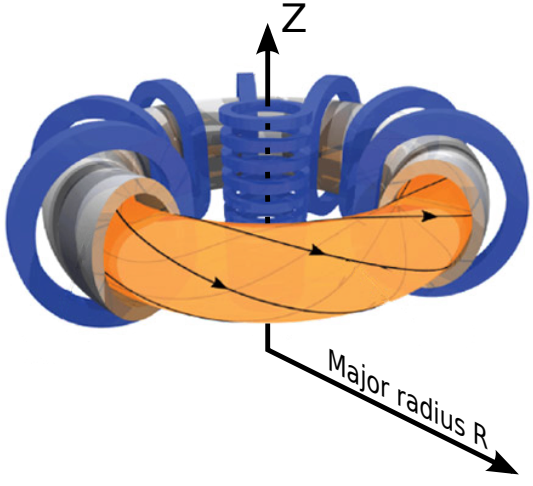

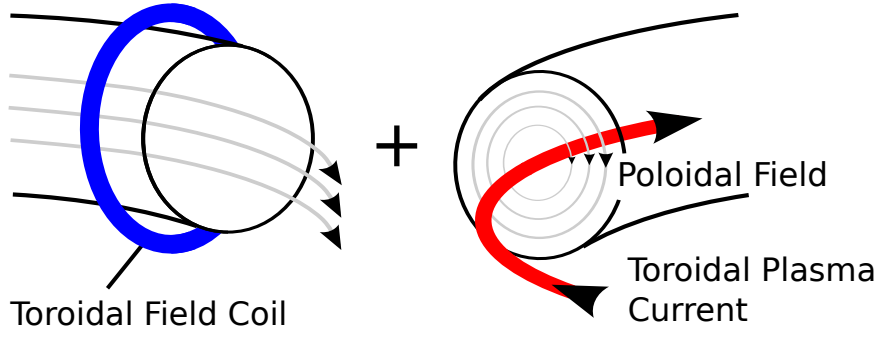

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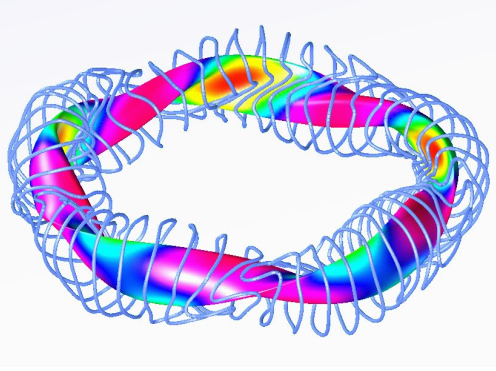

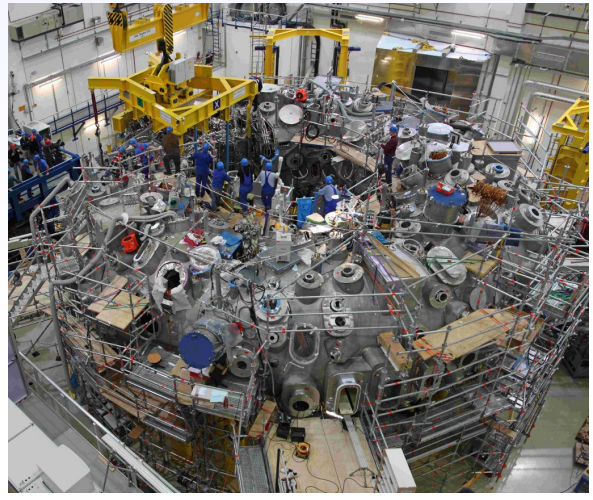

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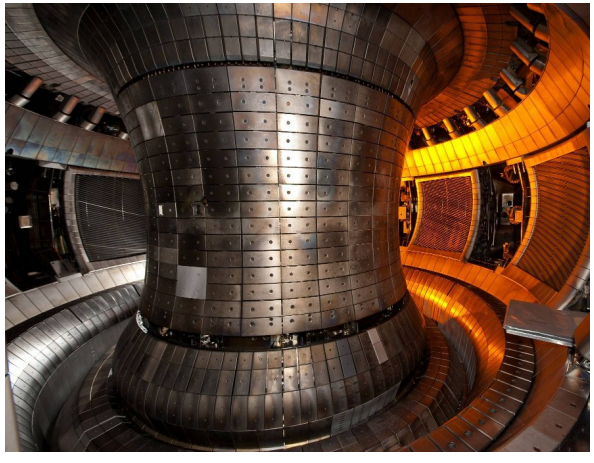

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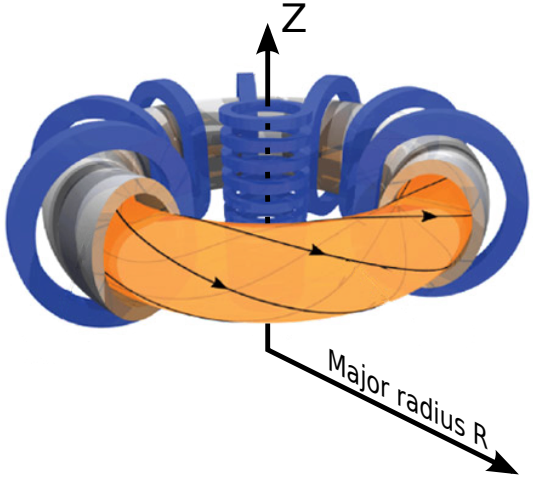

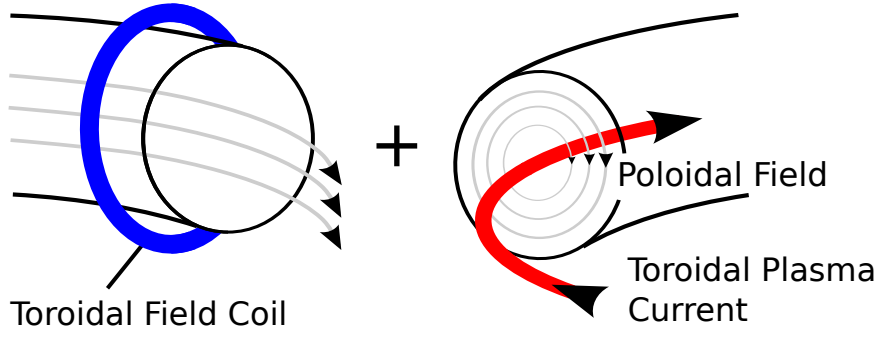

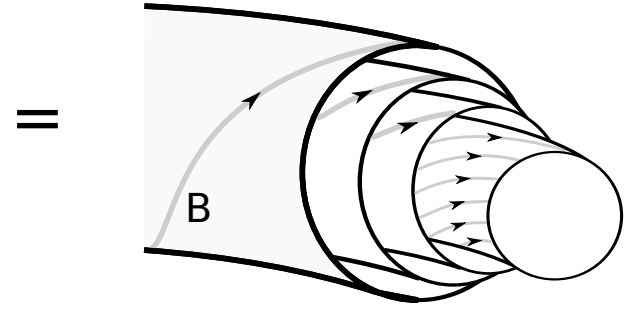

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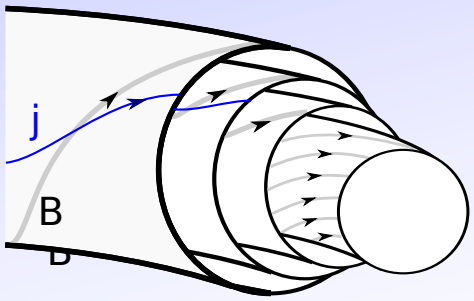

The current in the plasma is flowing through this field, and the Lorenz force must balance the pressure from the high temperature we are trying to confine, in a (hopefully stable) equilibrium.

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

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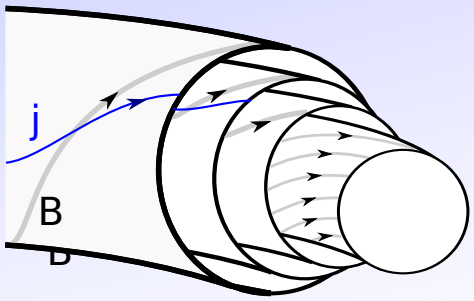

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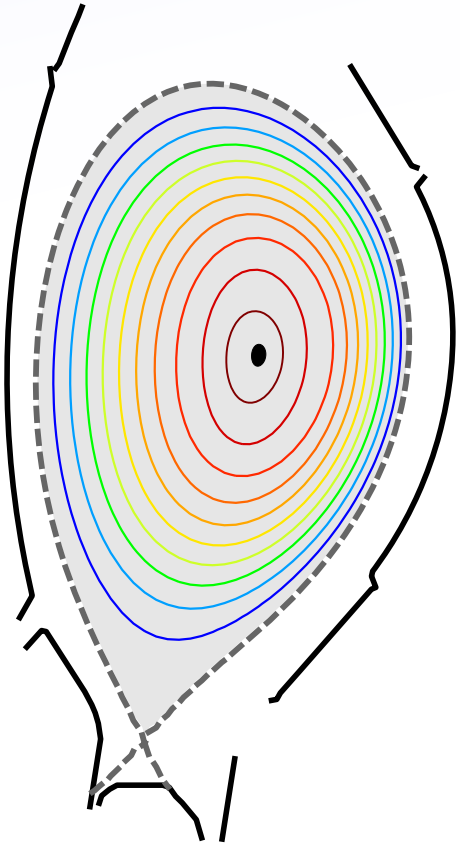

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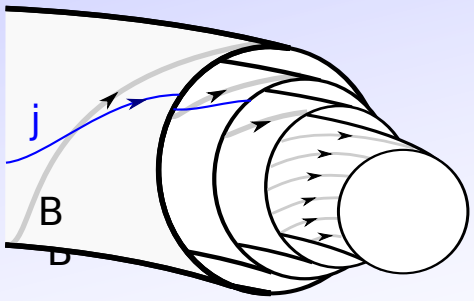

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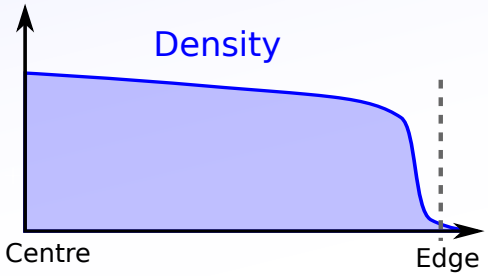

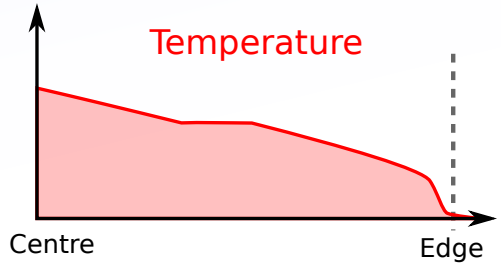

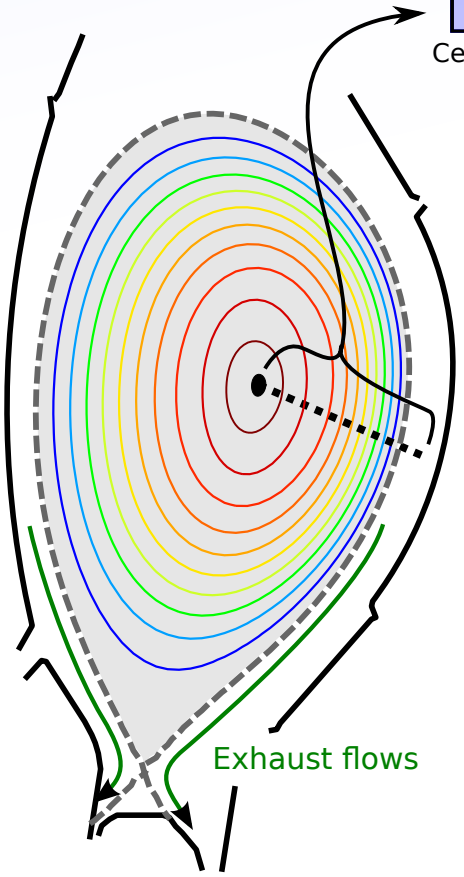

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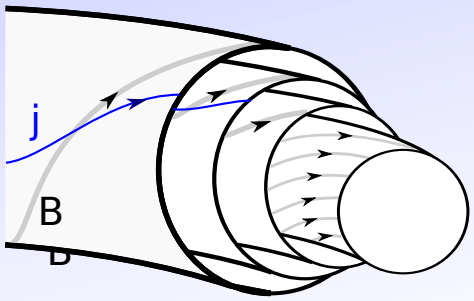

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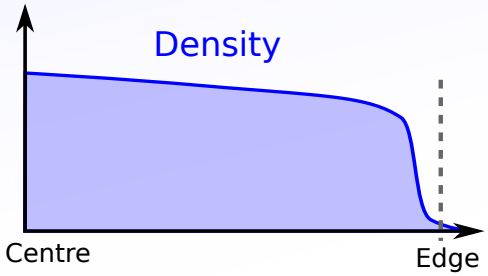

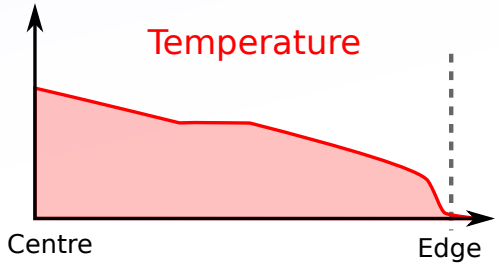

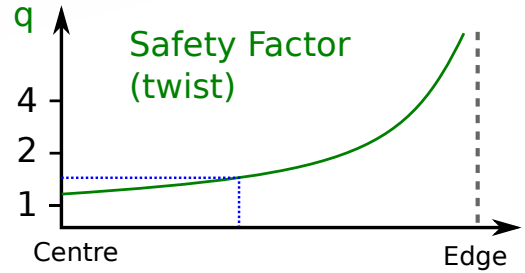

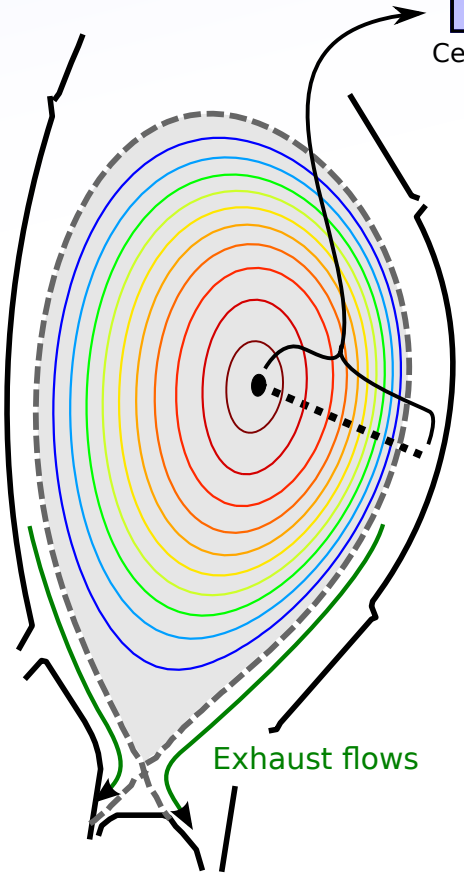

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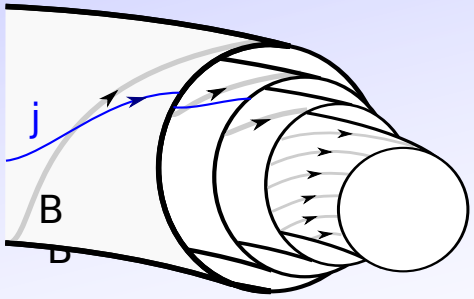

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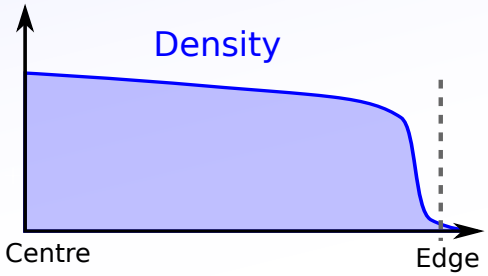

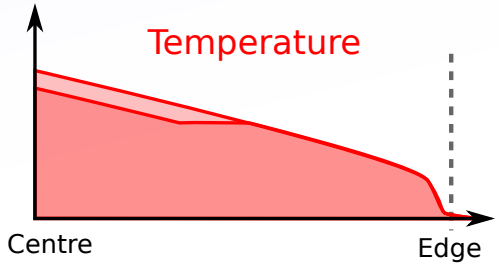

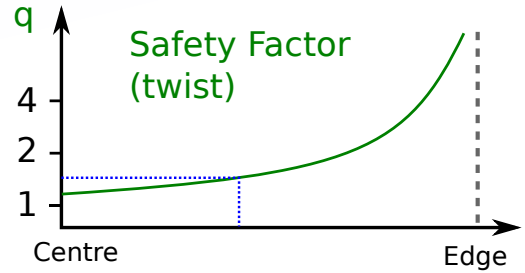

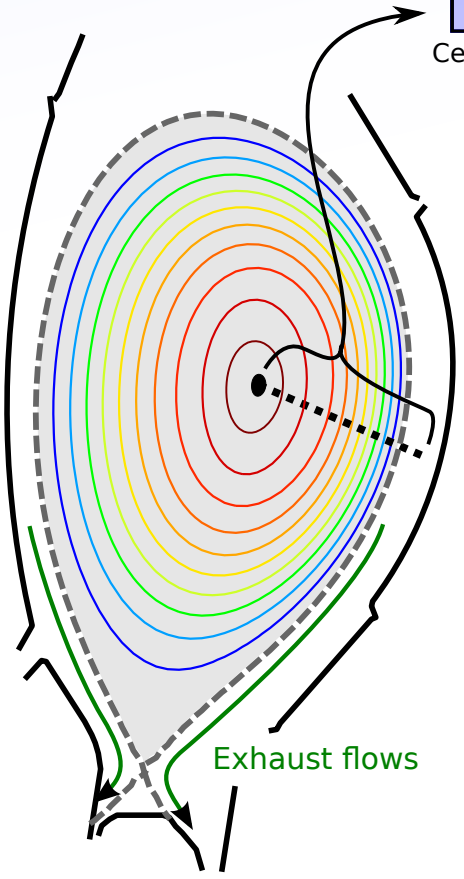

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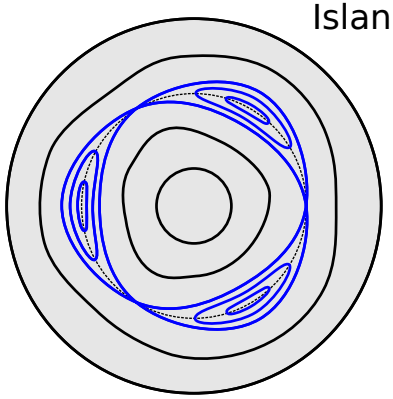
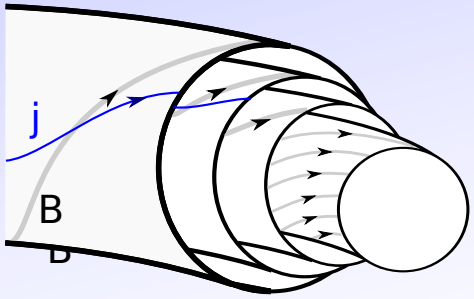
The twist of the surfaces is so important for the stability, that we call it the 'safety factor' ***q***. Where ***q*** is rational, e.g. 3/2, the surface can break up into islands. This increases the transport, so lowers the core temperature, reducing the Fusion reaction rate. Large islands can also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

Magnetic Islands



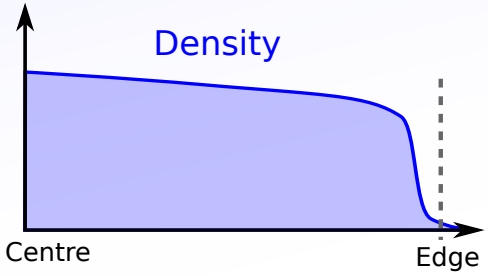
* Toroidal current follows ~ f(1/R) + f(R) within each surface.

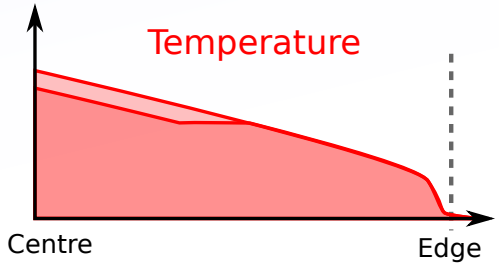
Magnetic Configuration

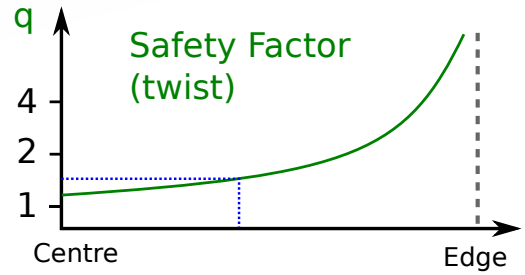


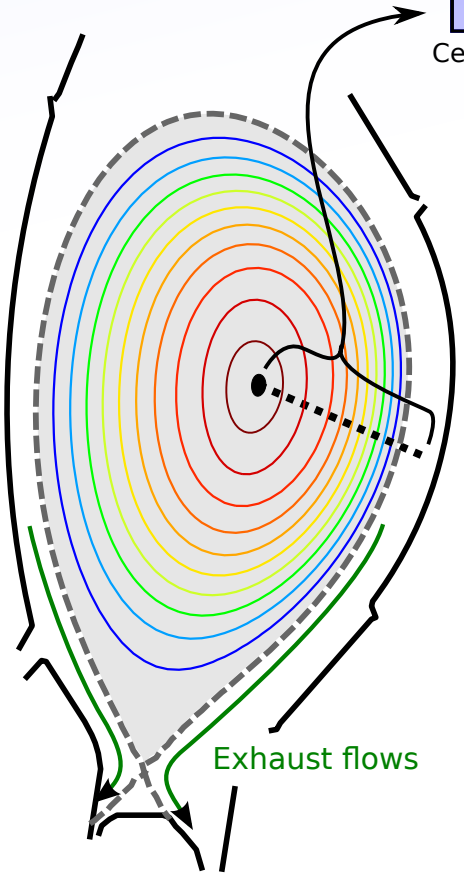
The current in the plasma is flowing through this field, and the Lorenz force must balance the pressure from the high temperature we are trying to confine, in a (hopefully stable) equilibrium.

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









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

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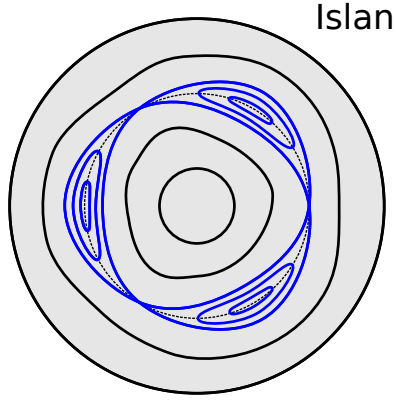

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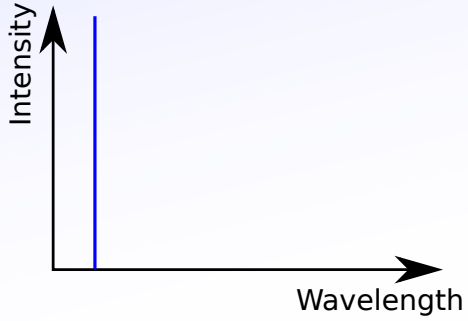

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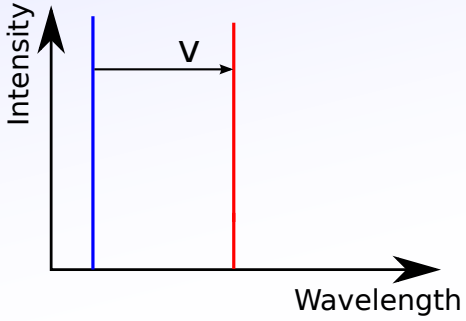

Doppler shift --> Bulk velocity

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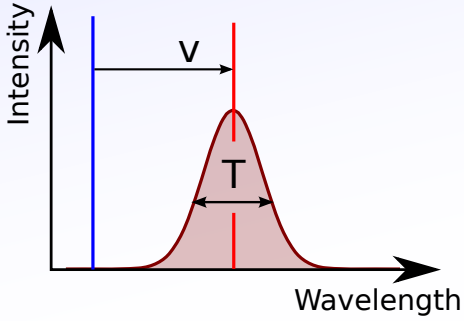

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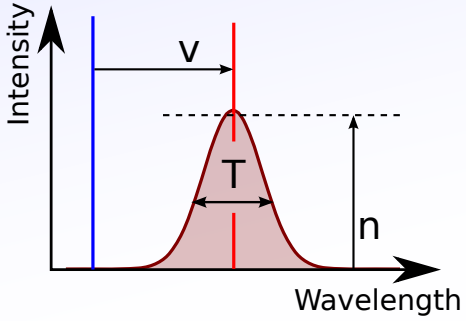

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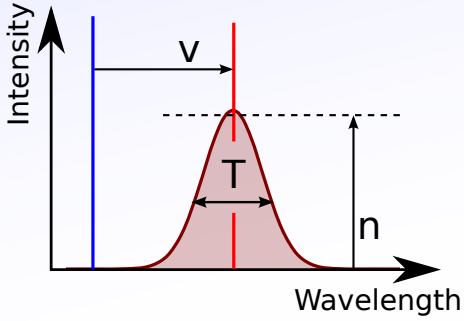

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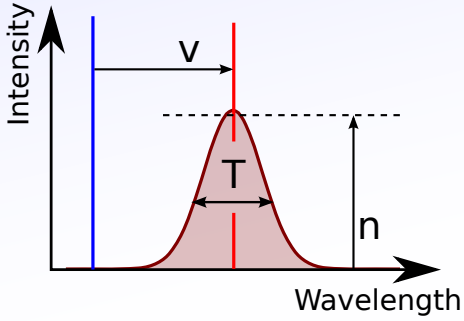

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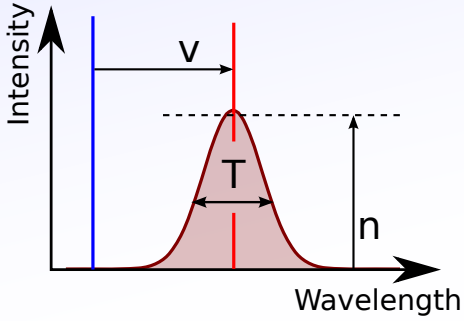

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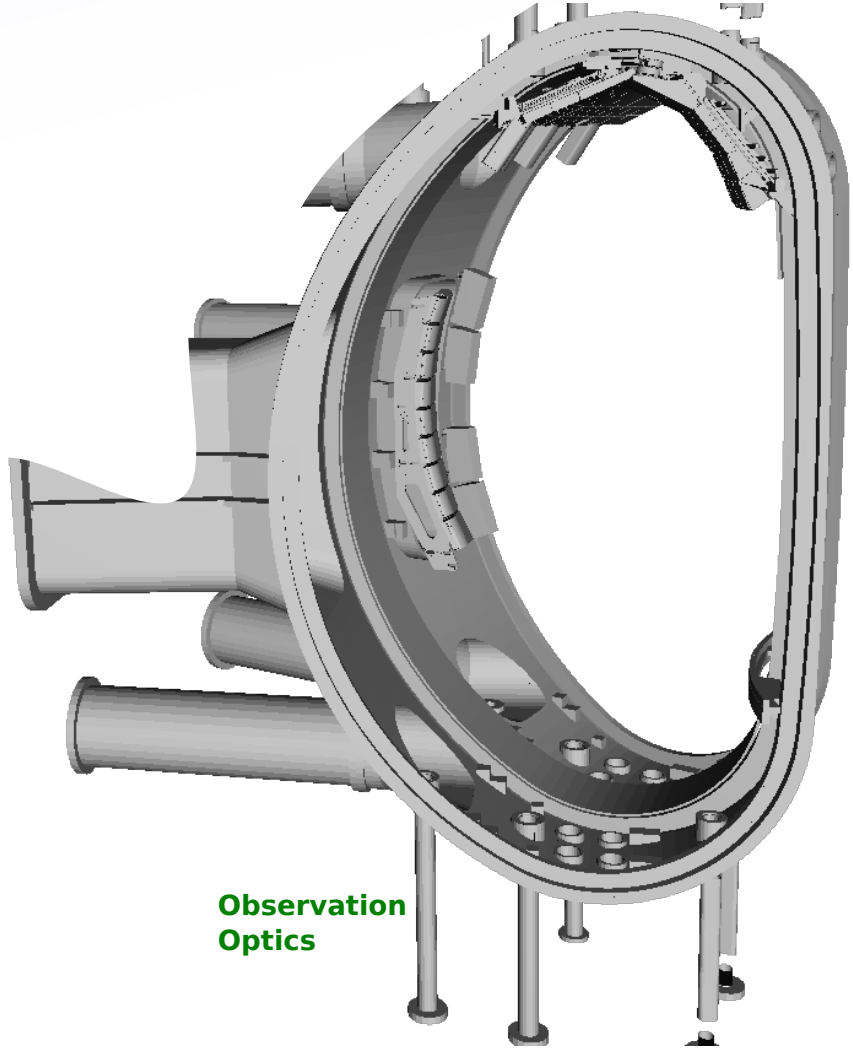

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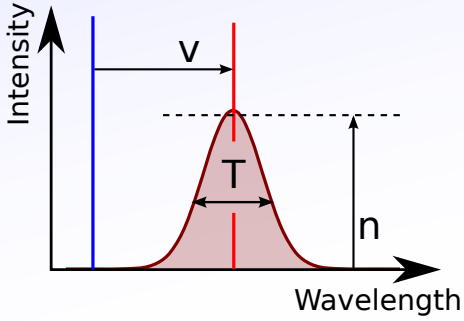

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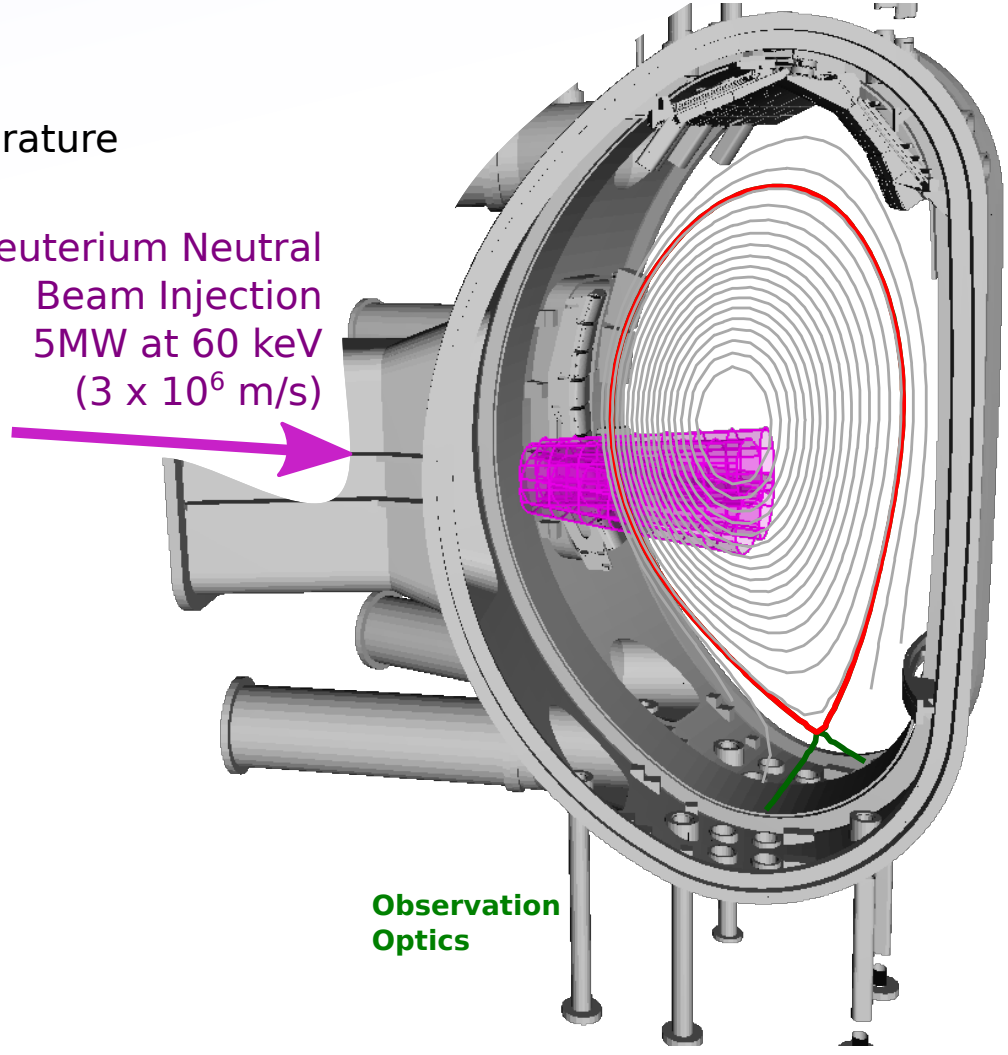

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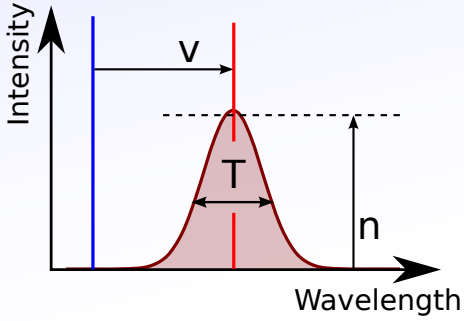

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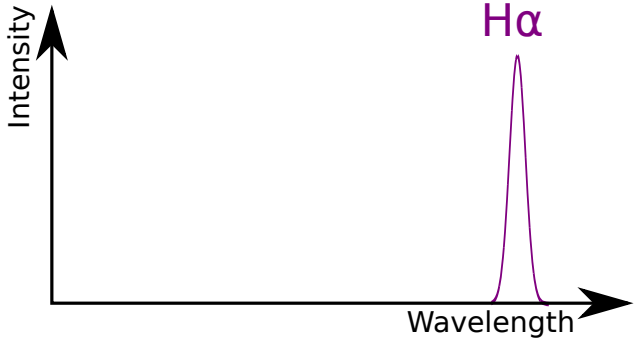

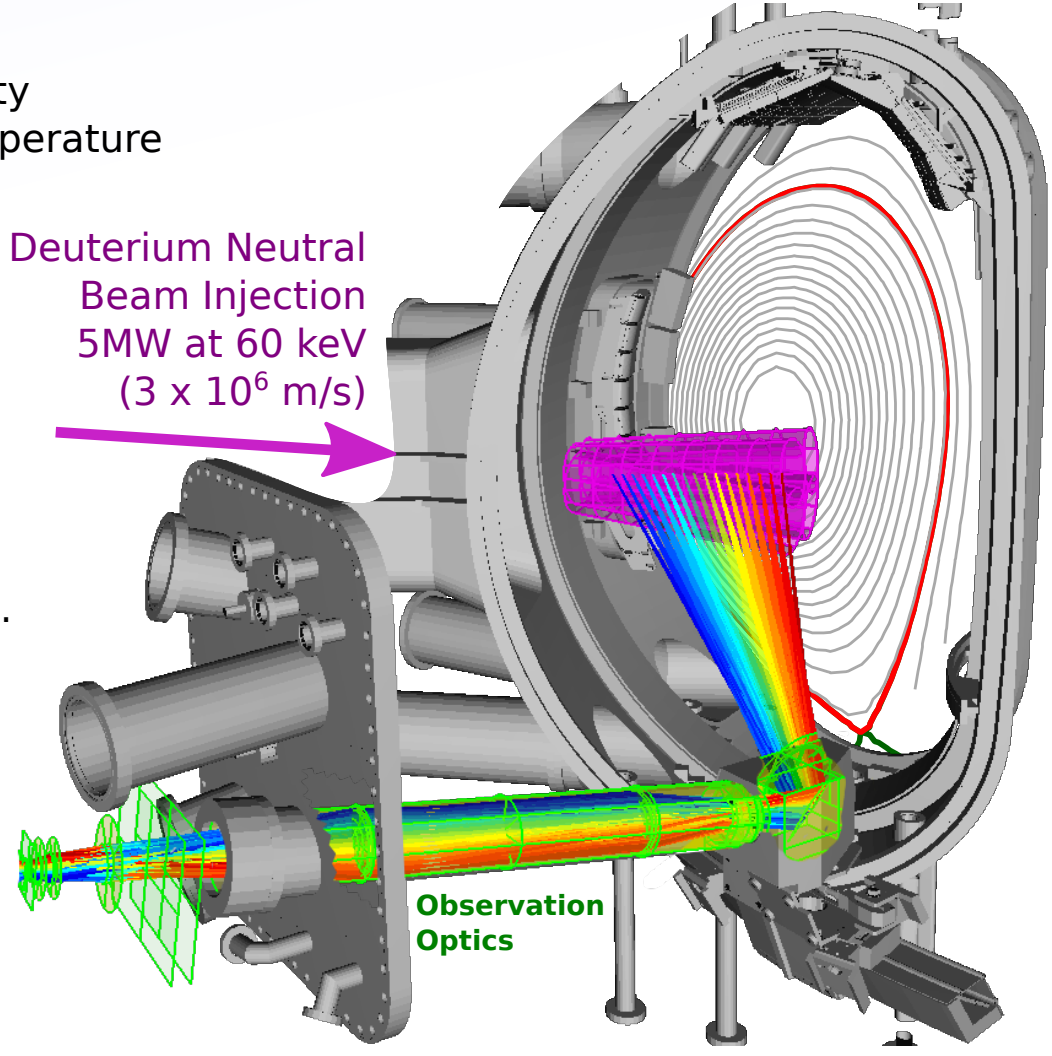

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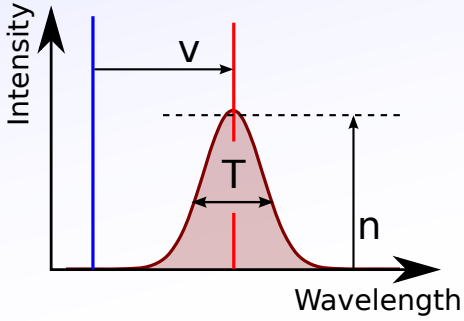

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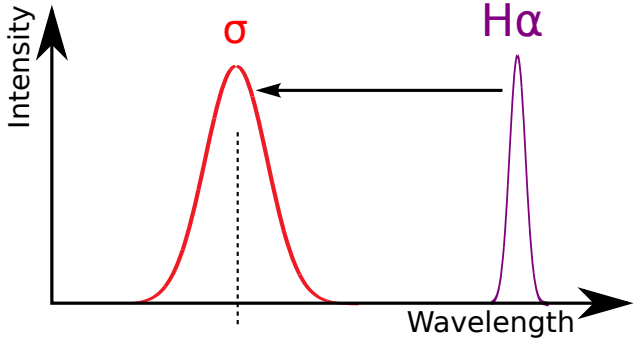

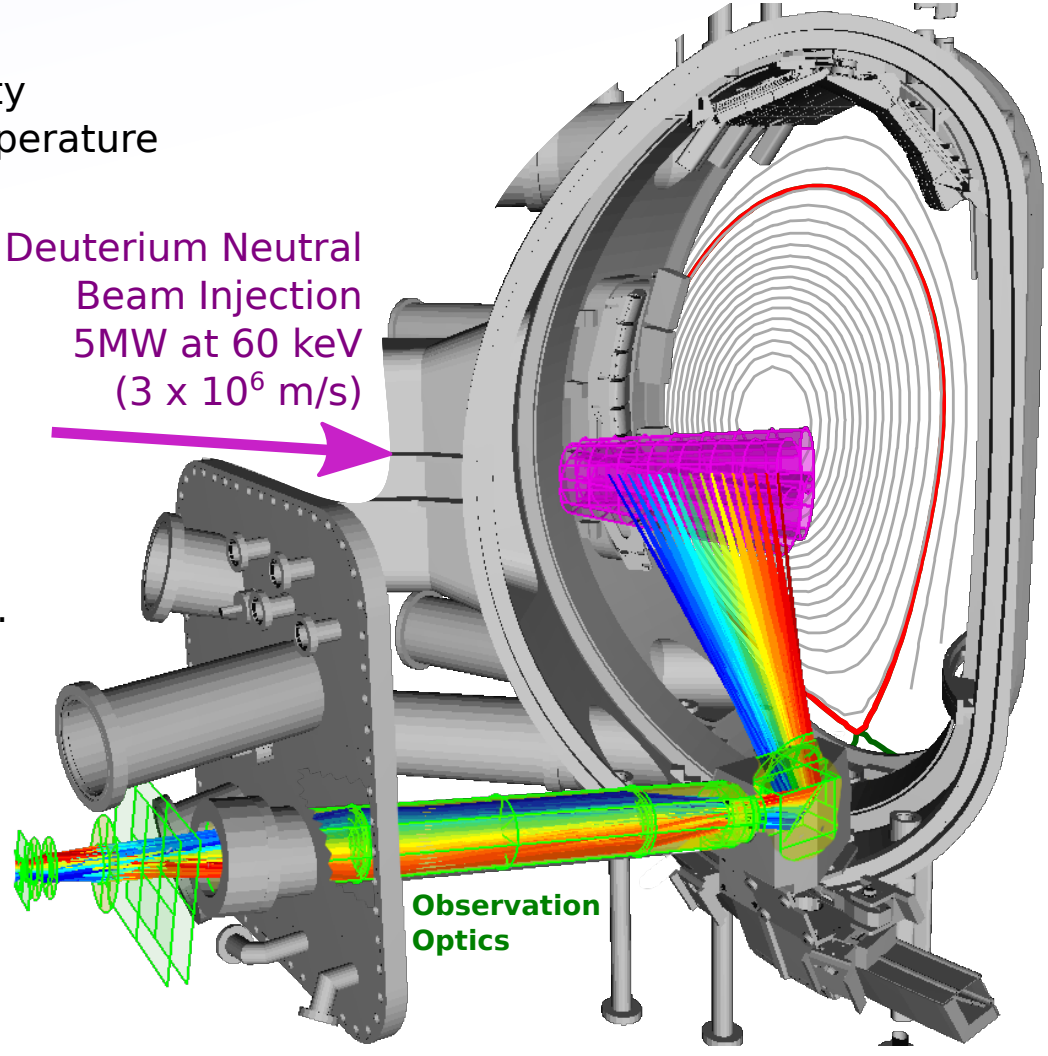

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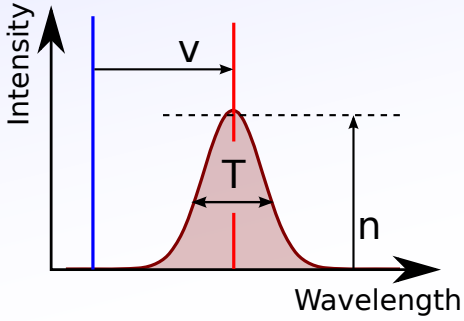

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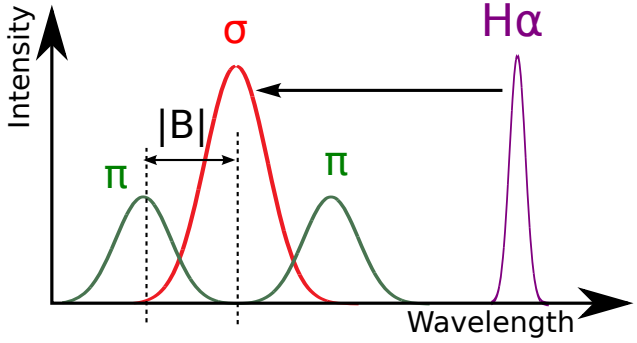

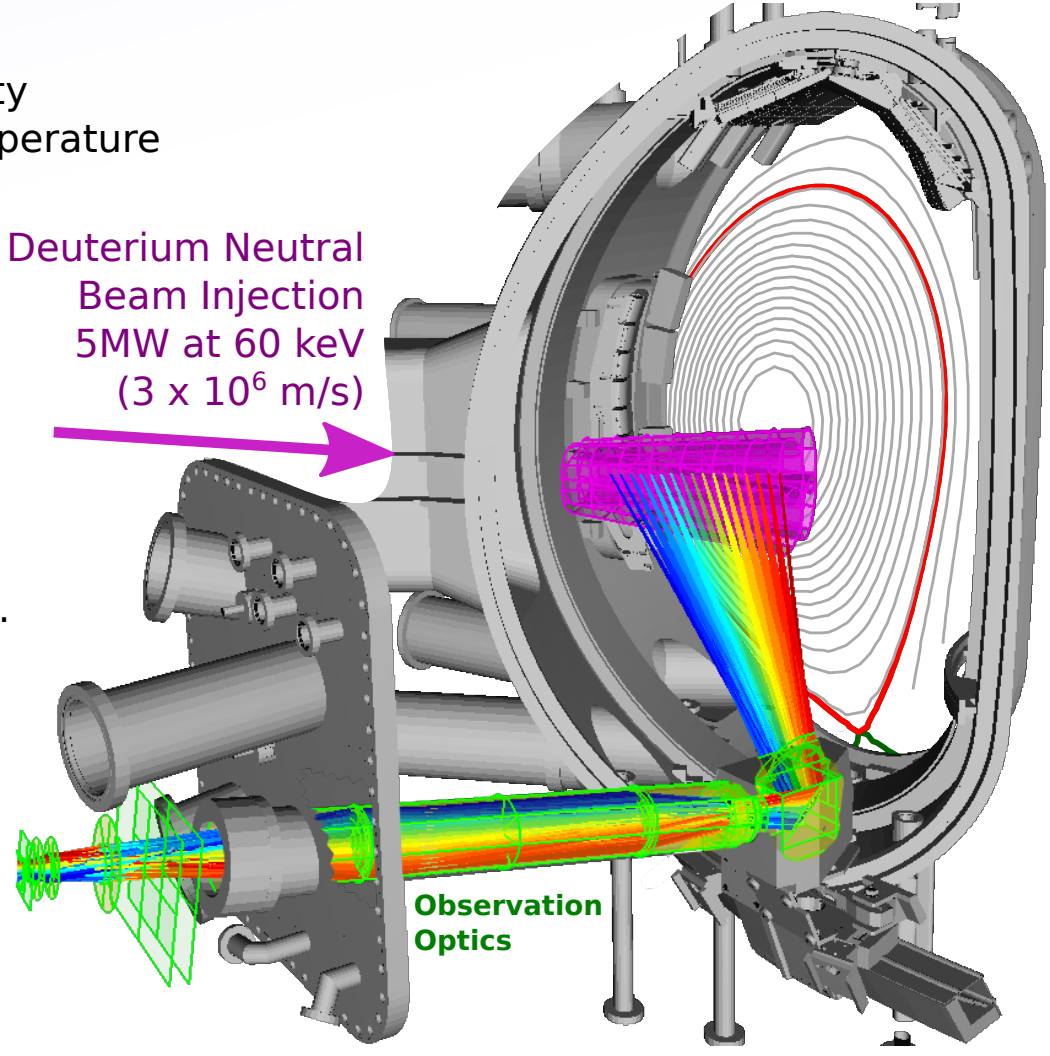

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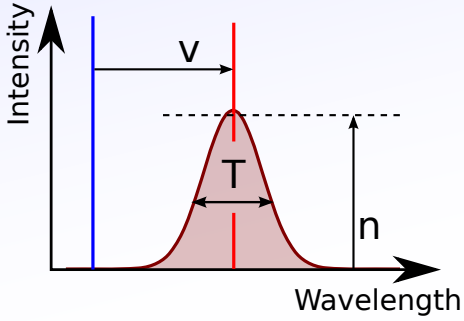

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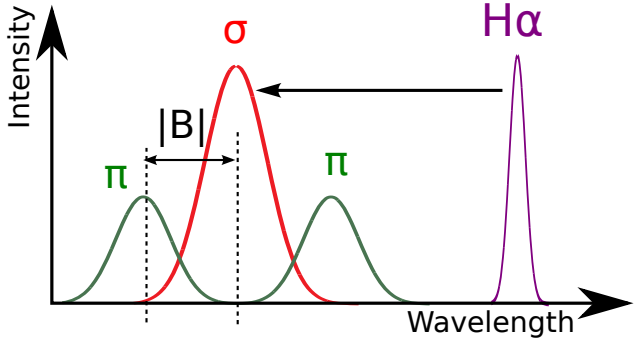

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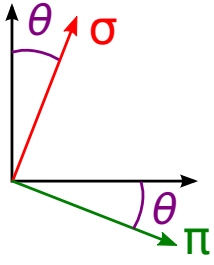

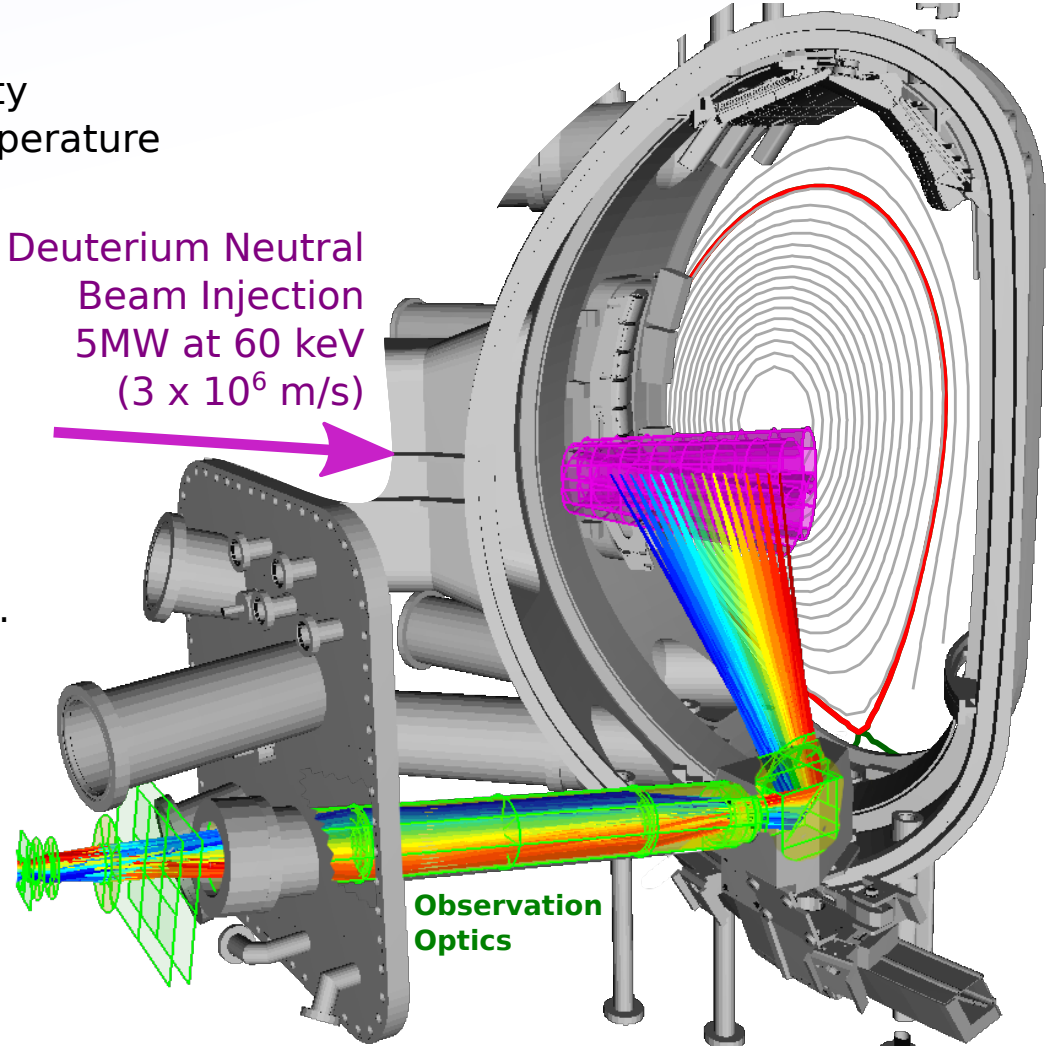

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Traditional Systems

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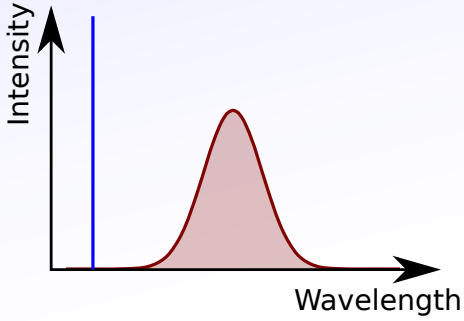

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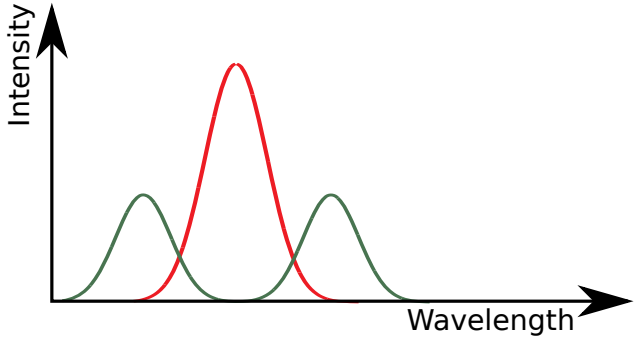

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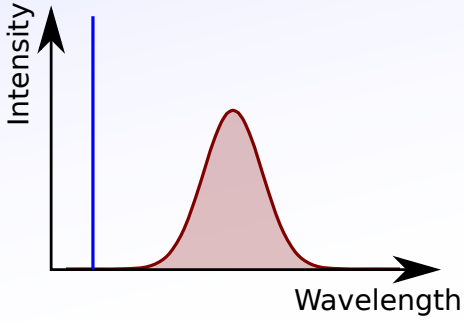
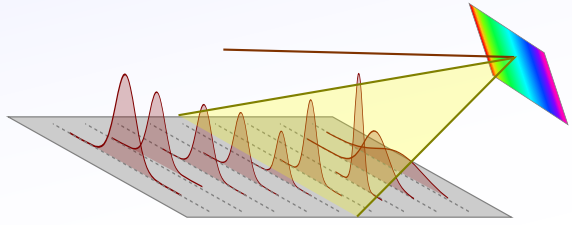
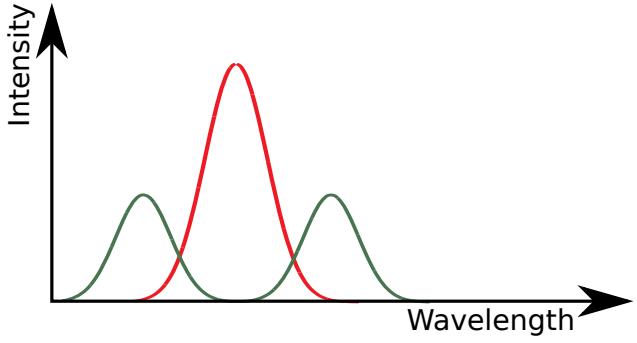




Low light levels. 1D set of points.

Polarimetry:



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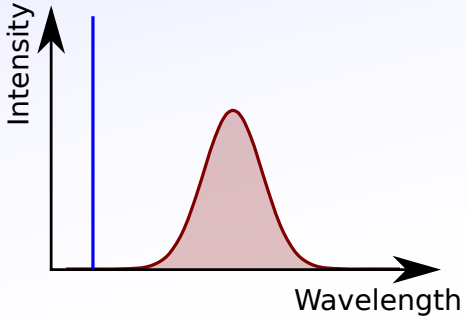
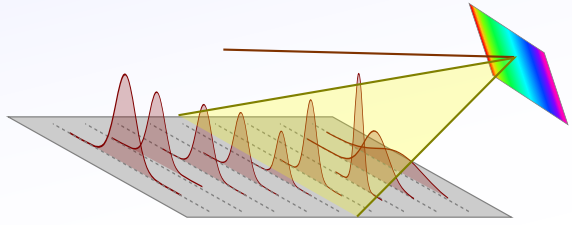


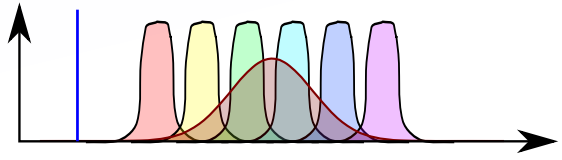
Diffraction grating and CCD camera, or individual detectors (PMTs/APDs)



Low light levels. 1D set of points.

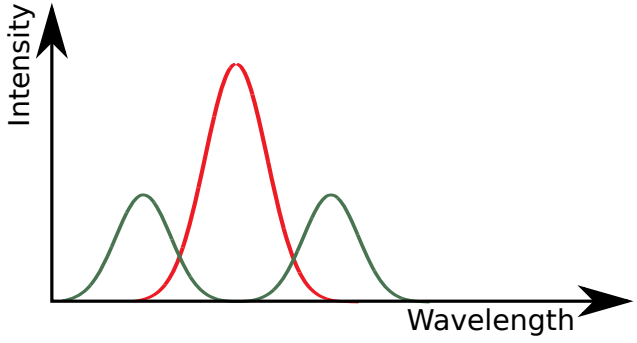
or

Individual spectral filters and fast sensitive detectors.



Very complex setup per channel.
Low spectral resolution.

Polarimetry:



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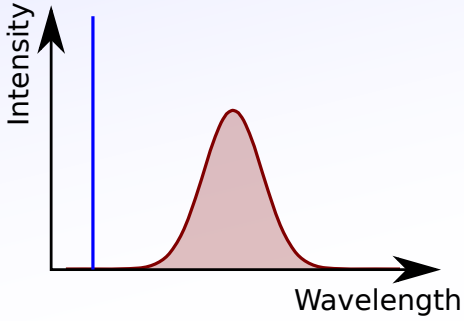

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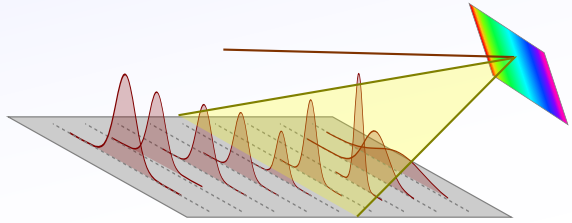

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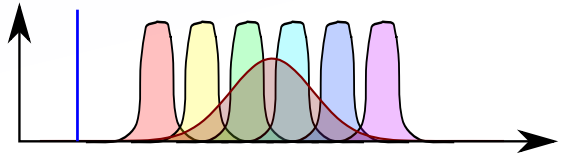
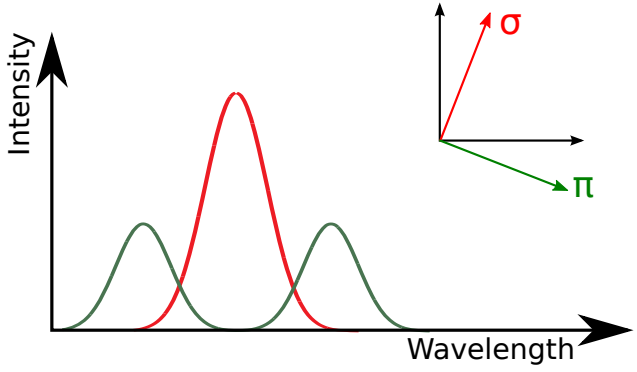


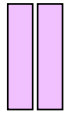
Very complex setup per channel.
Low spectral resolution.

Polarimetry:

Motional Stark Effect is usually done with a Photo-elastic modulator (PEM - an acoustically excited crystal)



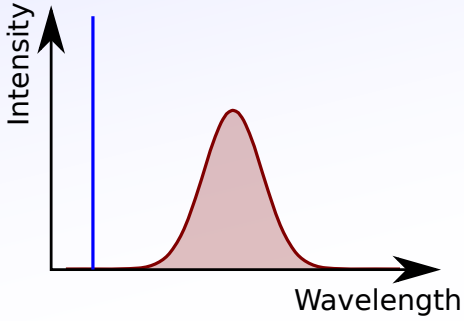
PEMs



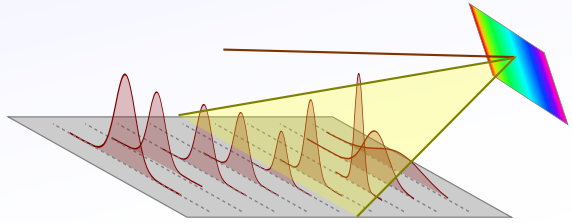
Traditional Systems

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

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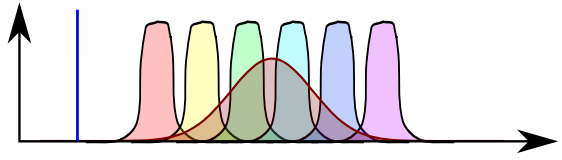

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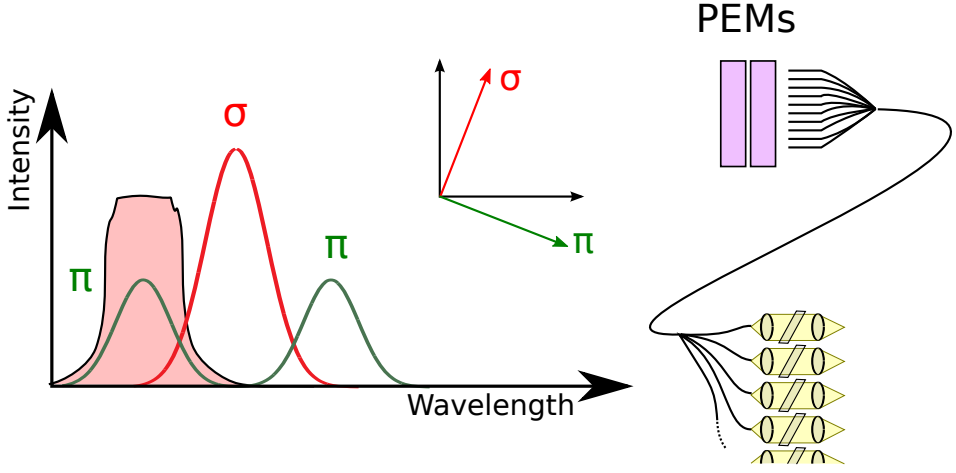

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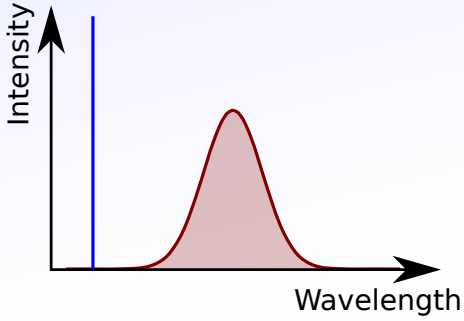

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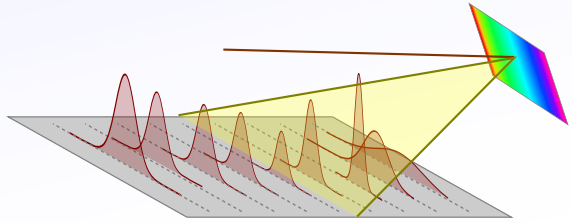

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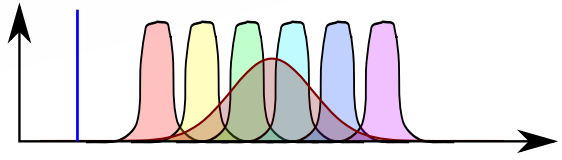

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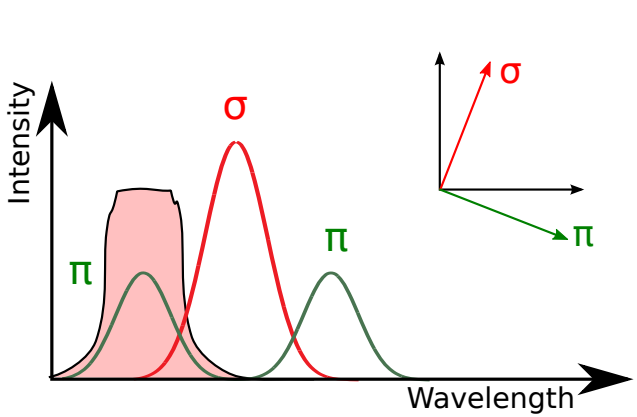
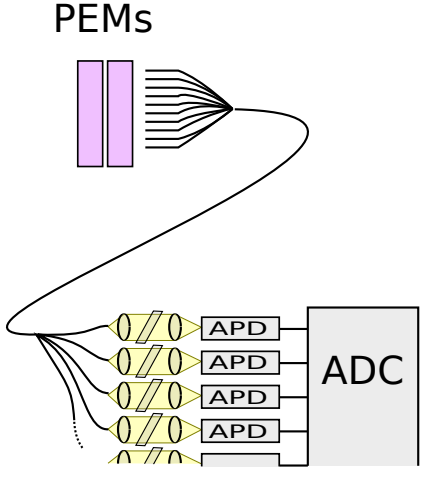
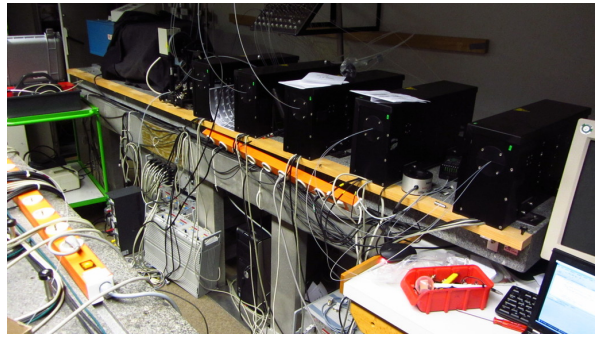
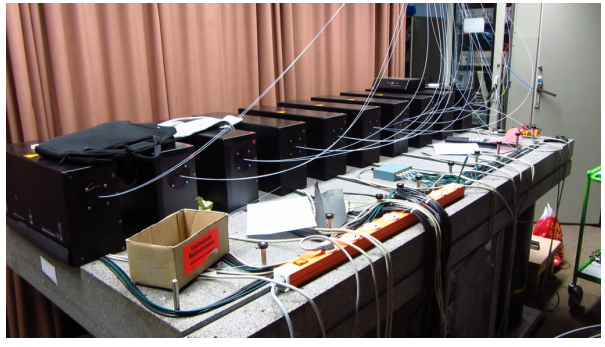
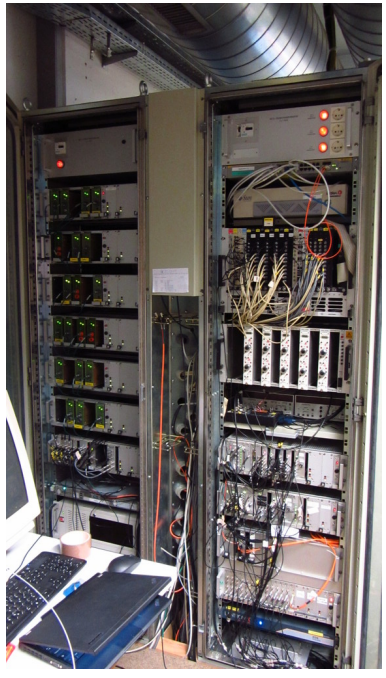


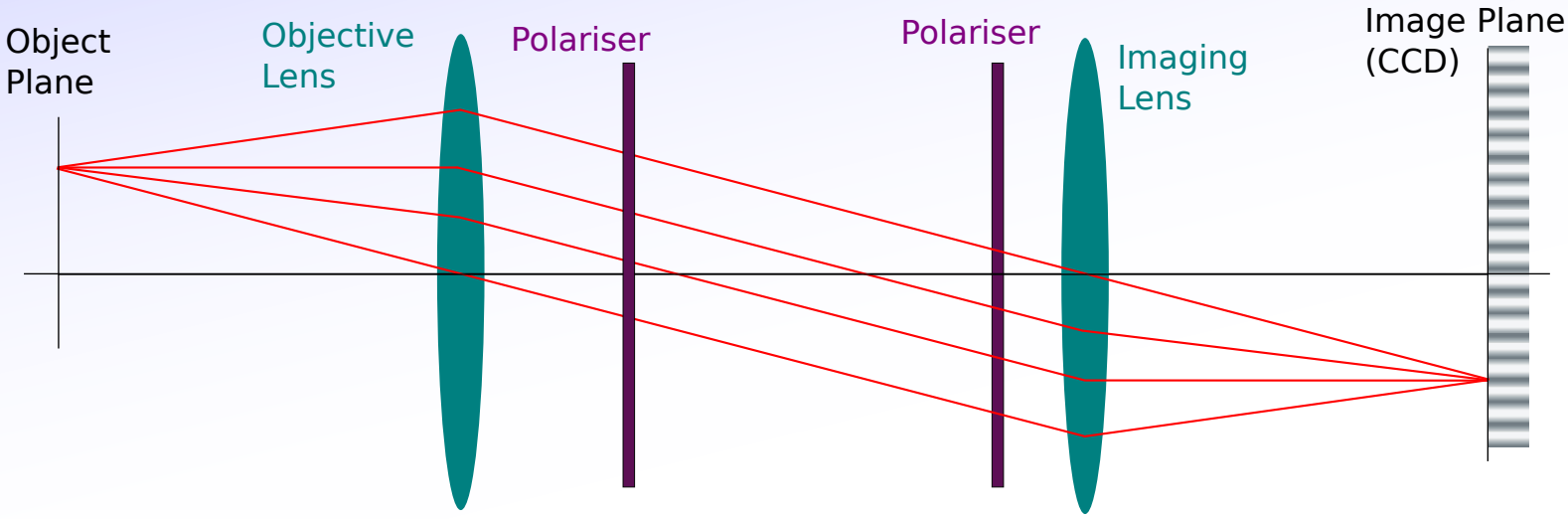


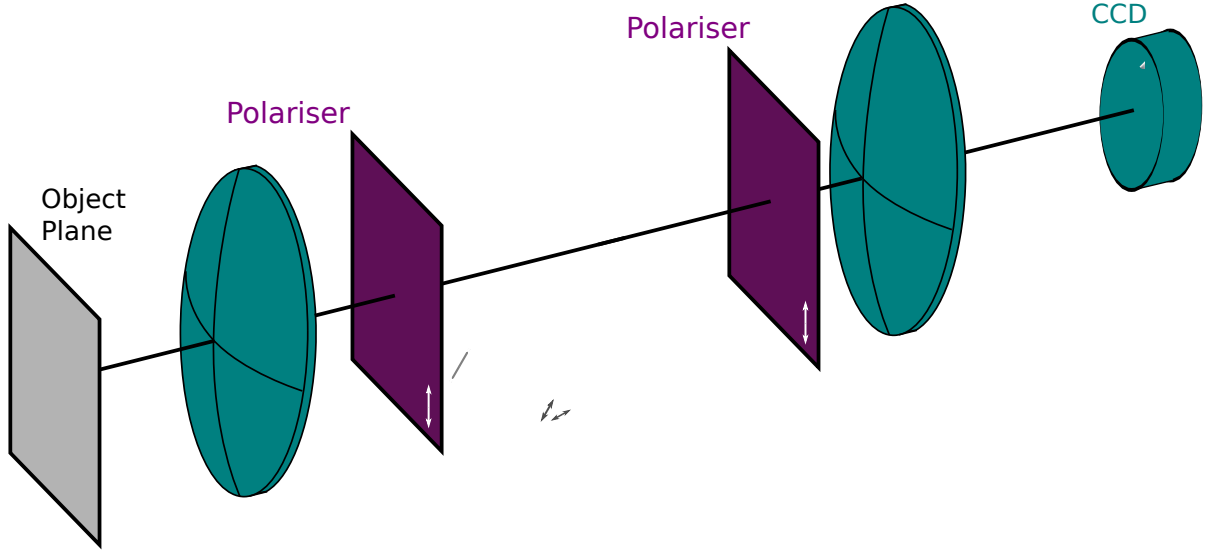






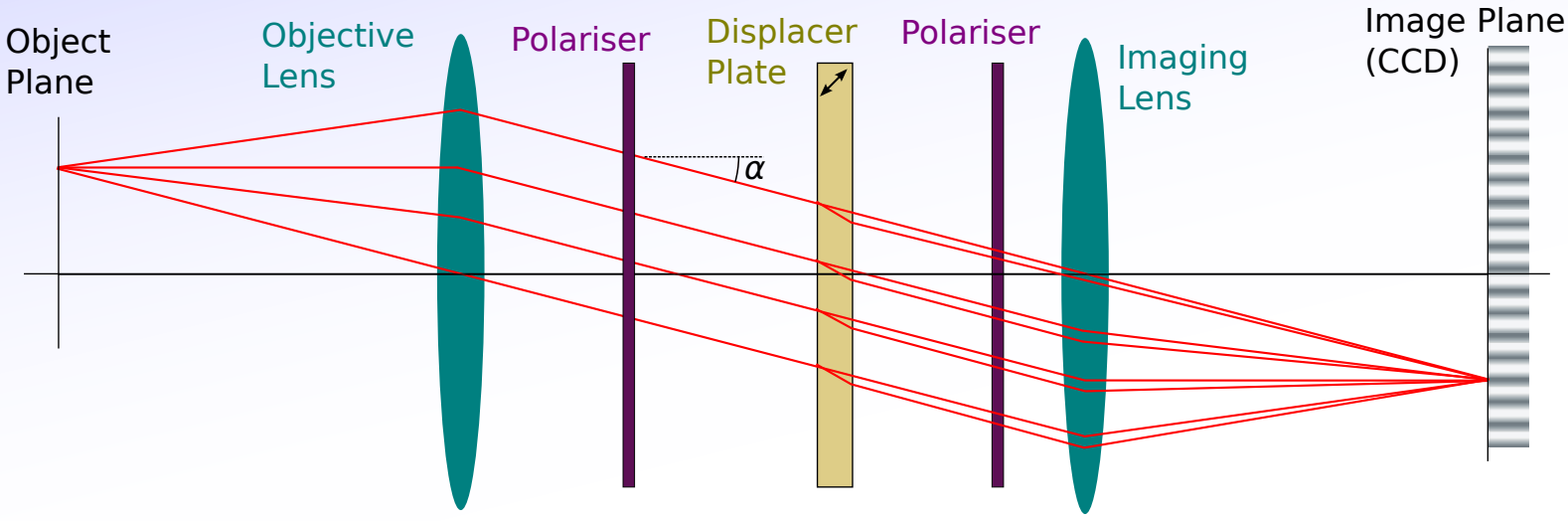
Coherence Imaging

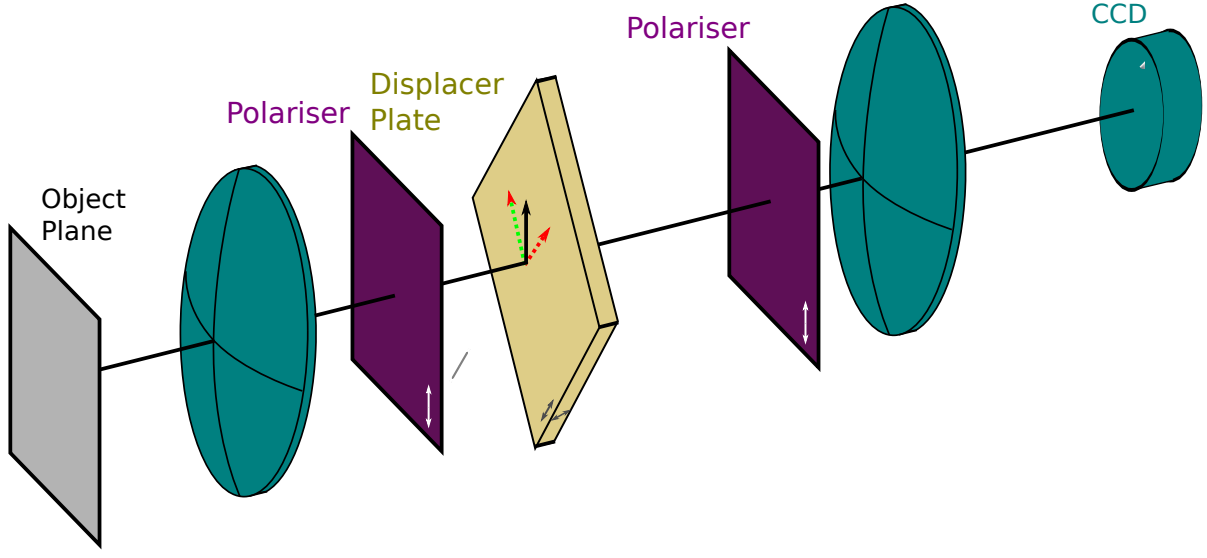




Coherence Imaging

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.





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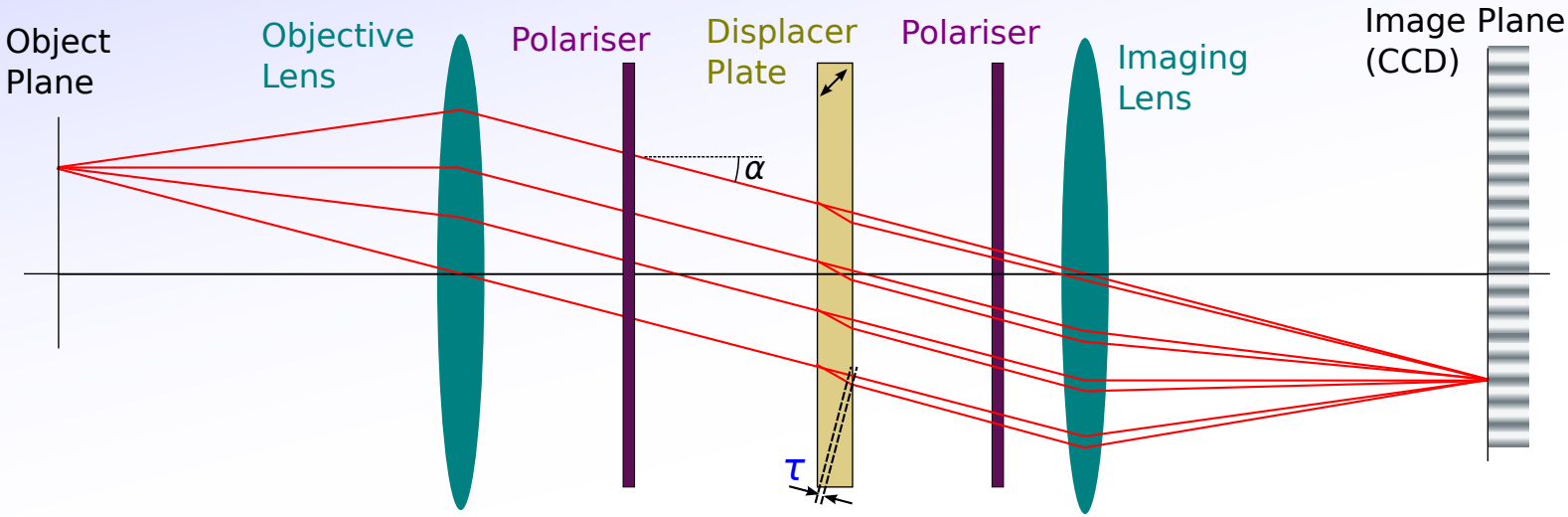

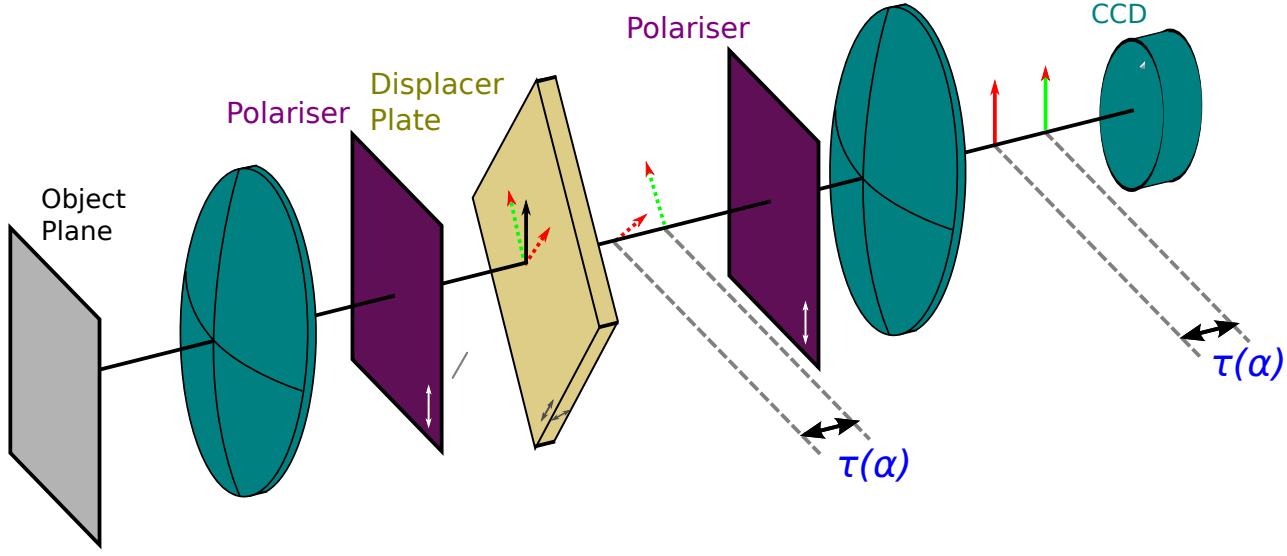

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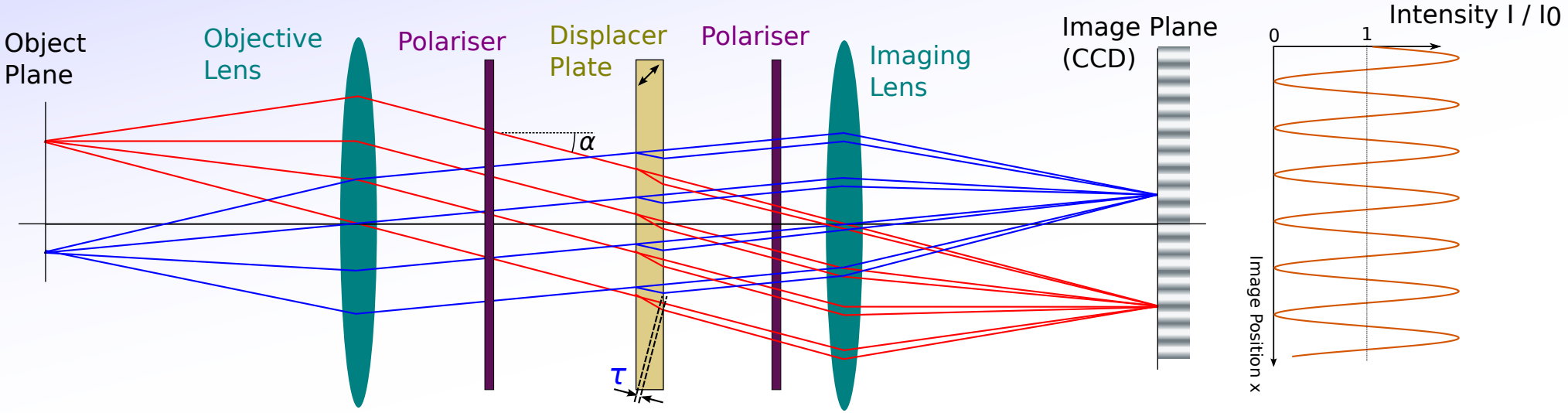

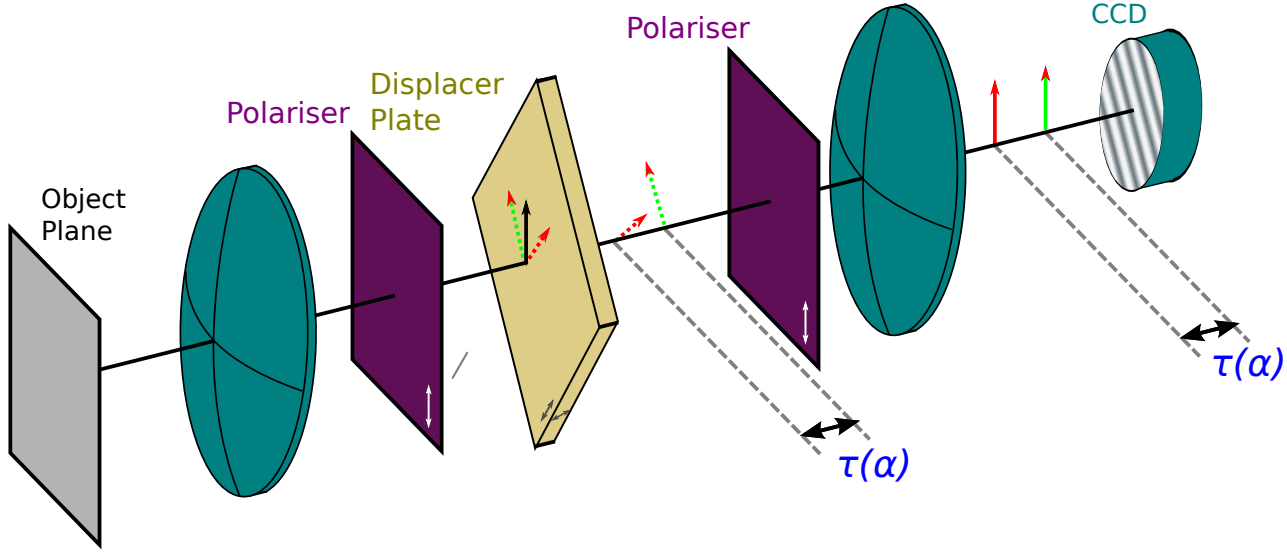

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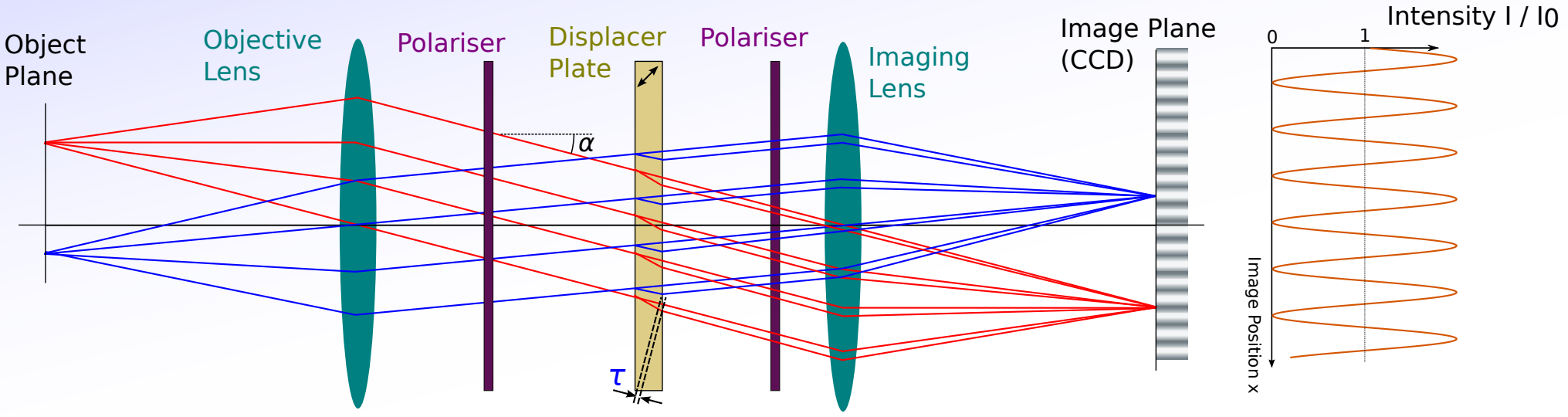

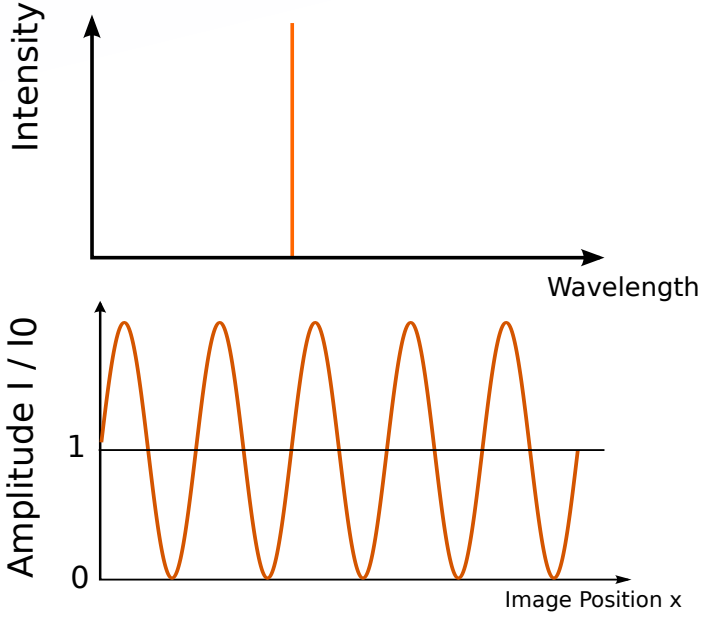

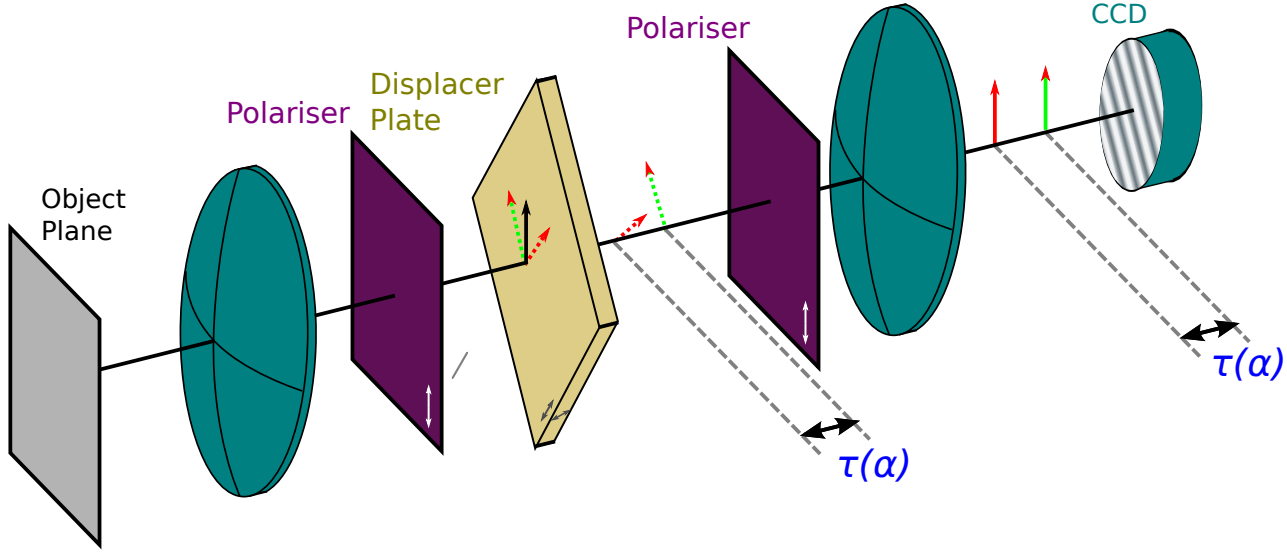

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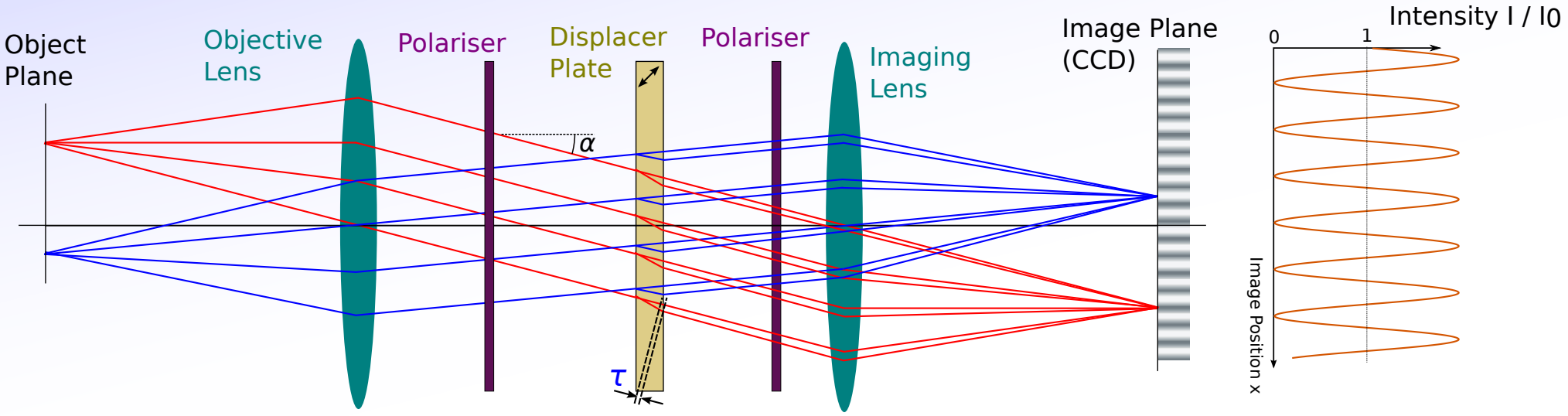
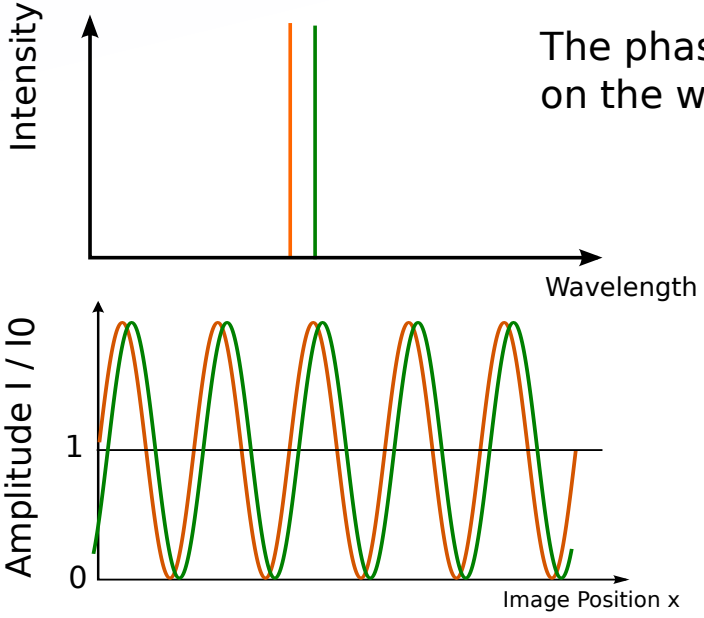
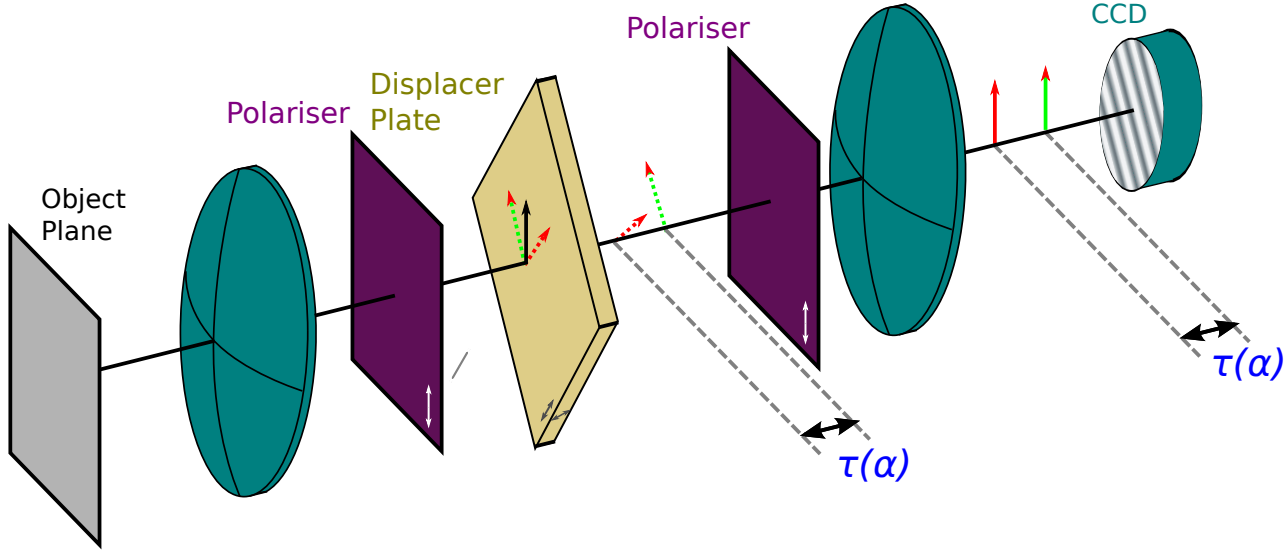




The phase of the interference pattern depends on the wavelength Δω.



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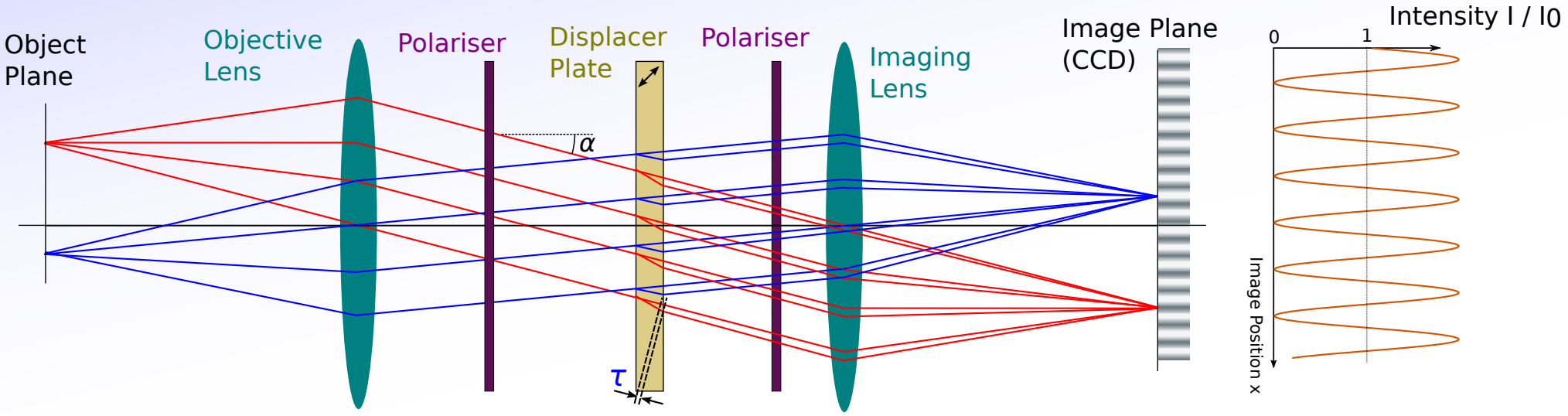
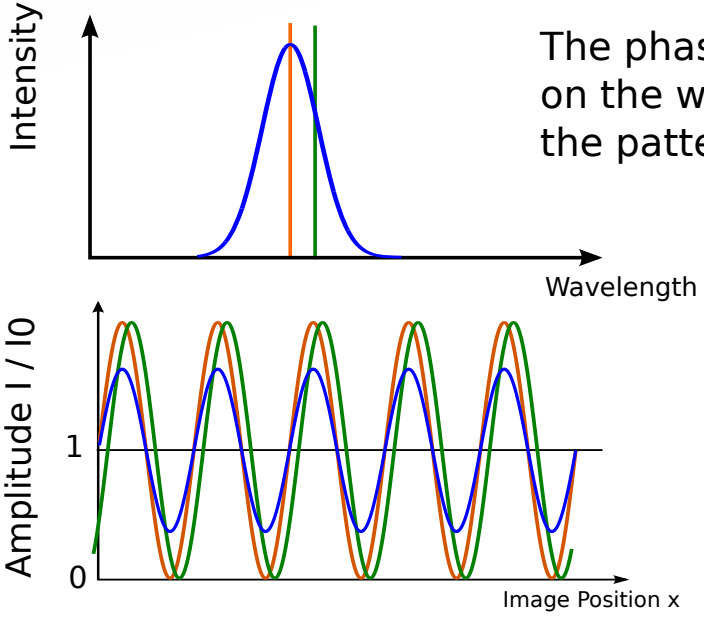
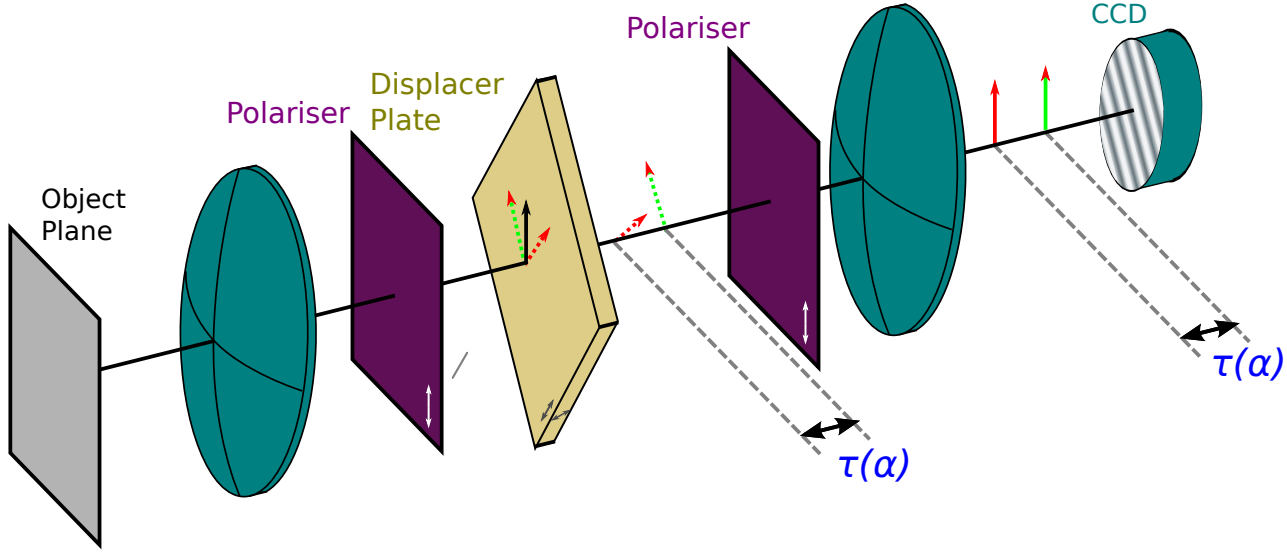




The phase of the interference pattern depends on the wavelength Δω. With multiple wavelengths, the pattern contrast ζ is reduced.



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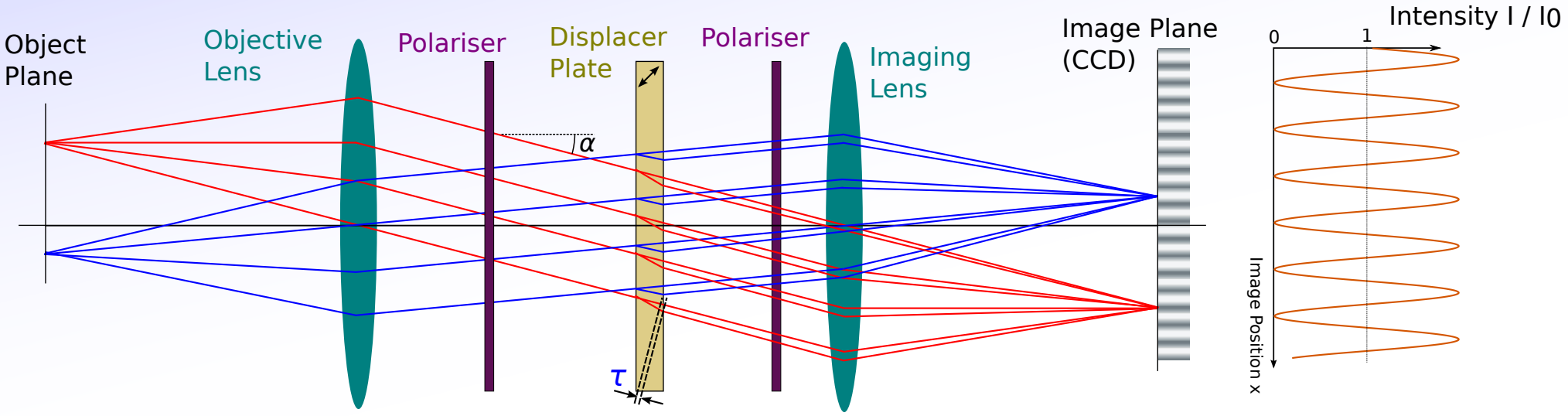

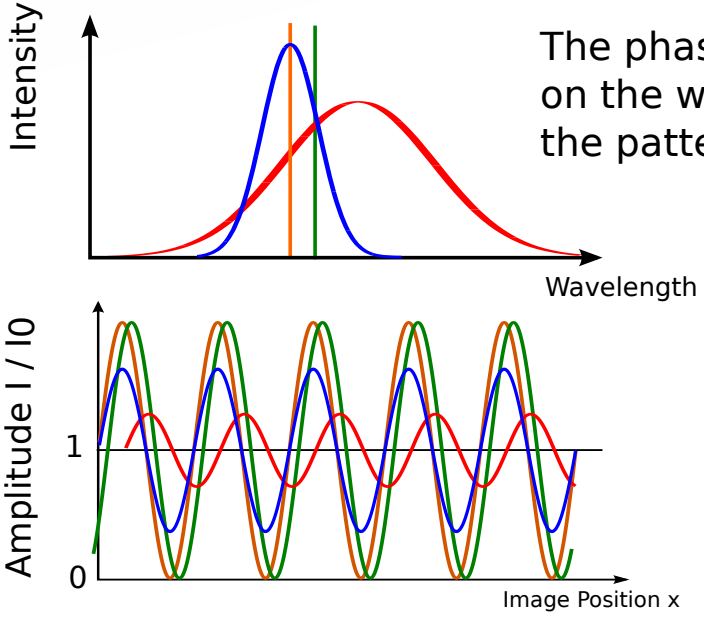

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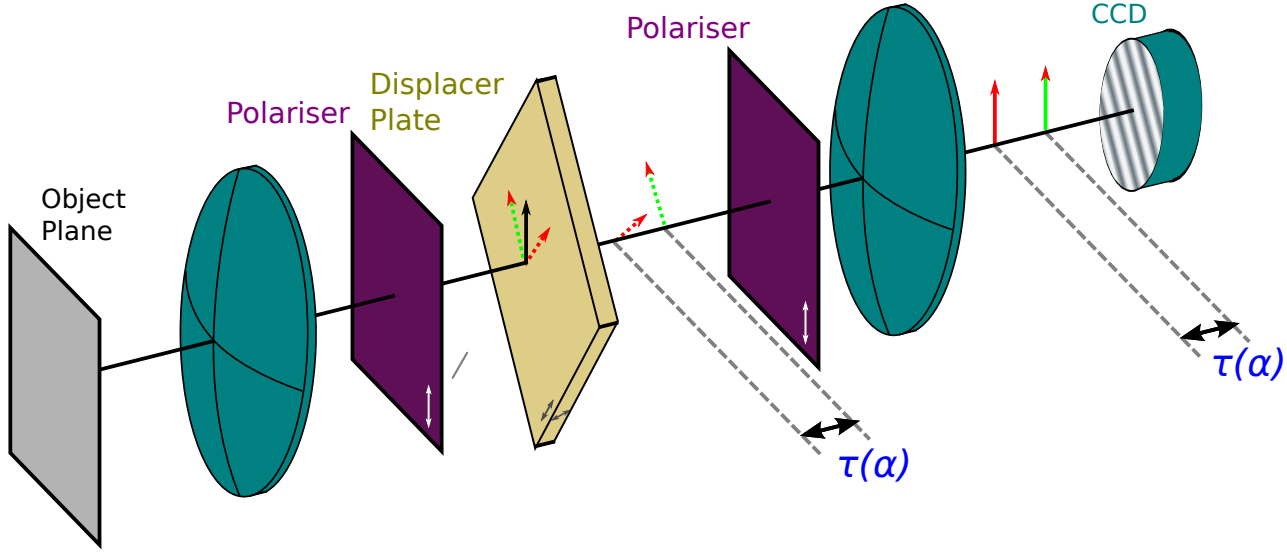
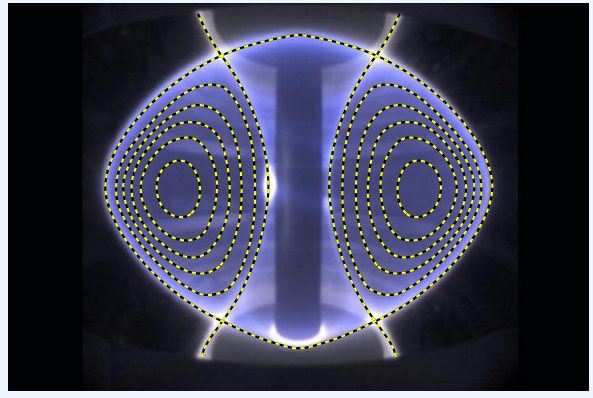
$$I \propto 1 + \zeta \cos((\omega + \Delta\omega)x)$$



Doppler Coherence Flow Imaging - MAST

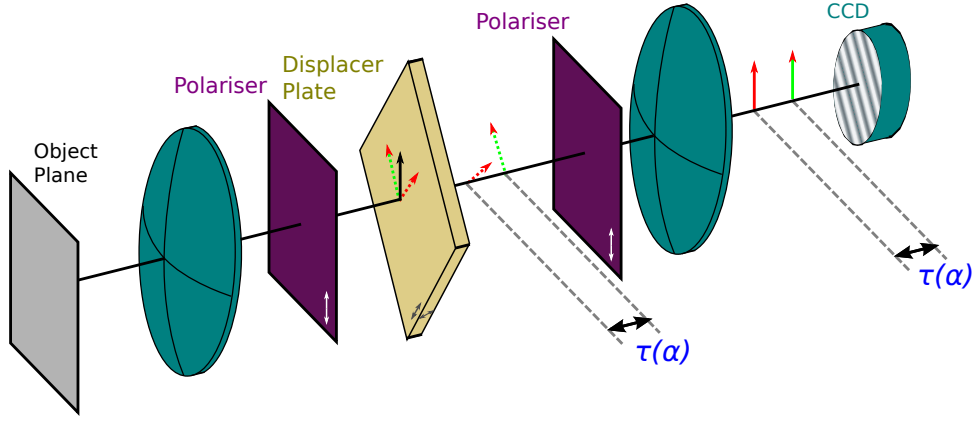
Some results of neutral Helium flow in the (relatively) cold edge of MAST:

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.

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



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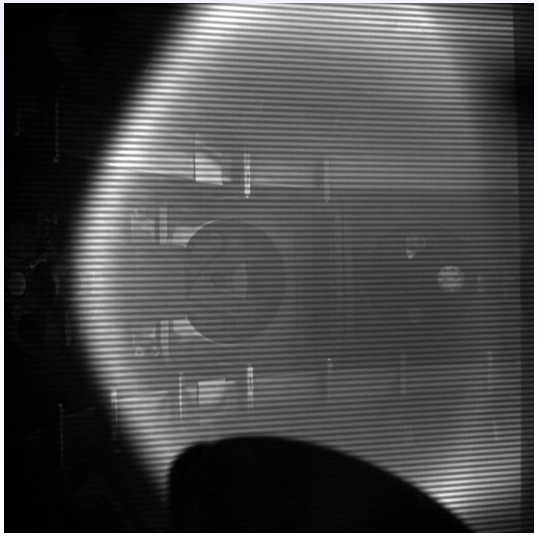

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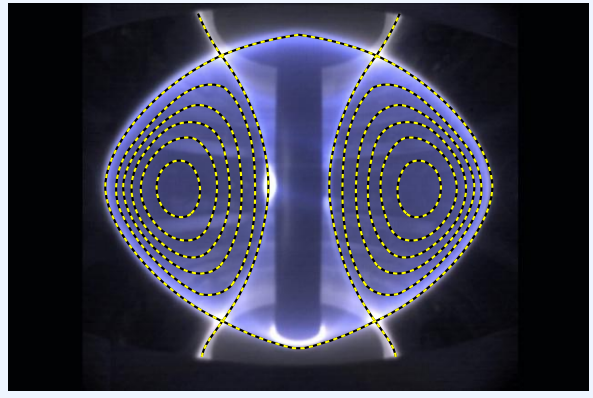

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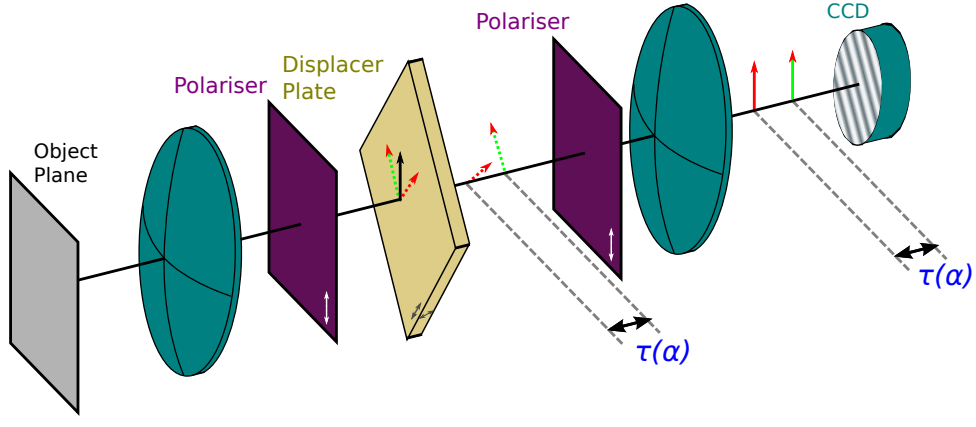

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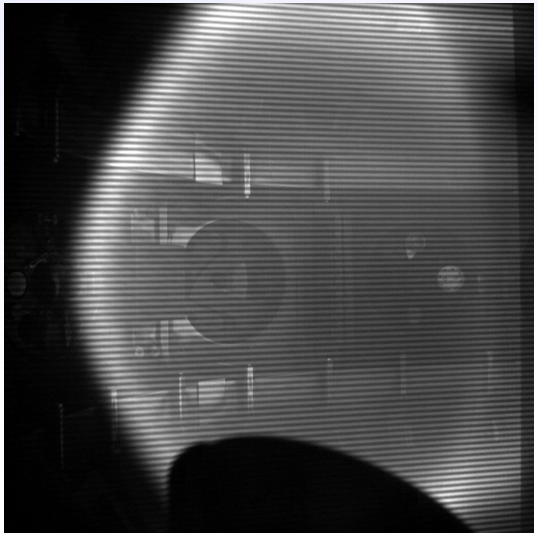
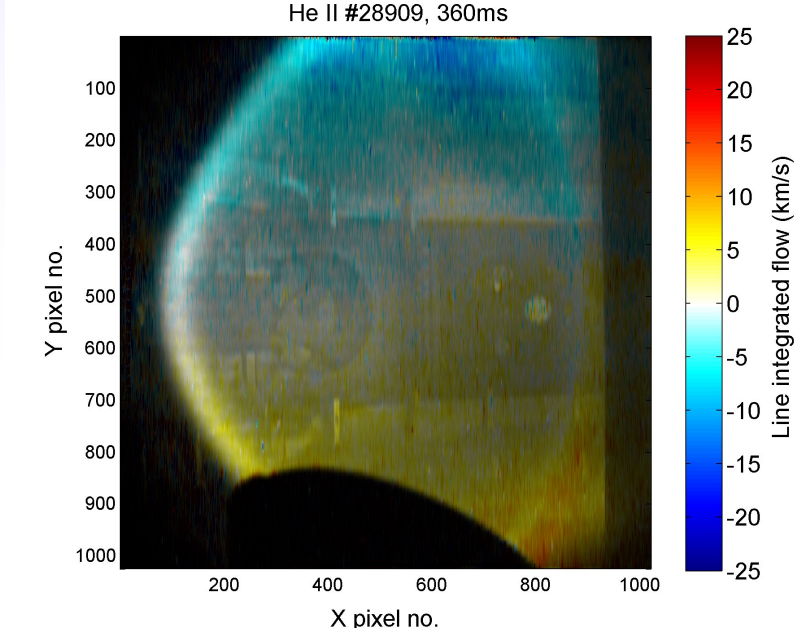


Helium Flow Velocity:



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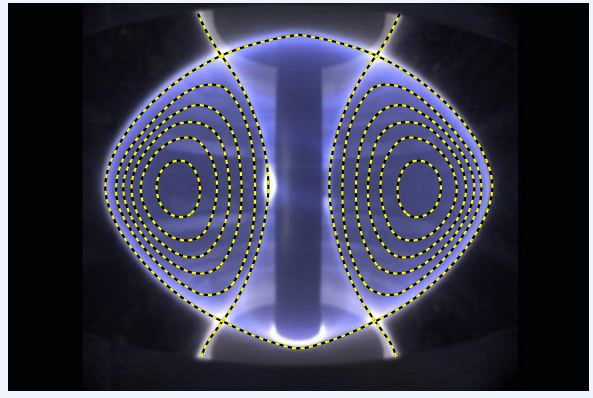

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And some videos...

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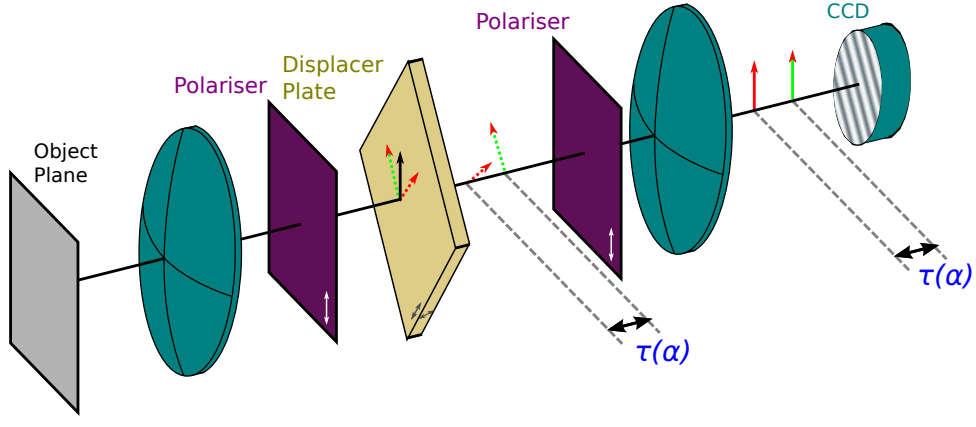
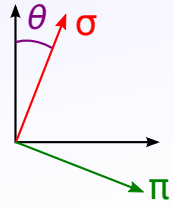
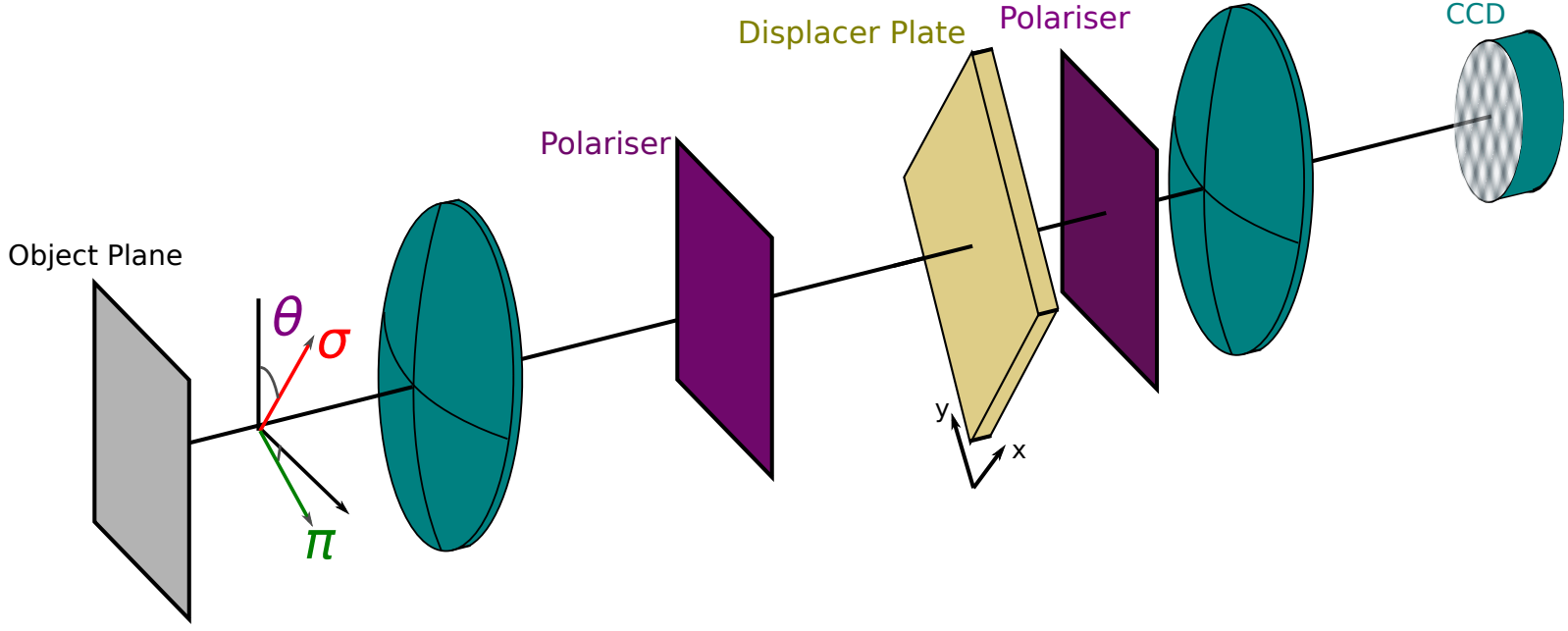


Multiplet Polarisation Coherence Imaging

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



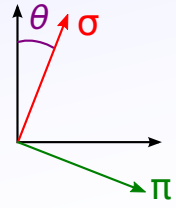


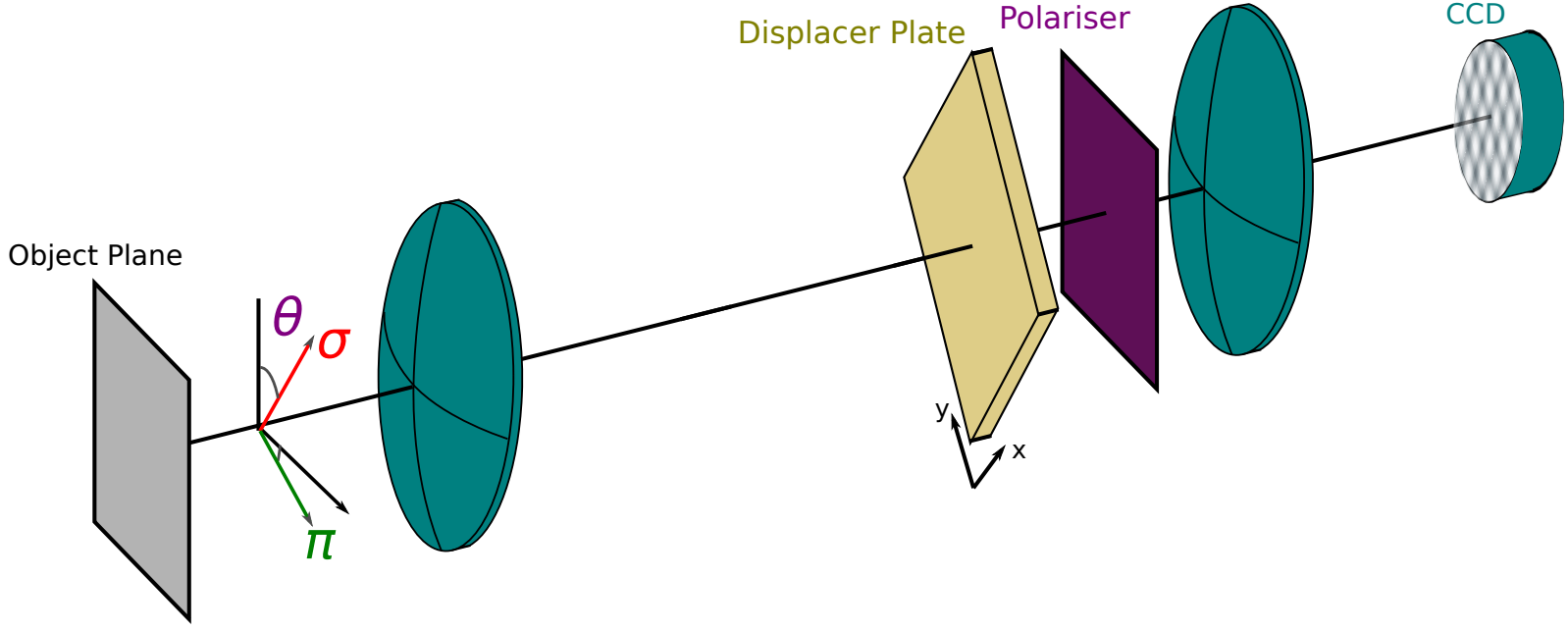
Multiplet Polarisation Coherence Imaging

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.





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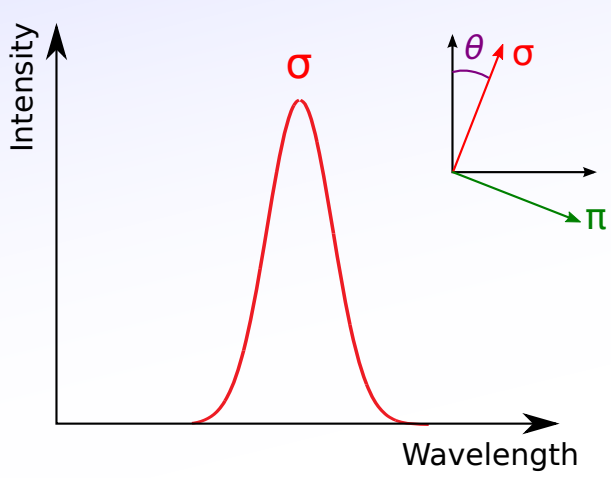
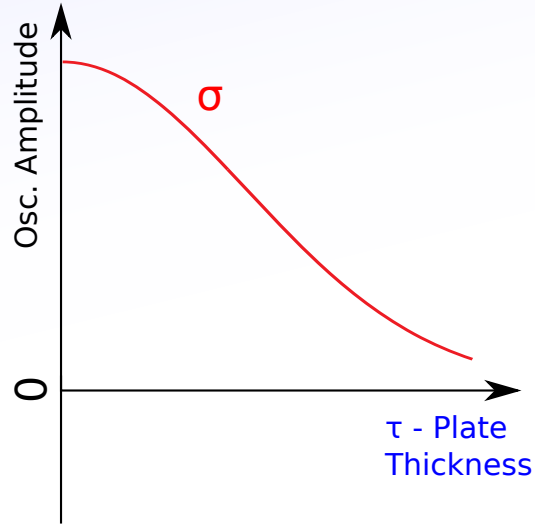
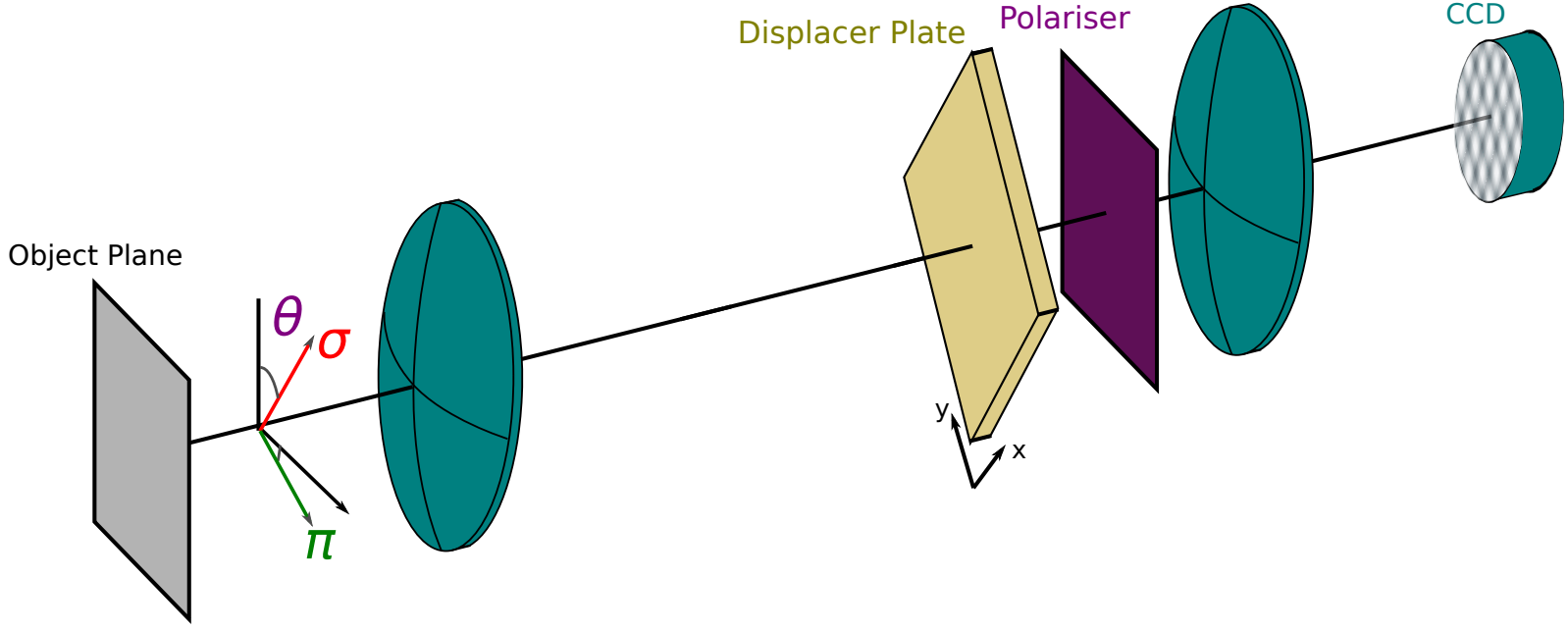






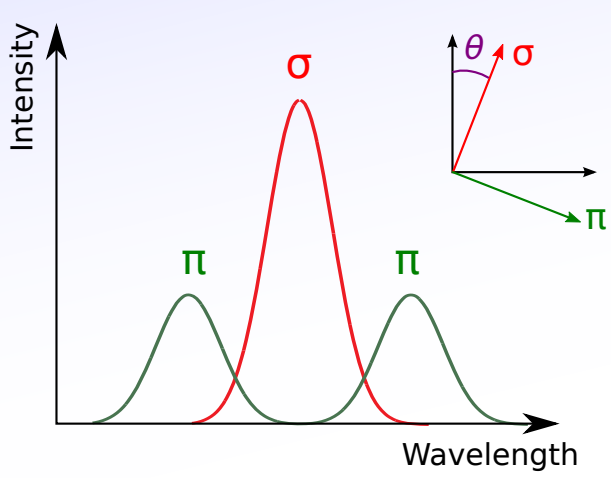
Multiplet Polarisation Coherence Imaging

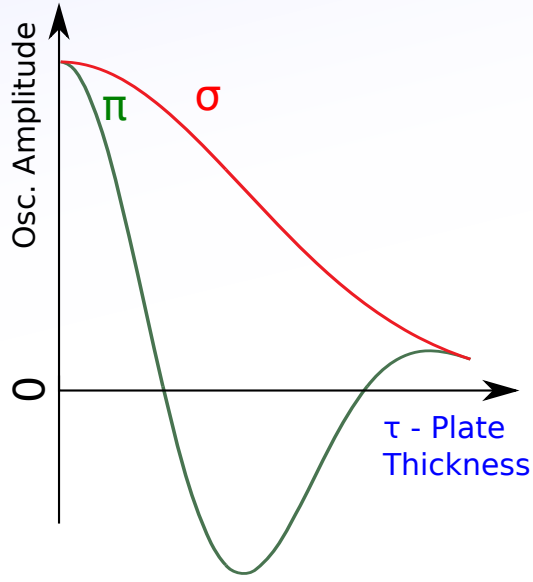
Removing the first polariser gives a dependence on the initial polarisation:

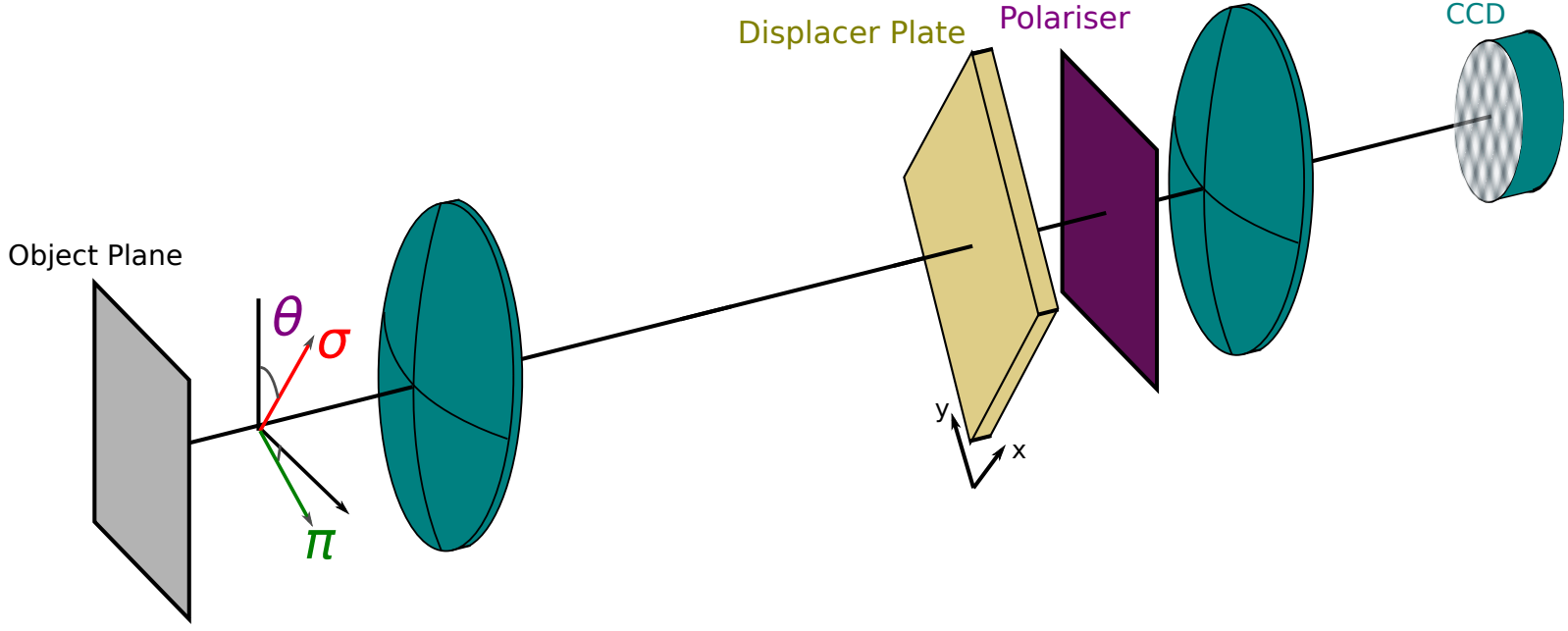
$$I \propto 1 + \zeta \, cos2\theta \, cos(x)$$

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.







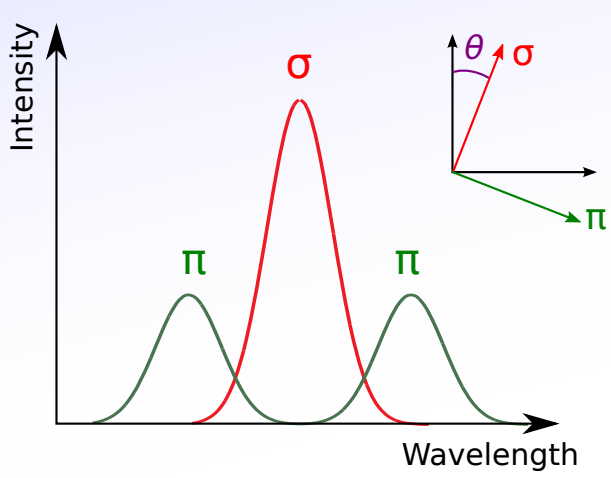
Multiplet Polarisation Coherence Imaging

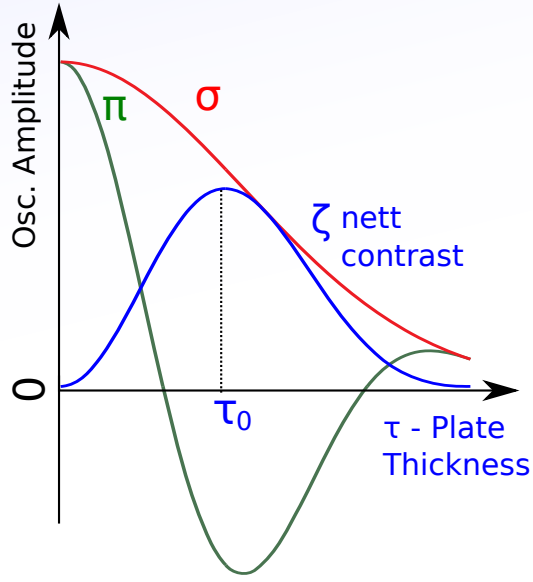
Removing the first polariser gives a dependence on the initial polarisation:

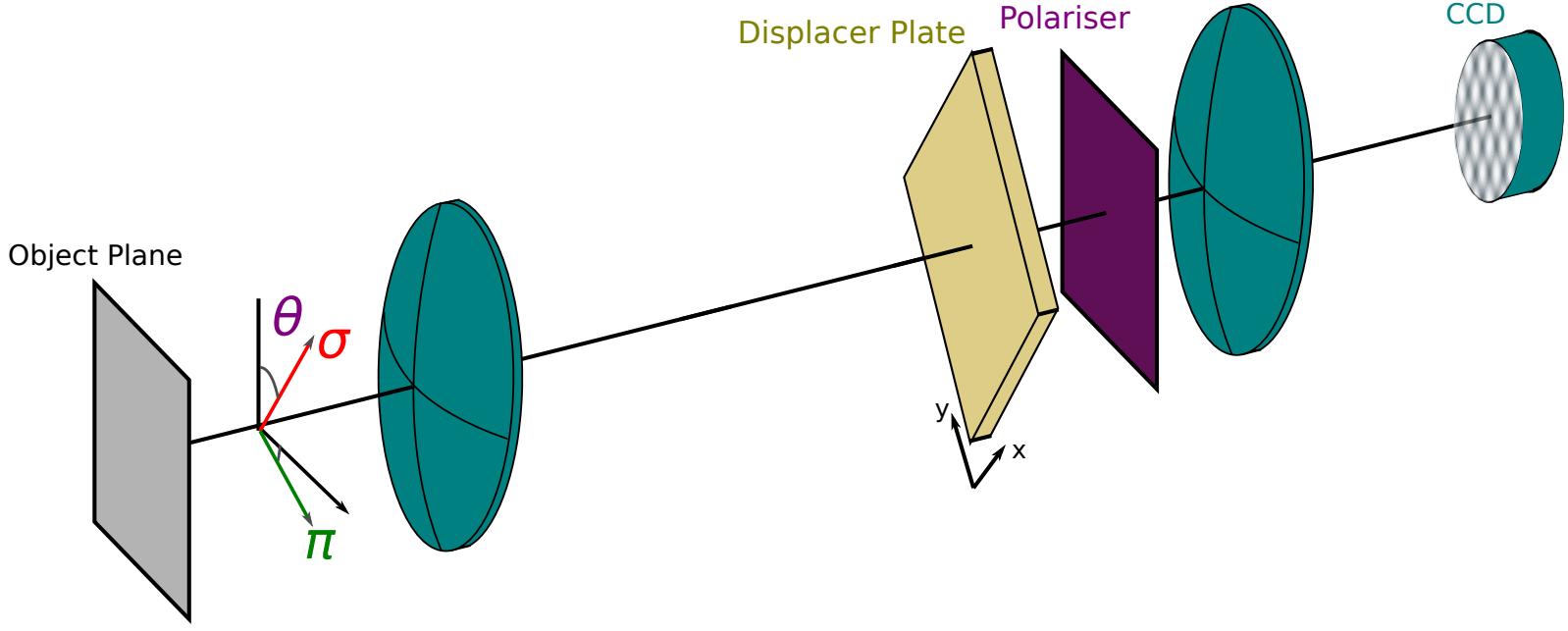
$$I \propto 1 + \zeta \, cos2\theta \, cos(x)$$

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.







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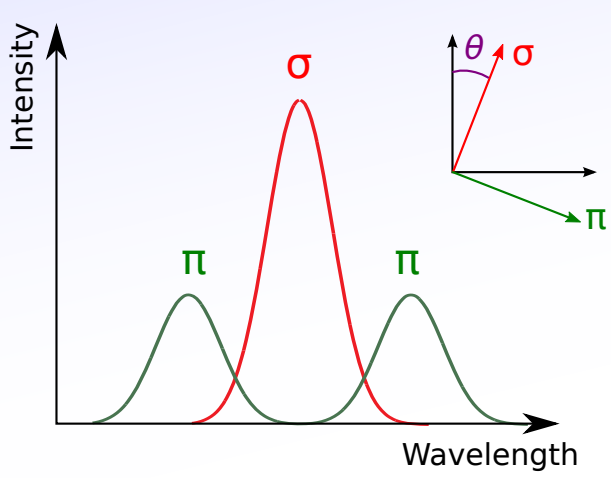

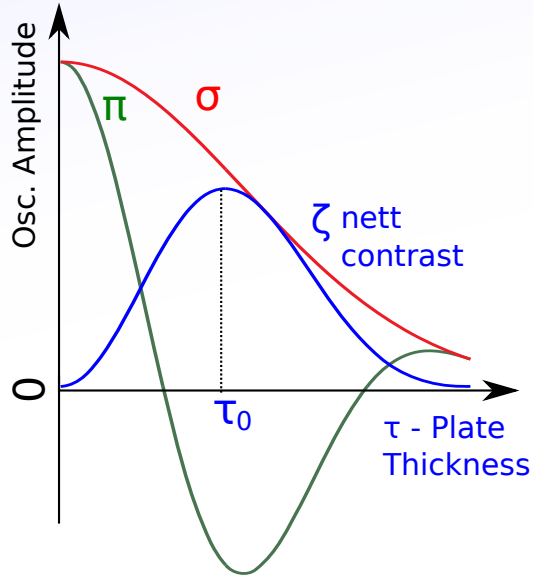

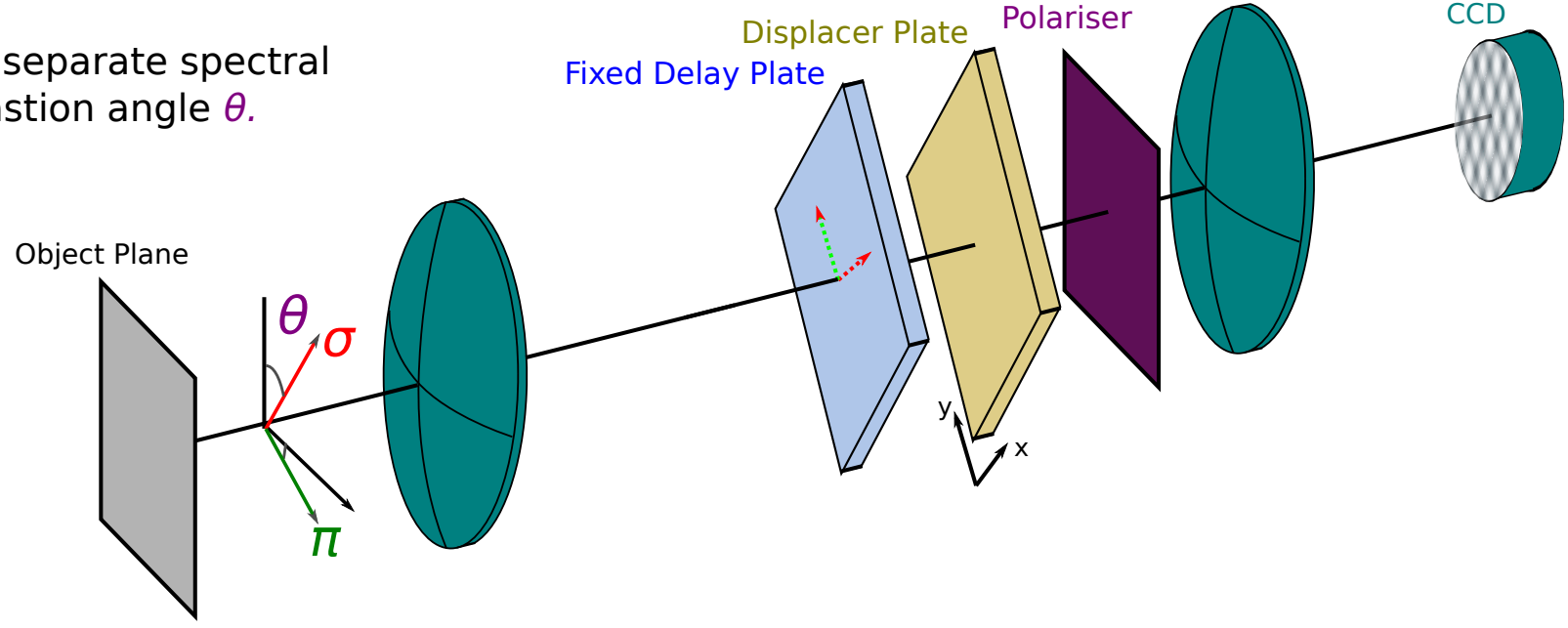

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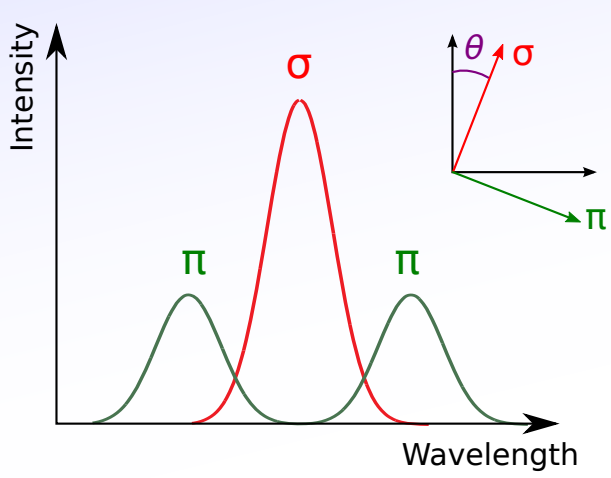

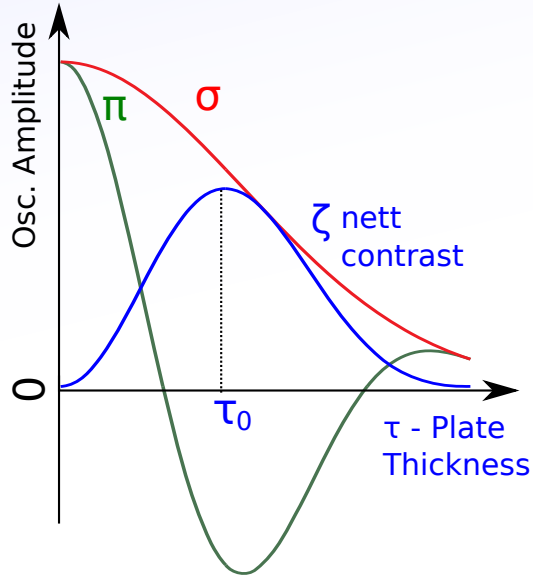

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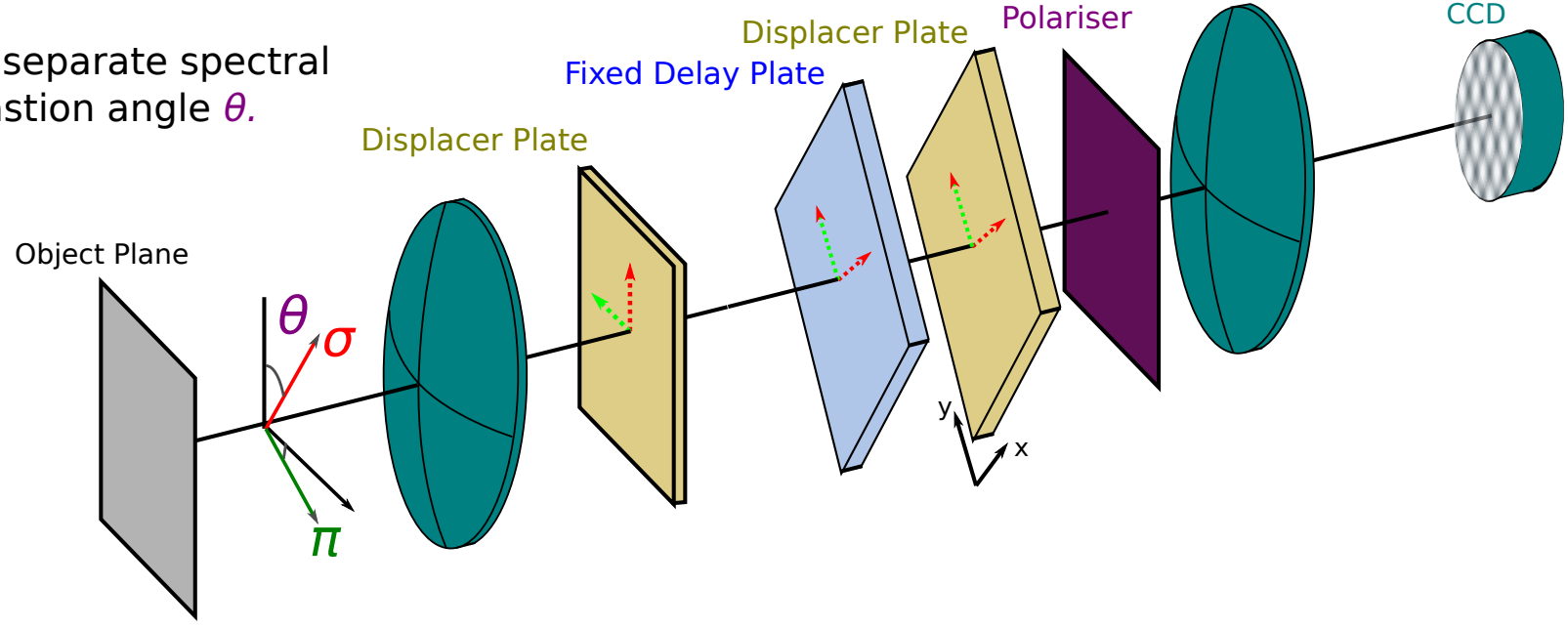

add another displacer at 45°. Combined effect adds 2 extra terms:

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

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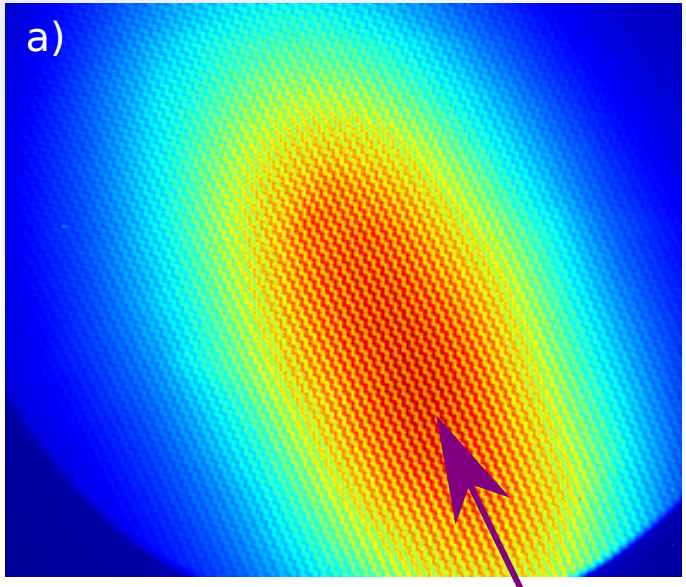

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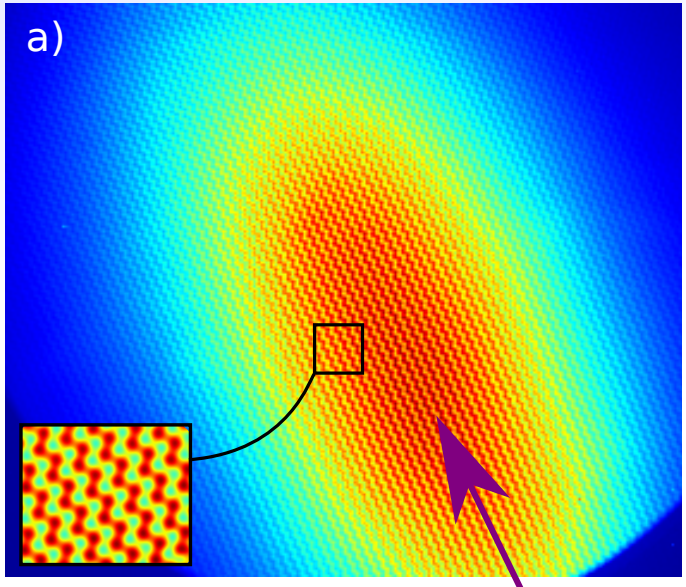

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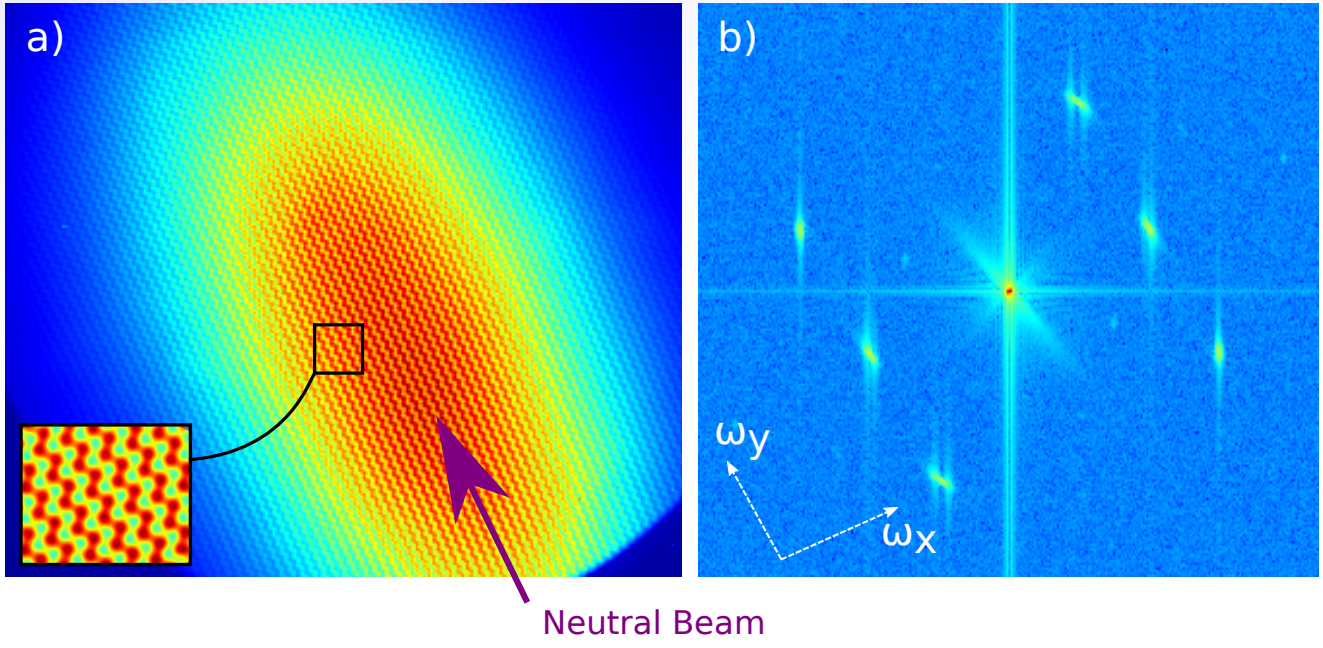

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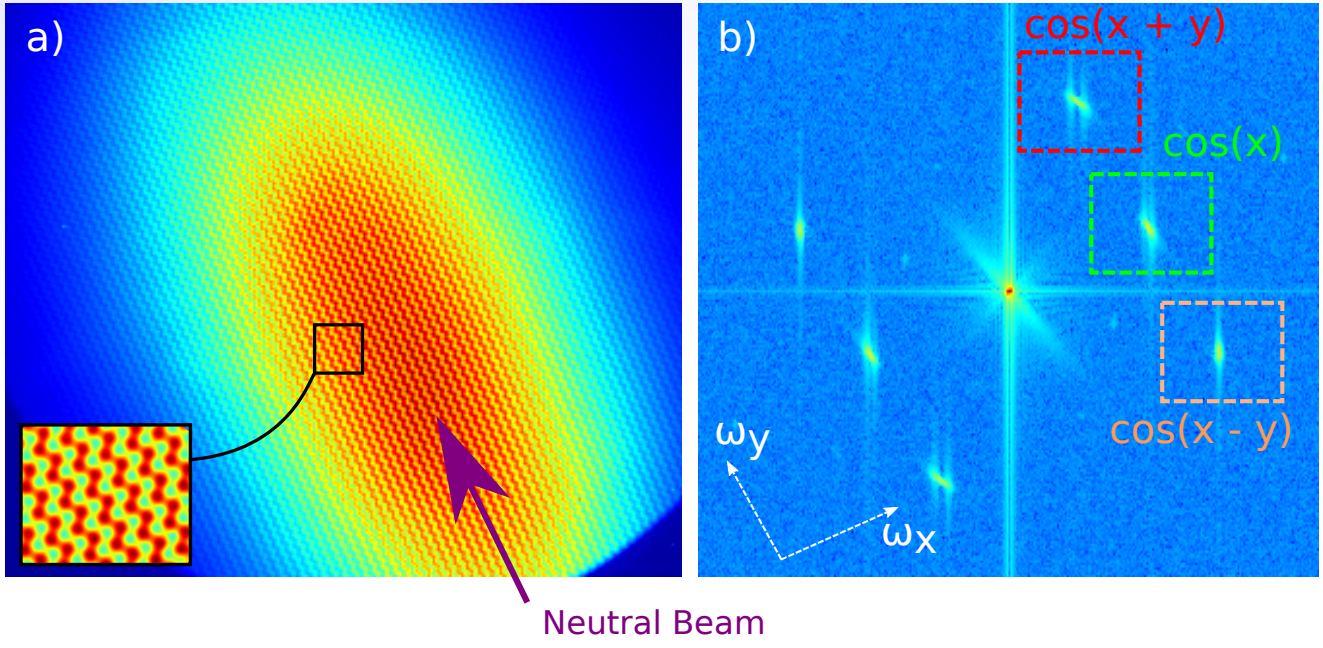

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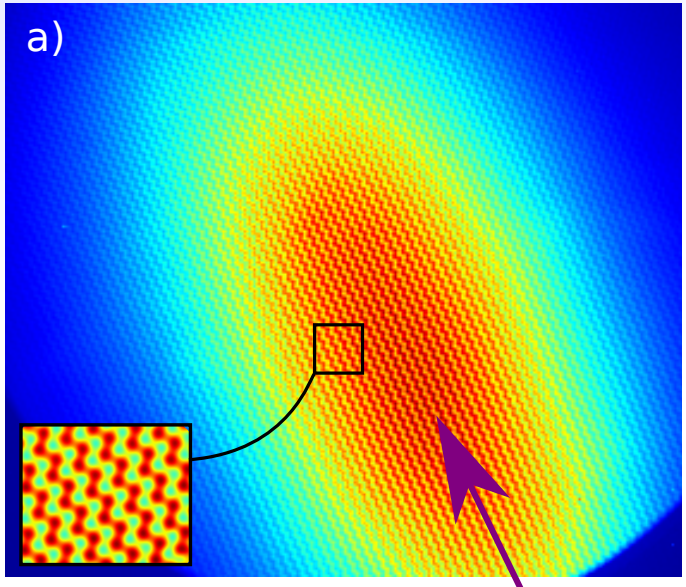

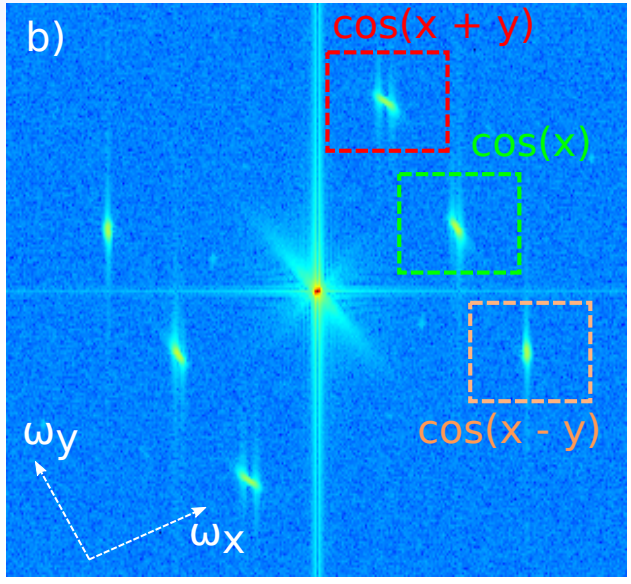

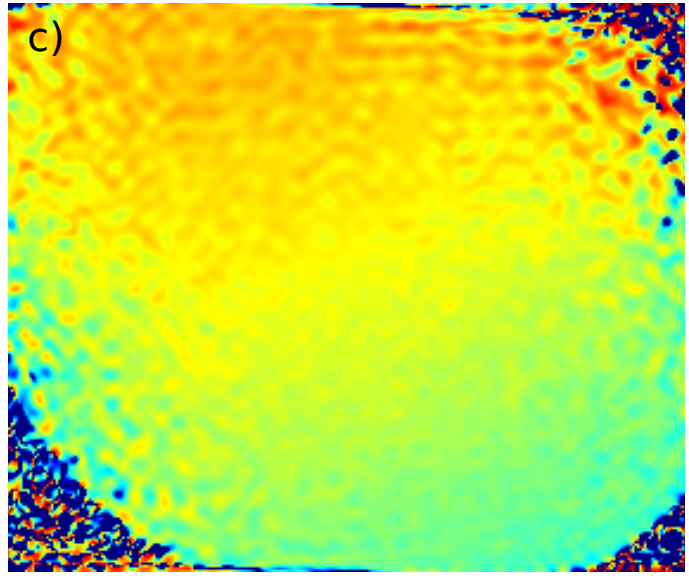

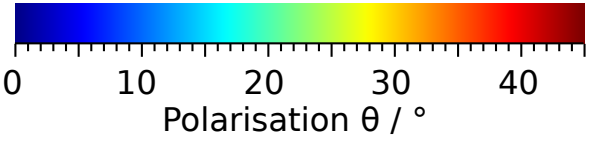

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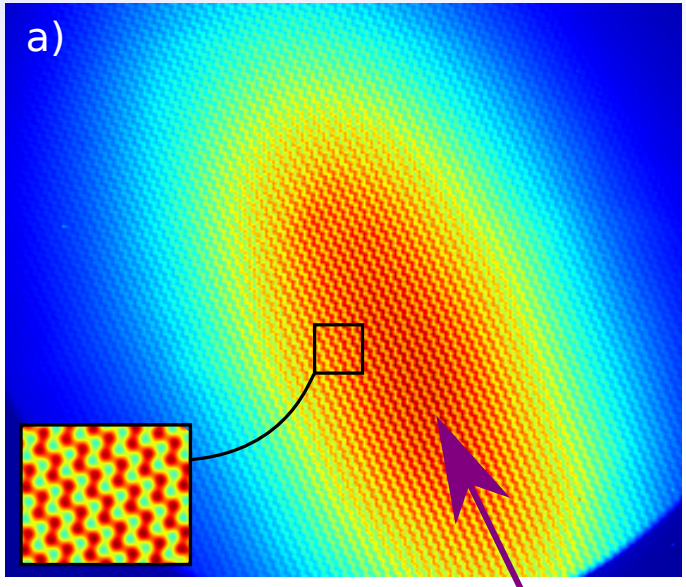

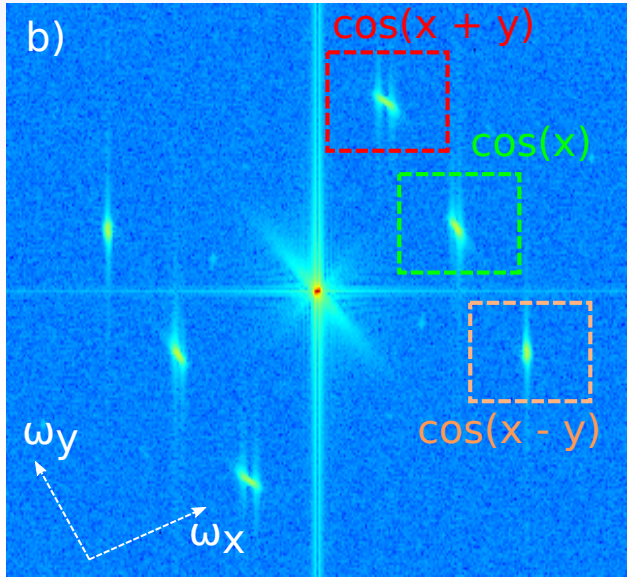

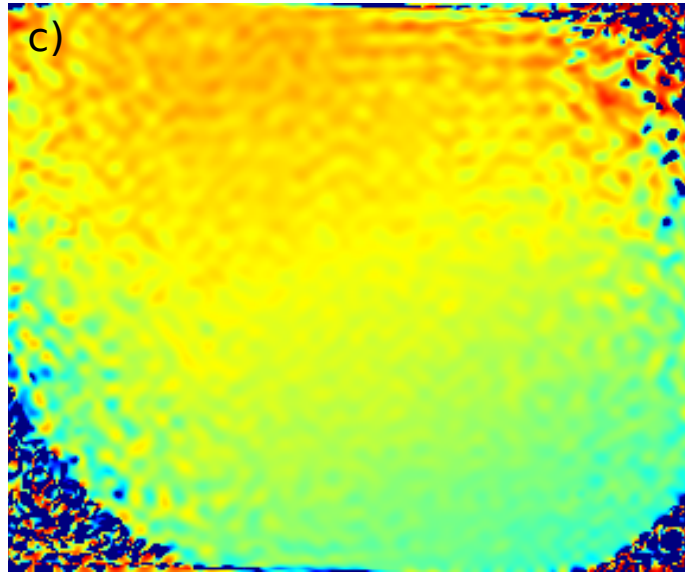

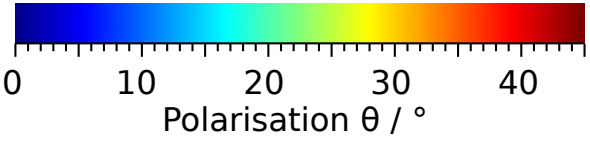

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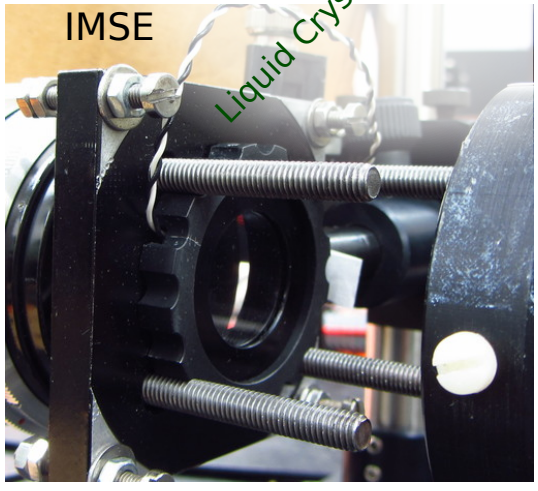

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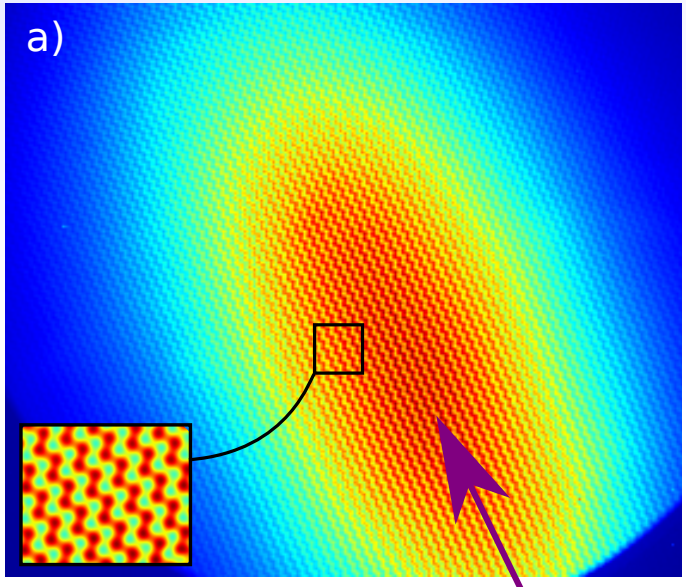

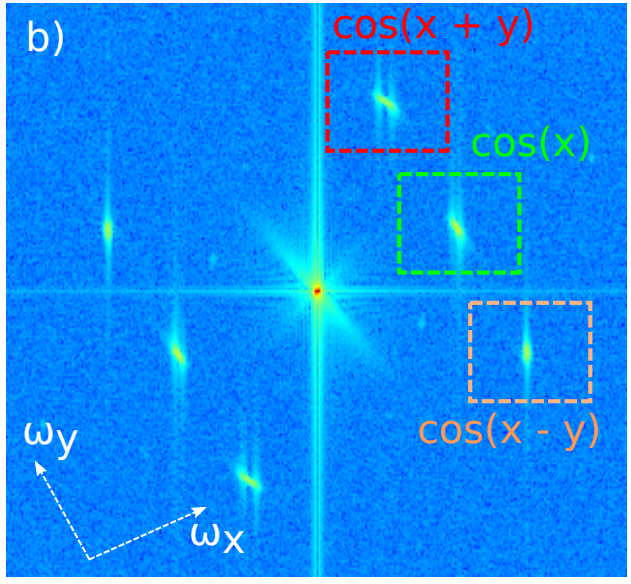

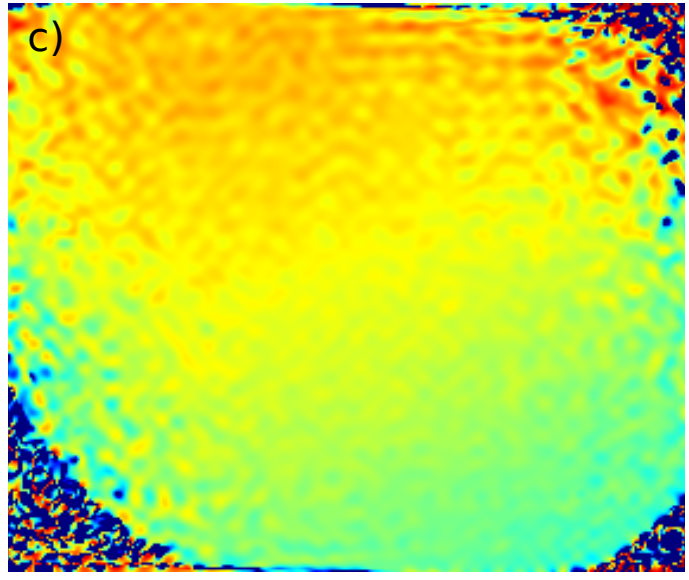

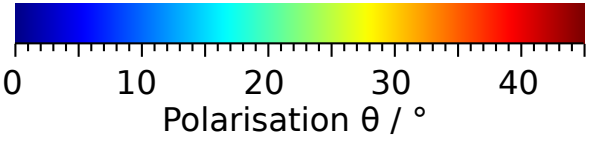

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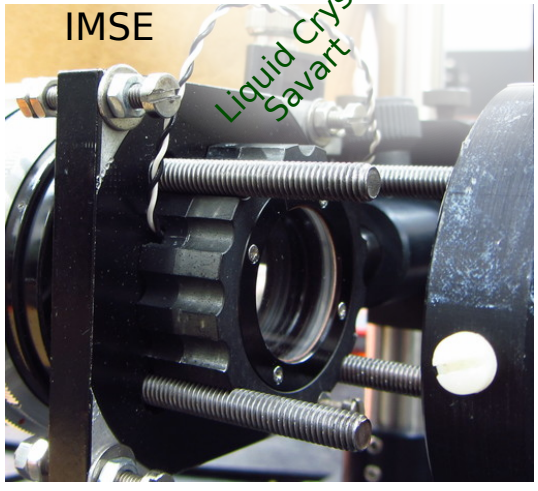

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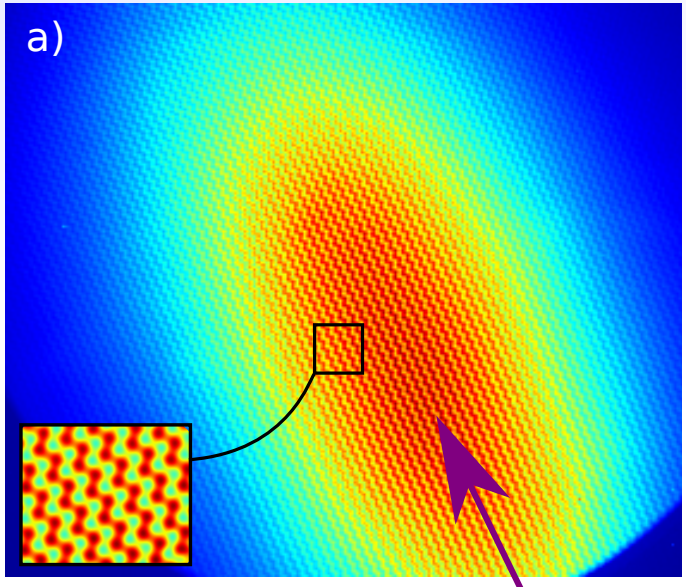
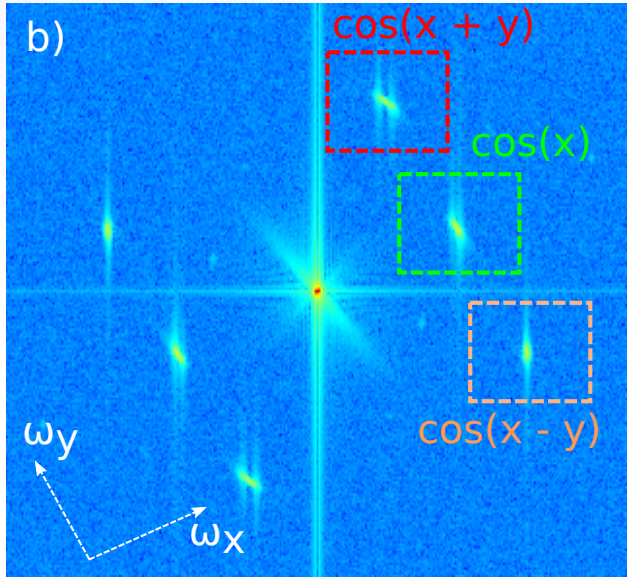
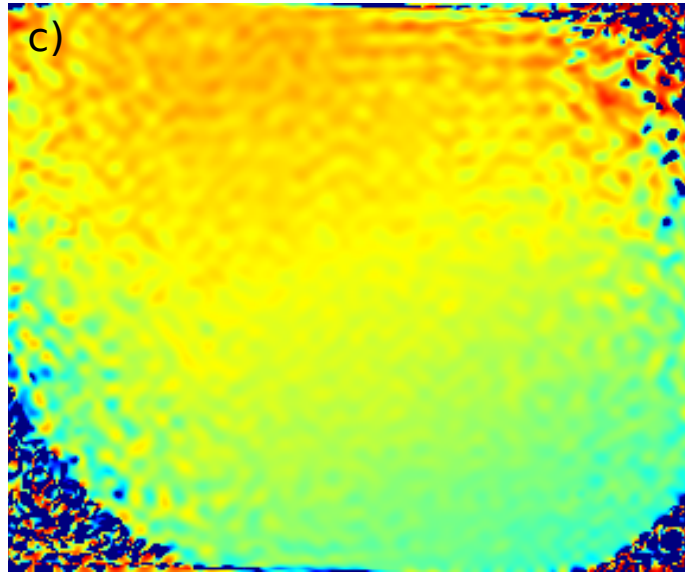
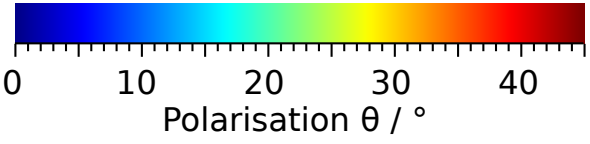






Neutral Beam



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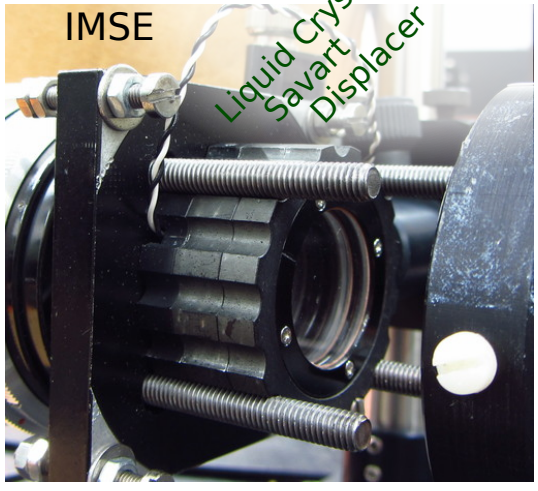

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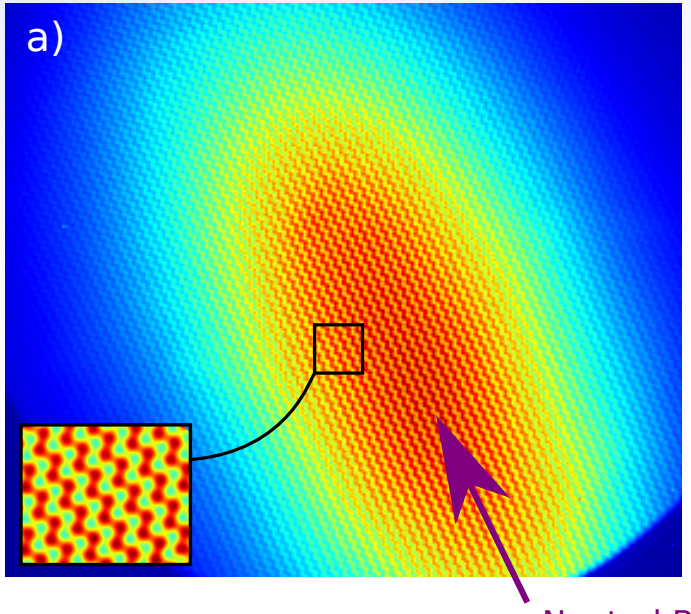

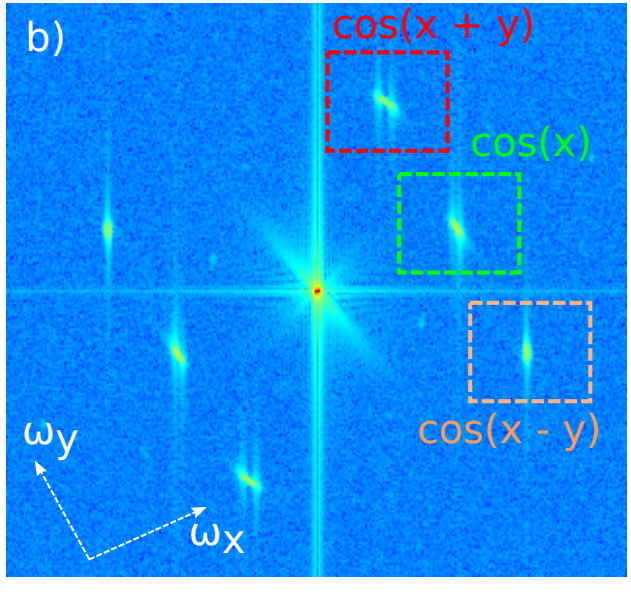

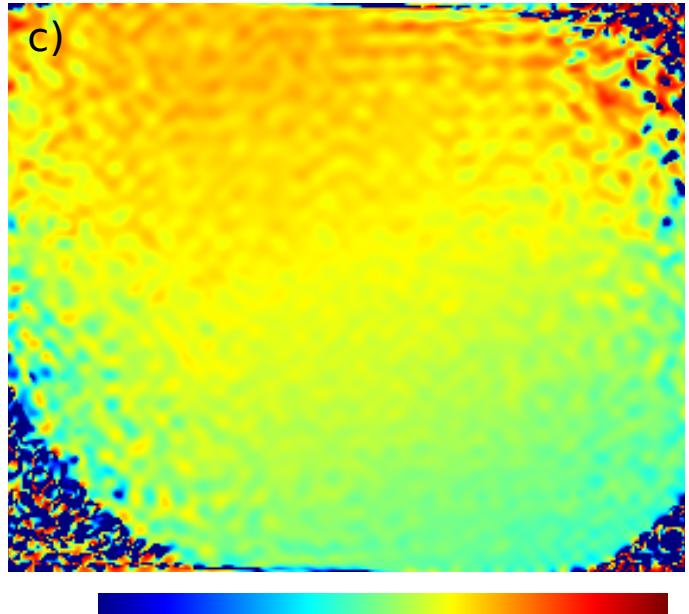

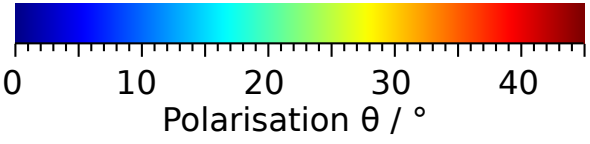

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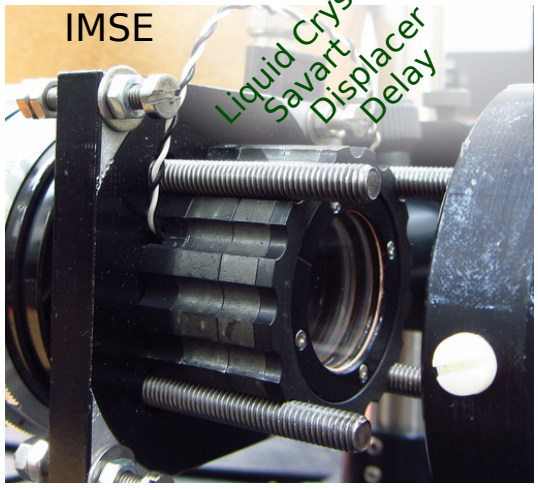

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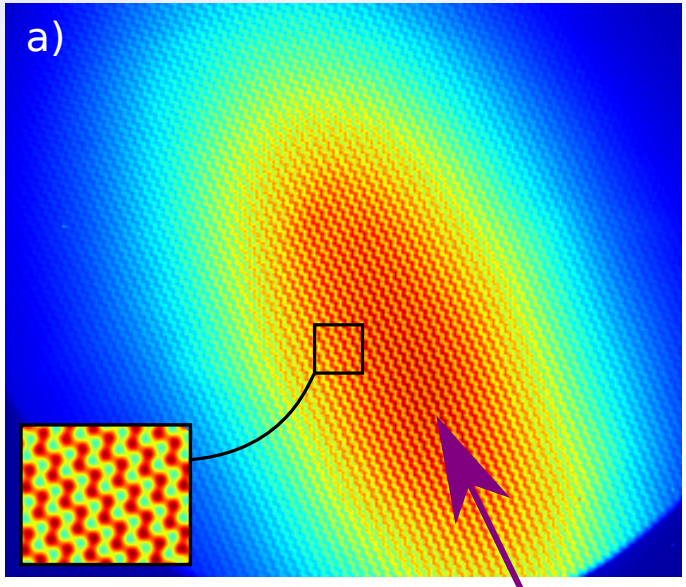

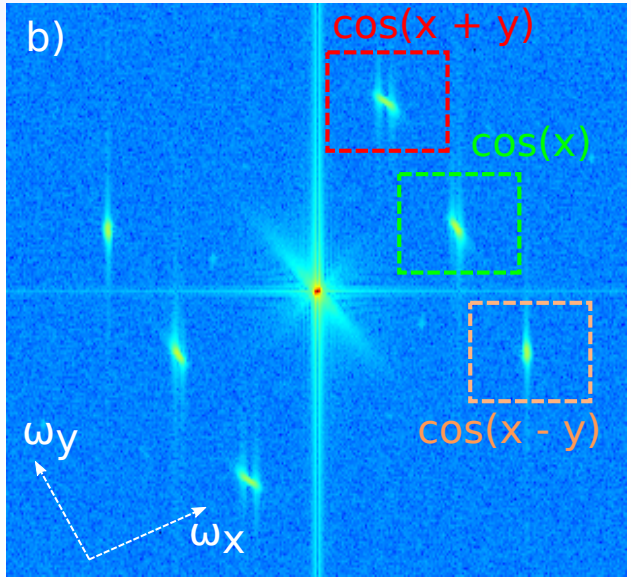

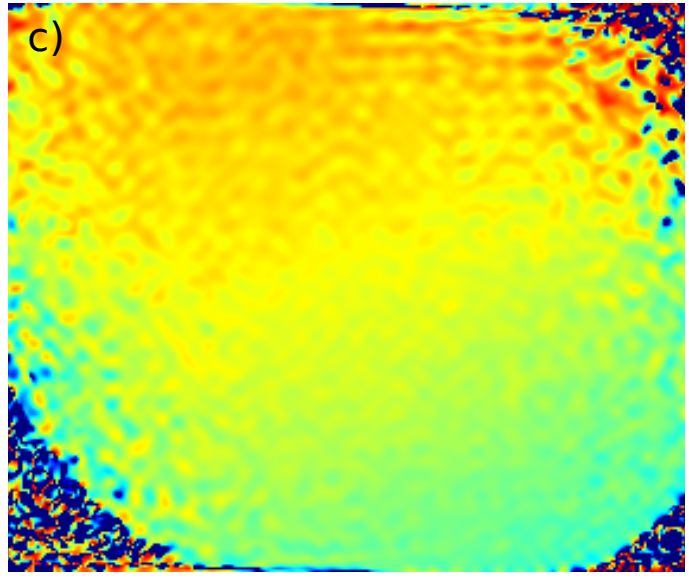

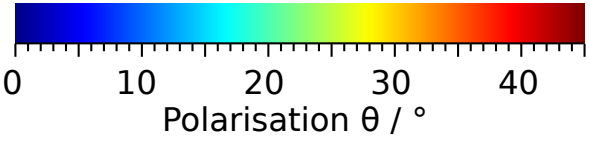

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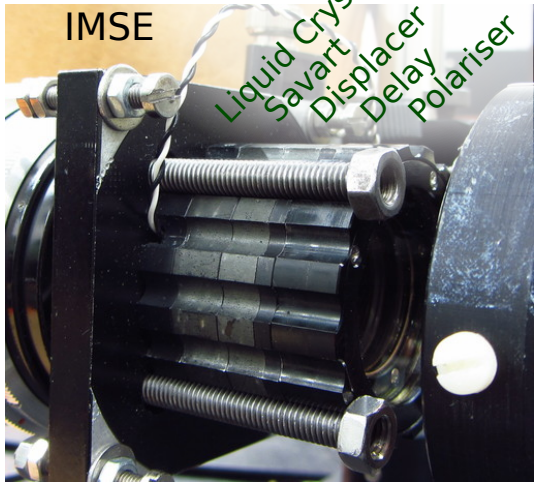

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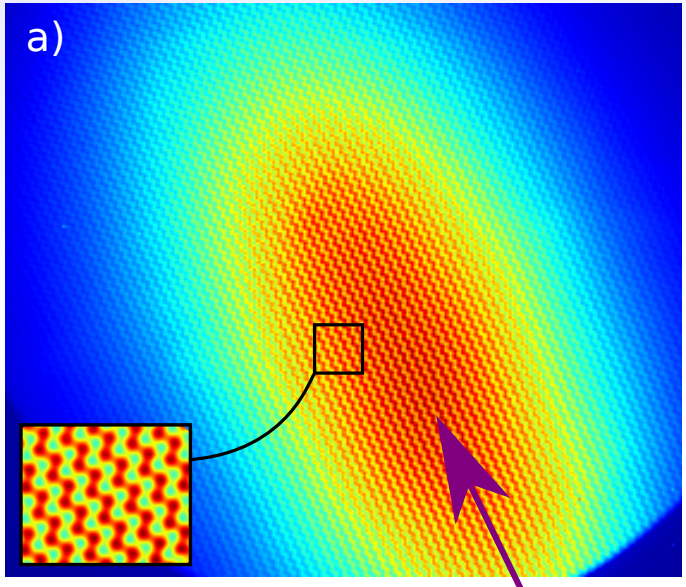

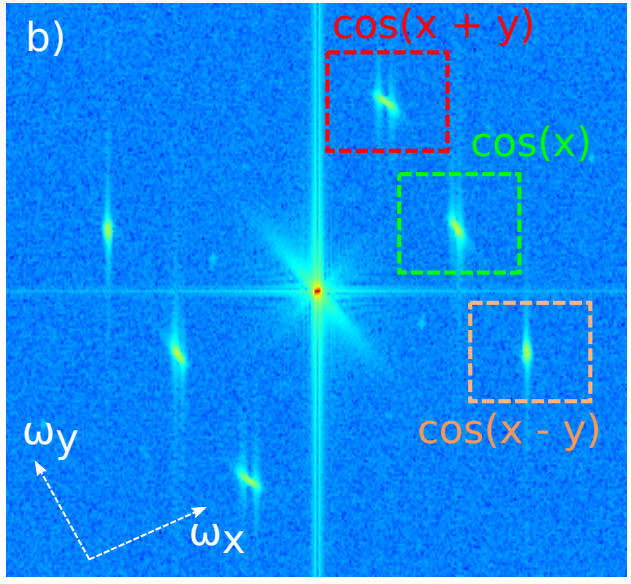

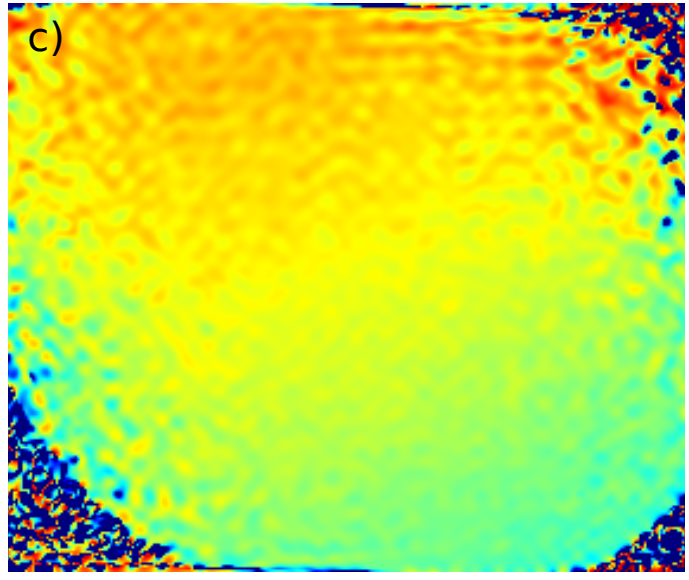

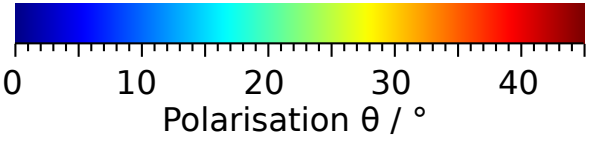

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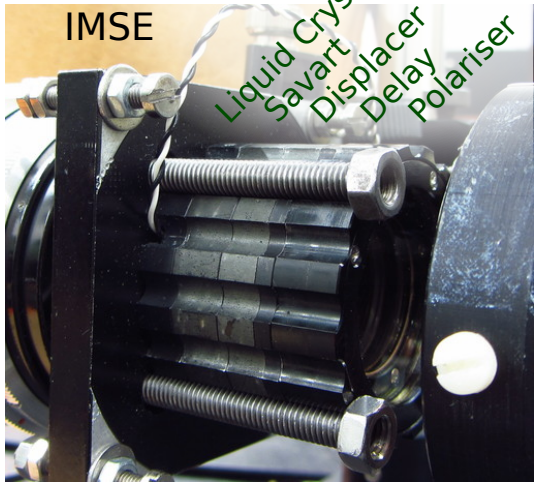

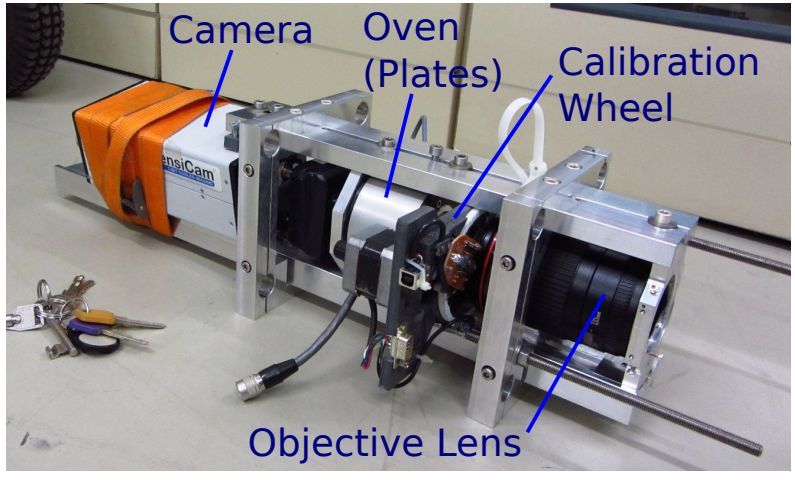

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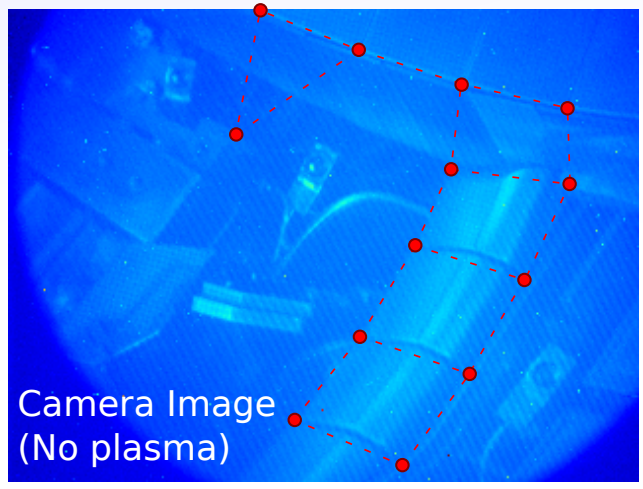

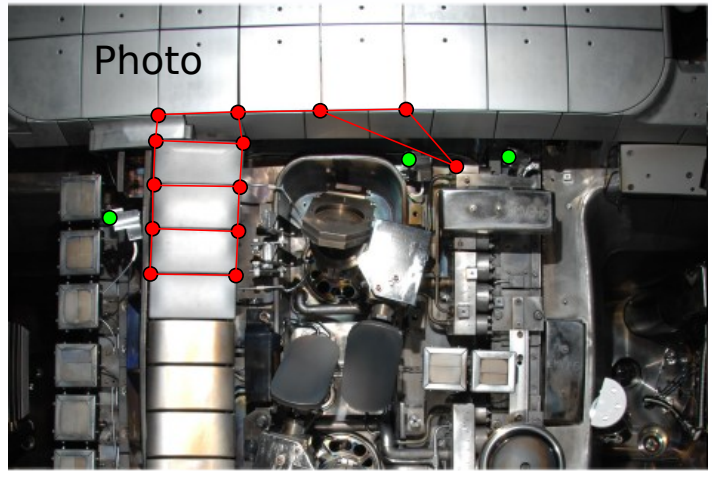

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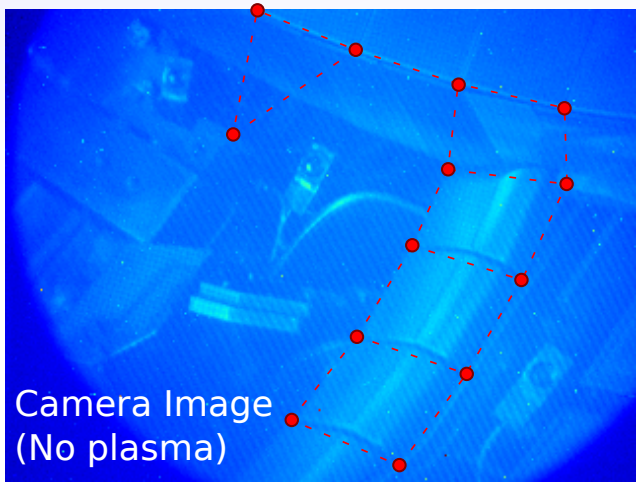

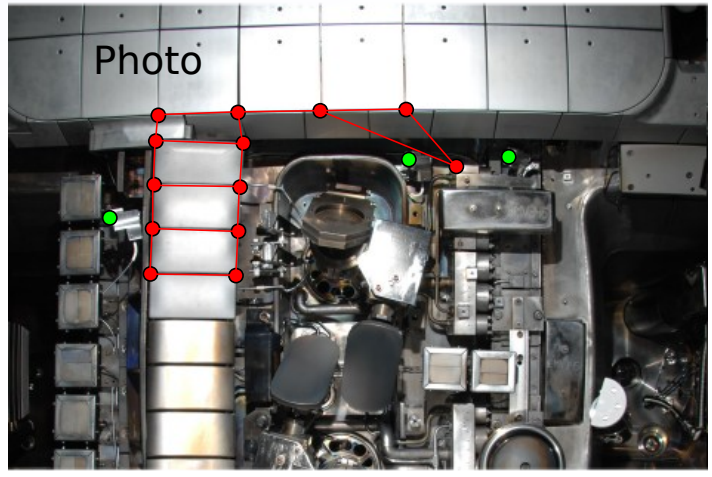

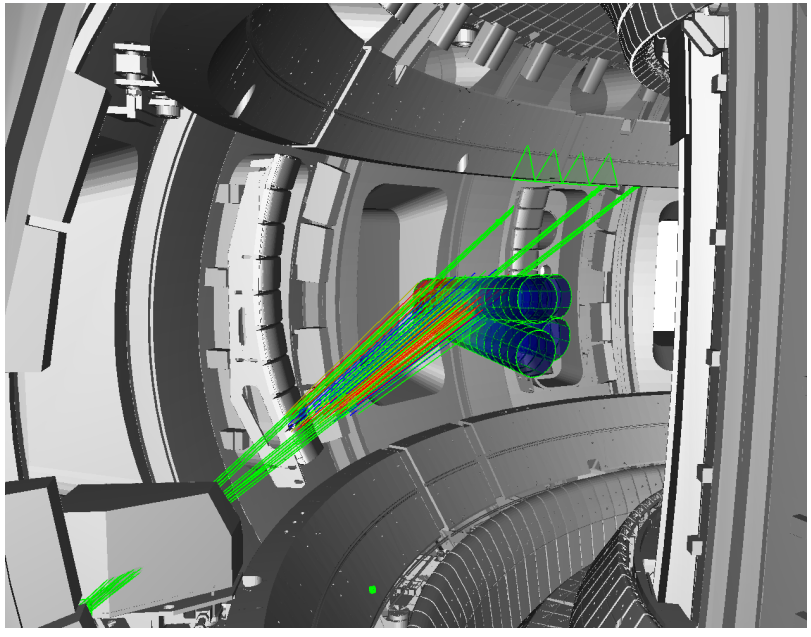

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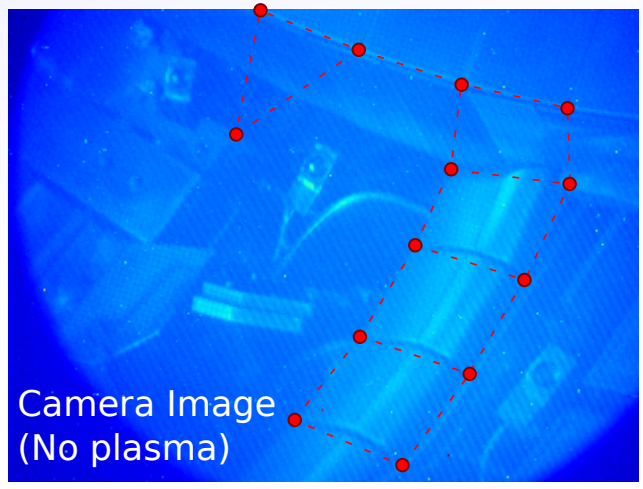

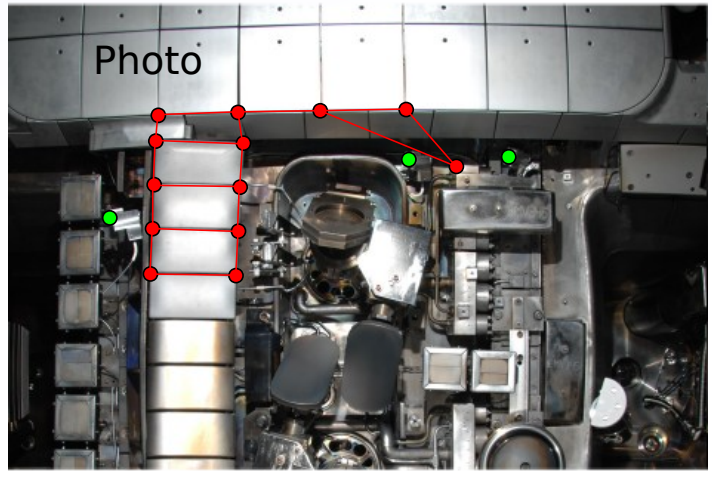

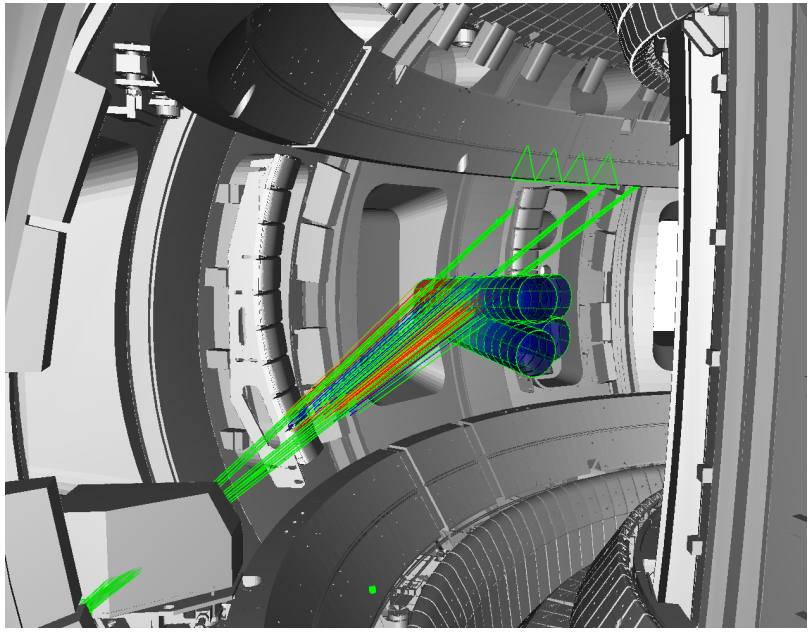

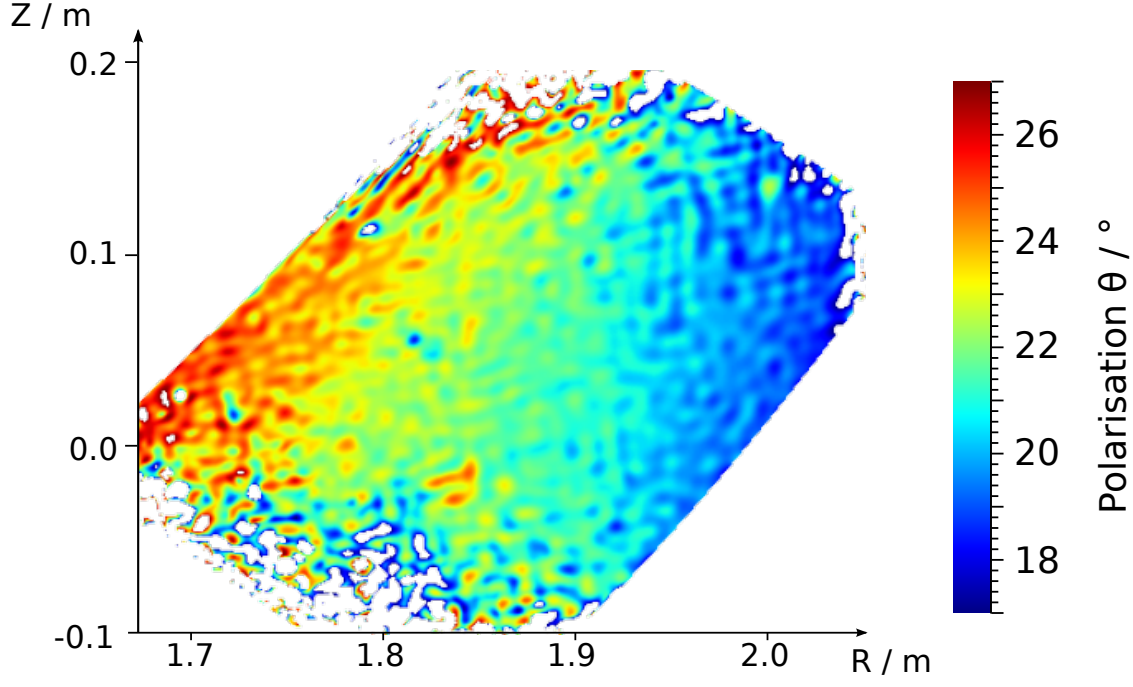

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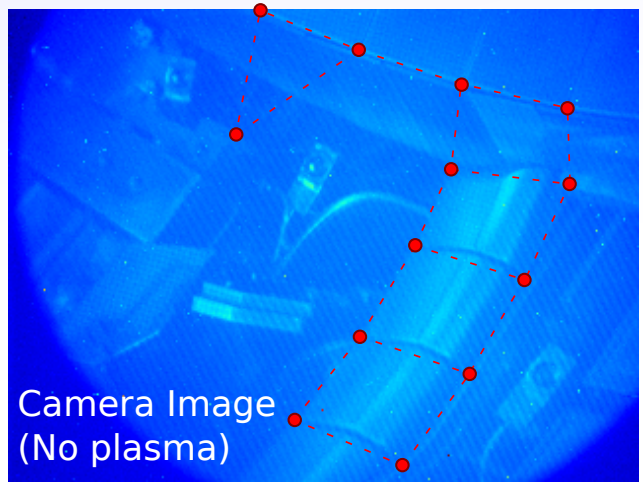
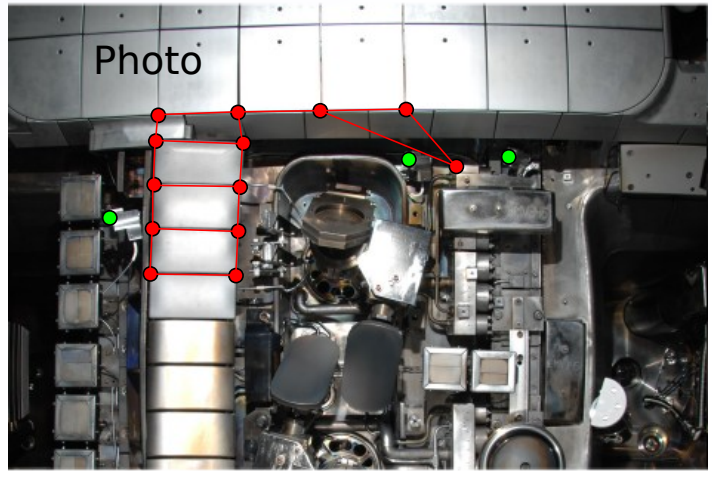
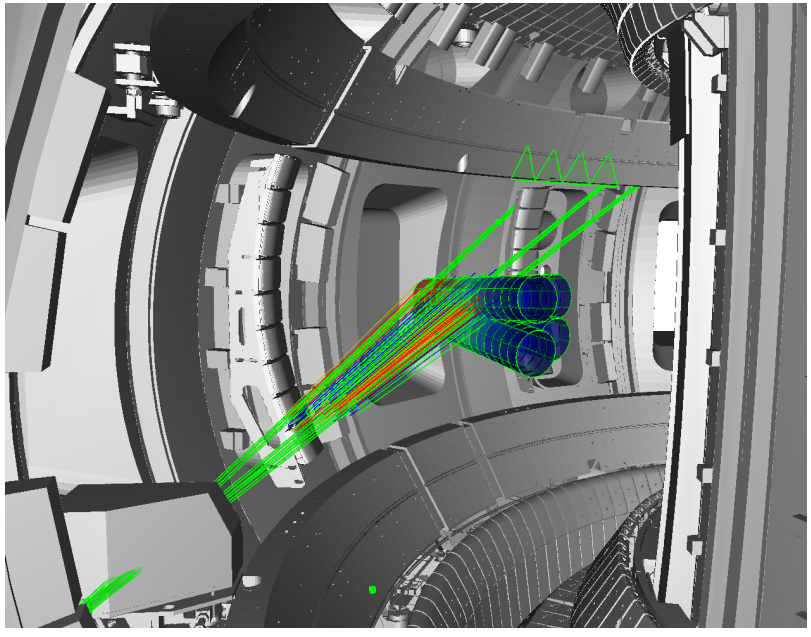
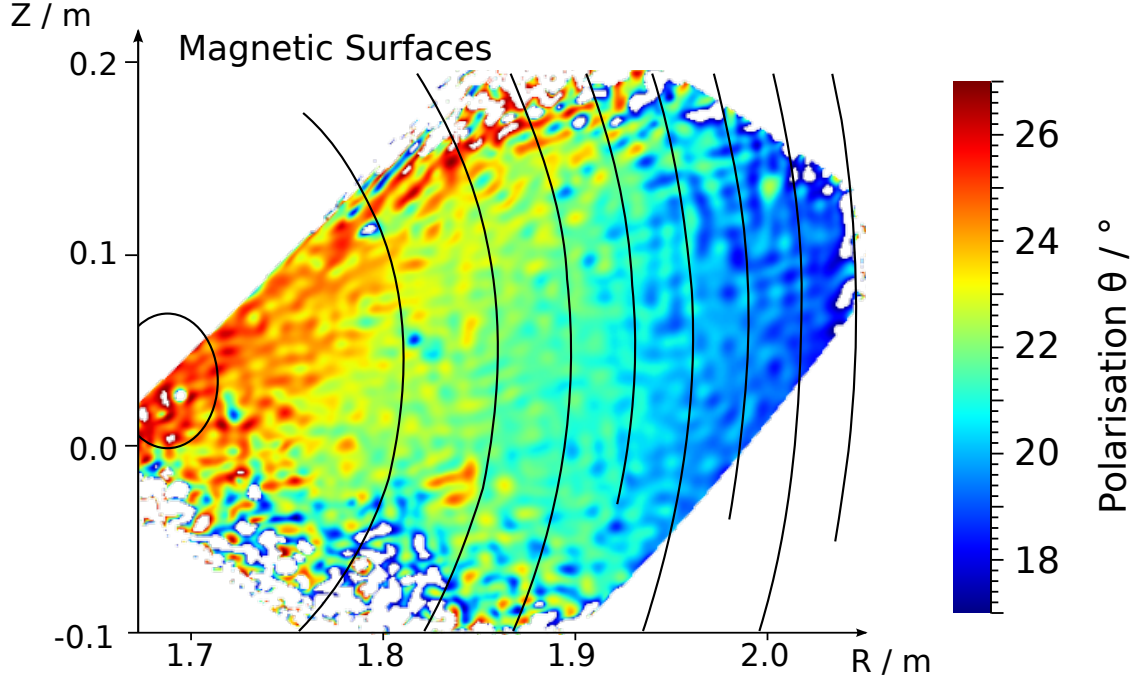
The IMSE has required no torus access to calibrate (so far).









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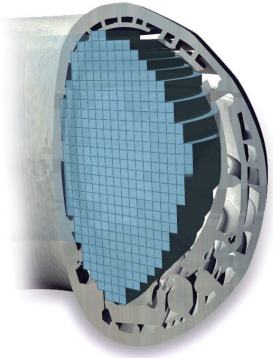
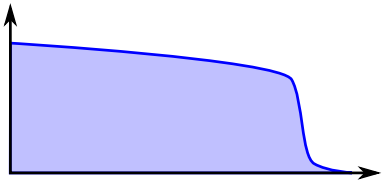


Plasma Current (2D)



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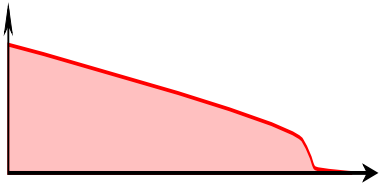

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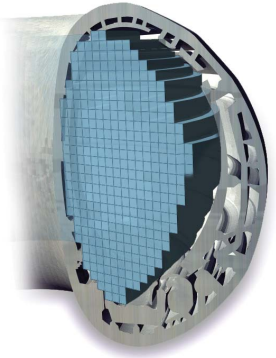

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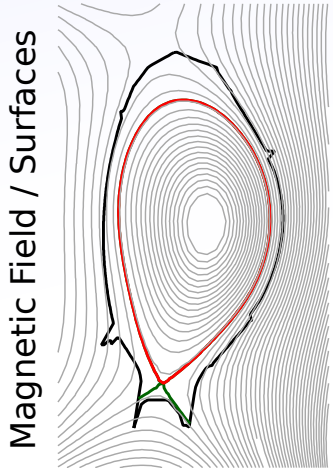

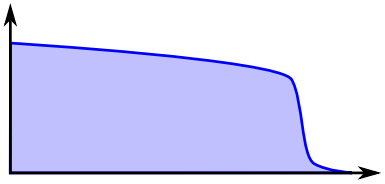

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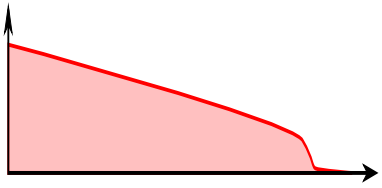

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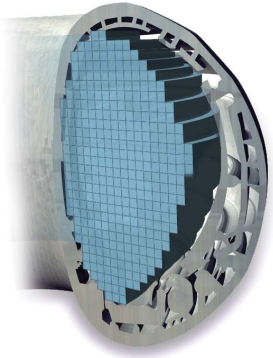

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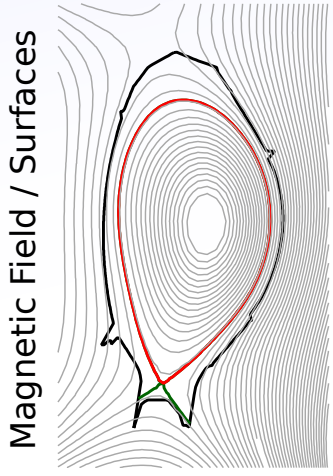

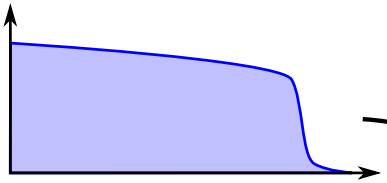

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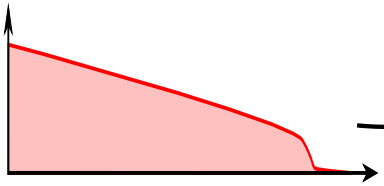

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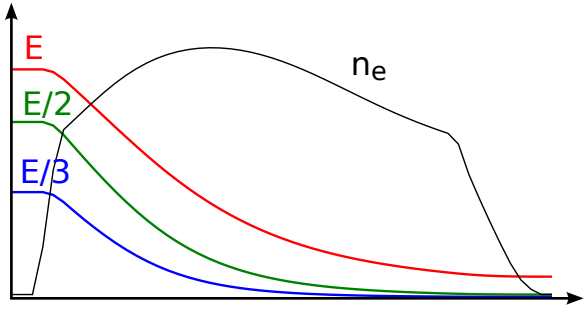

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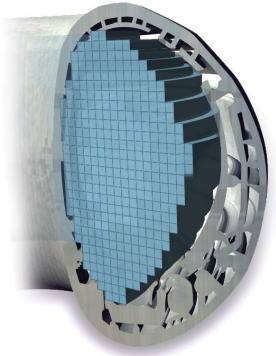

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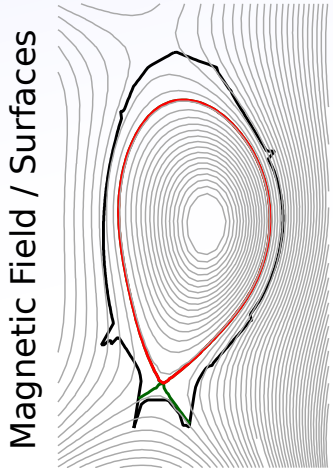

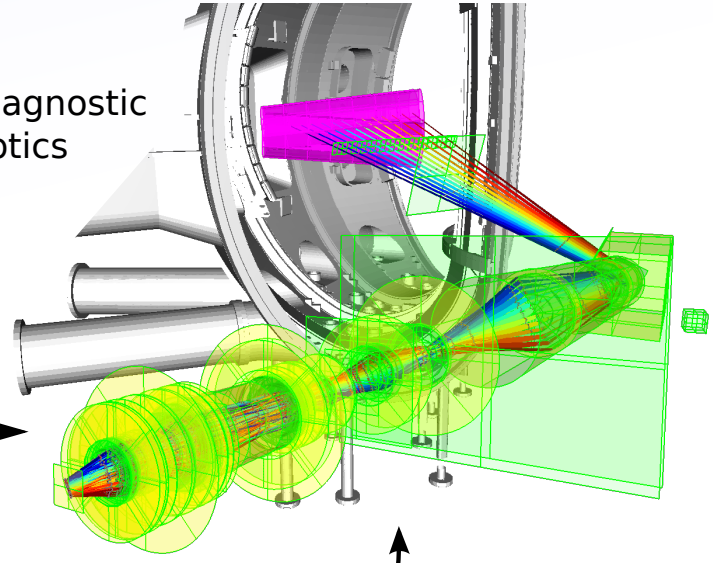

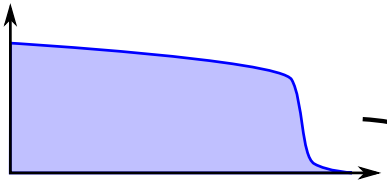

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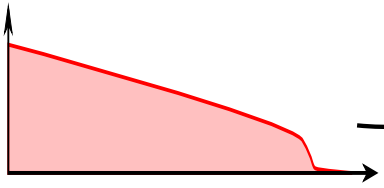

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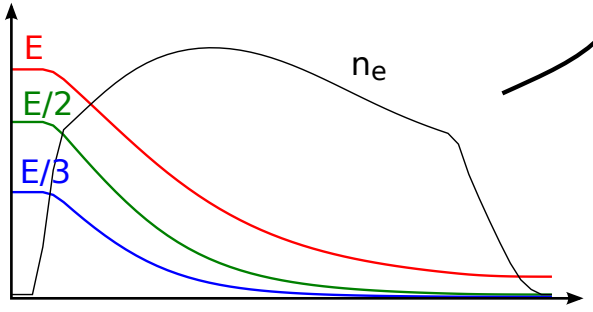

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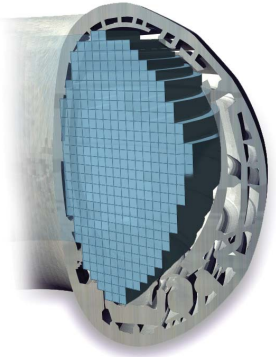

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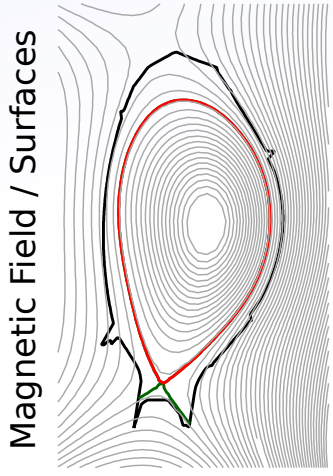

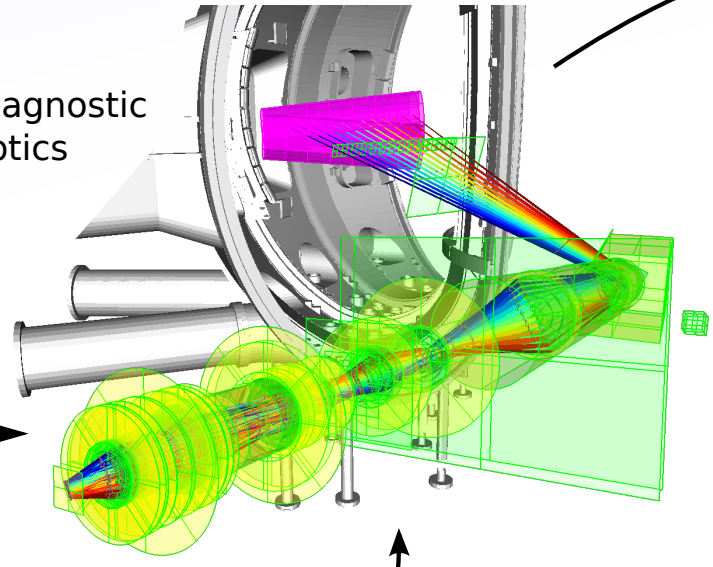

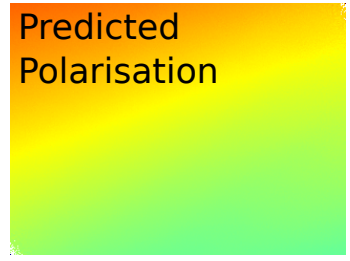

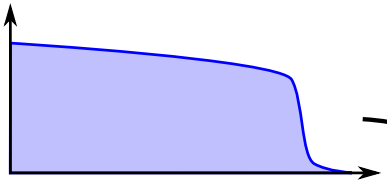

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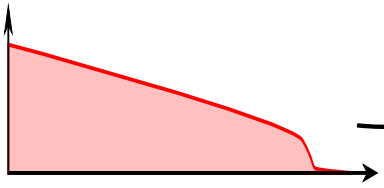

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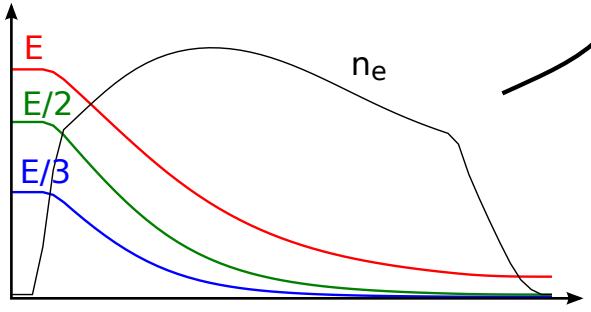

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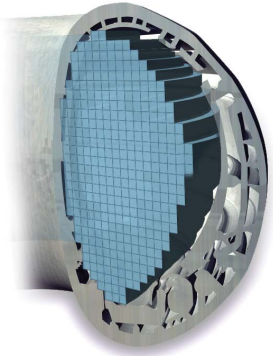

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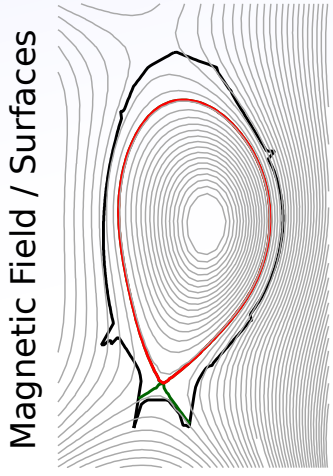

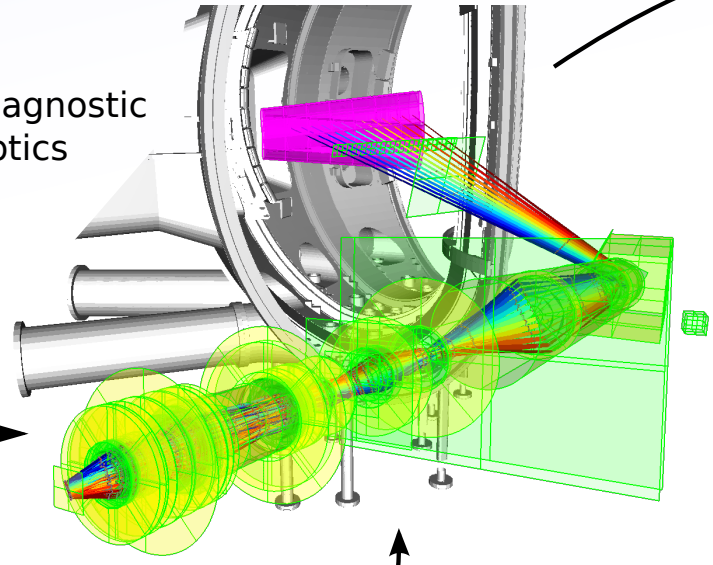

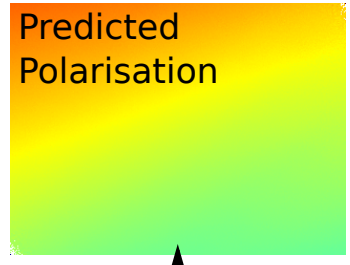

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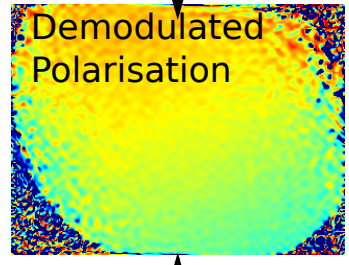
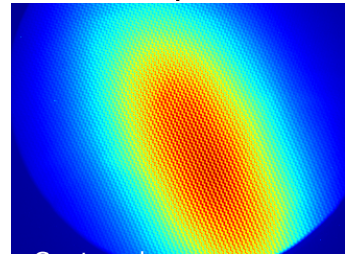
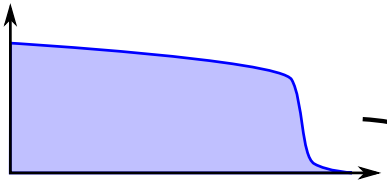




Captured Image



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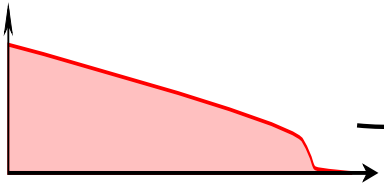

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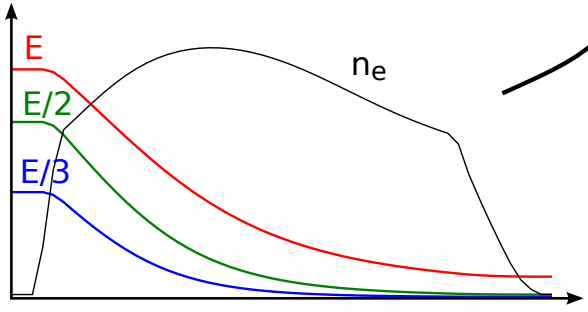

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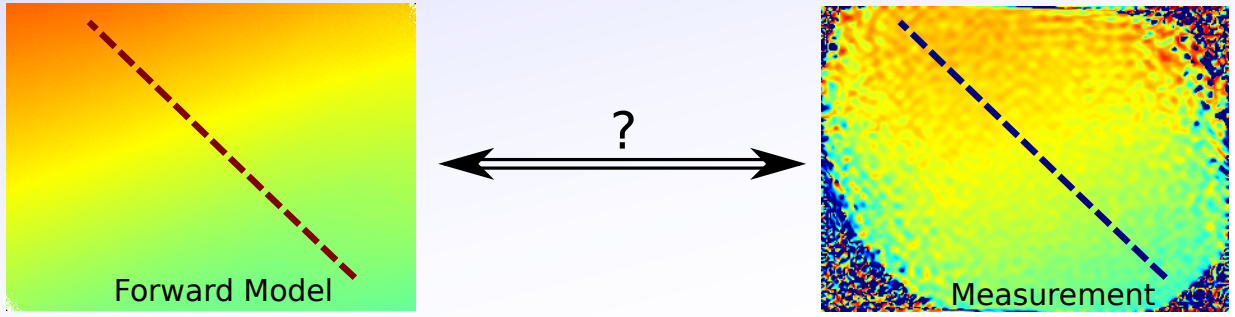

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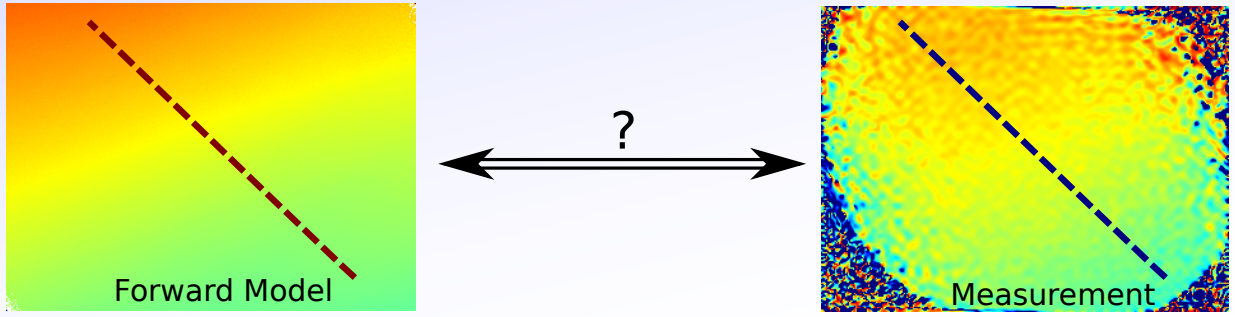

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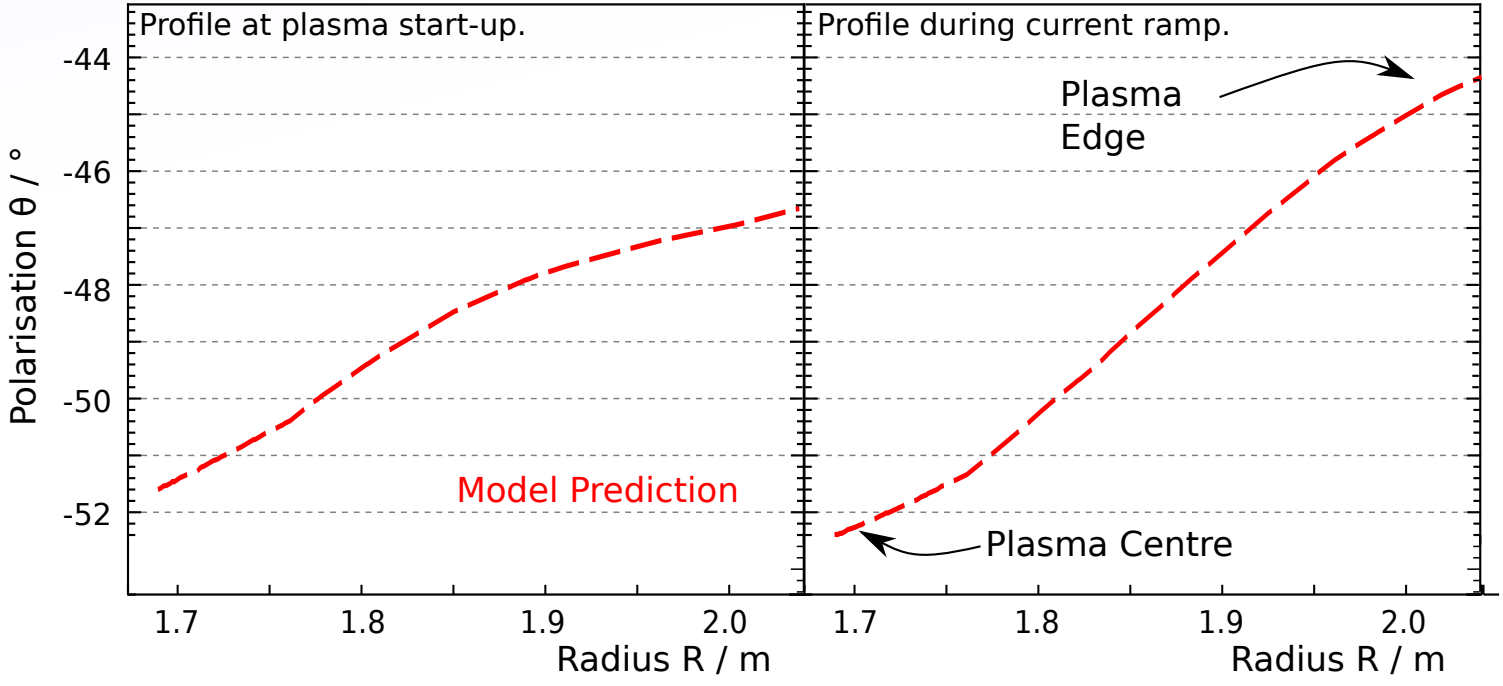

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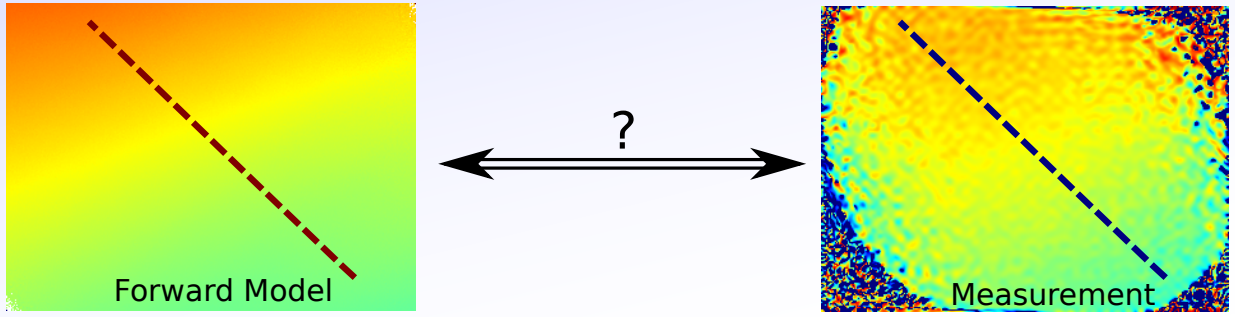

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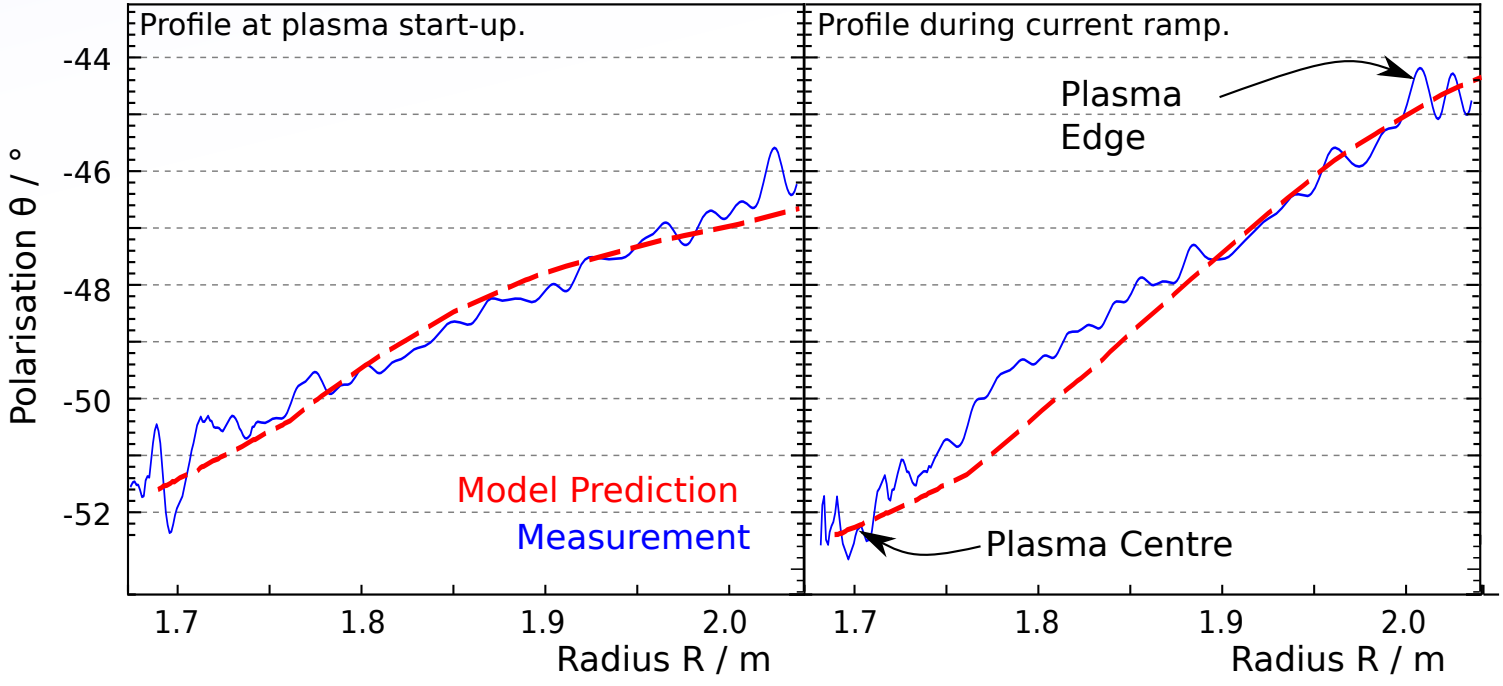

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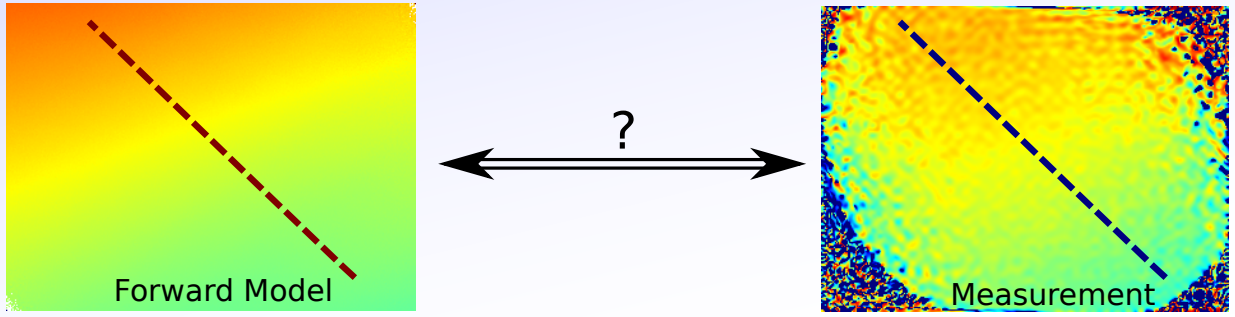

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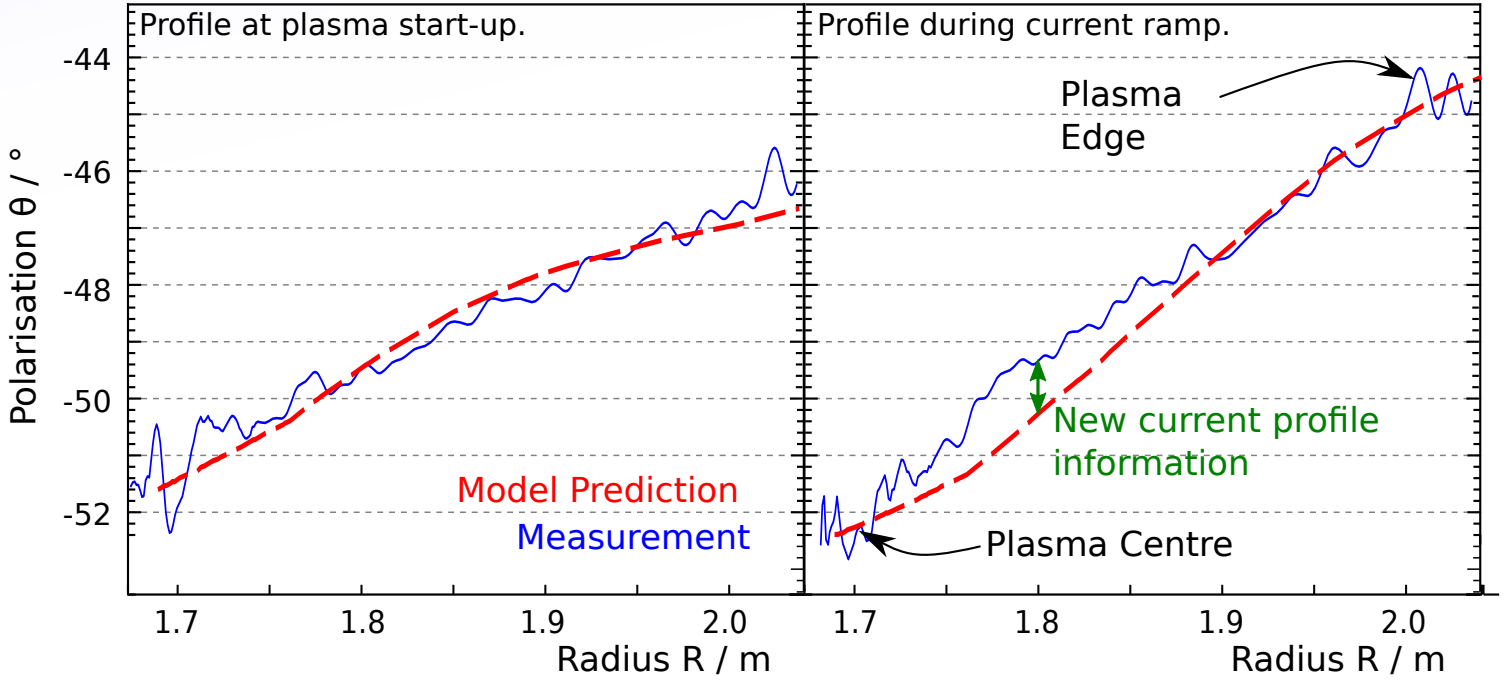
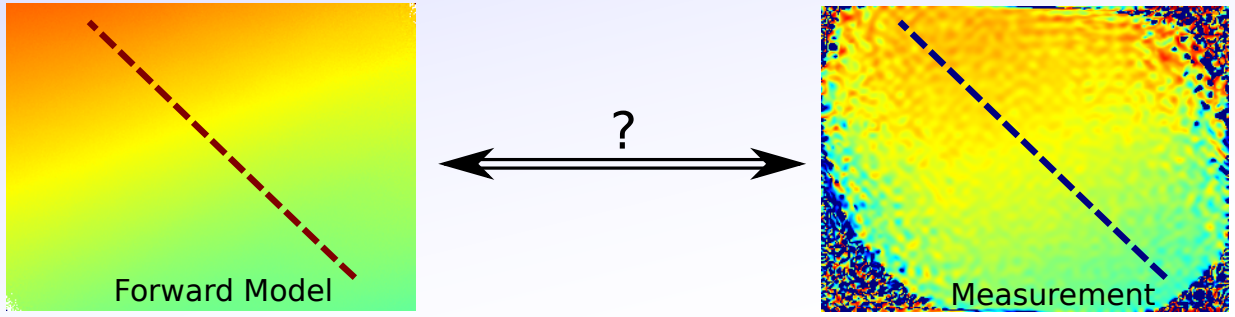


Preliminary comparison with Forward Model



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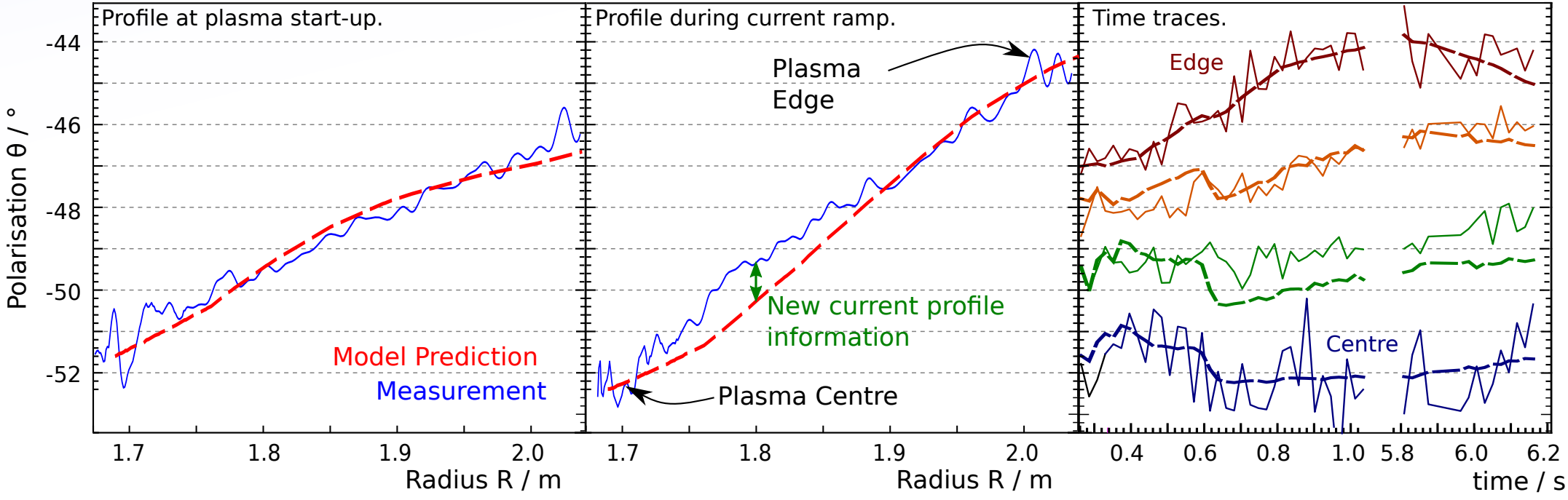

Inferring the plasma current and q-profiles from the polarisation is far from trivial and the analysis work is still on-going.

Oliver Ford
IPP Greifswald

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    - 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.