

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

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J. Svensson,<sup>1</sup> R. Wolf,<sup>1</sup> ASDEX Upgrade Team

1: Max-Planck Institut für Plasmaphysik, Greifswald/Garching, Germany

2: Plasma Research Laboratory, Australian National University, Canberra

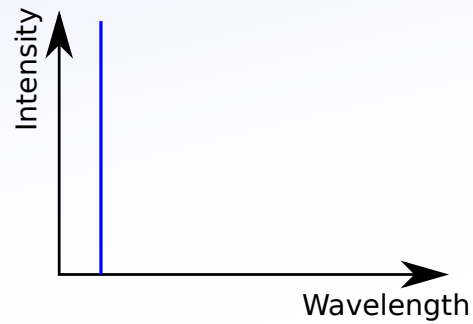
With special thanks to S. Silburn, CCFE / Durham University, UK



# Doppler Spectroscopy

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

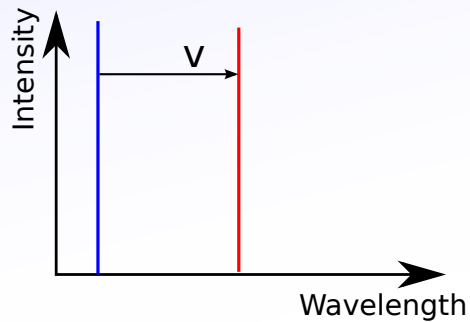
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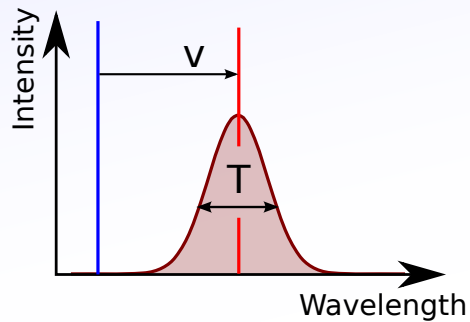


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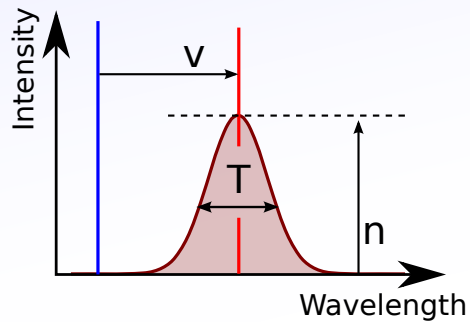
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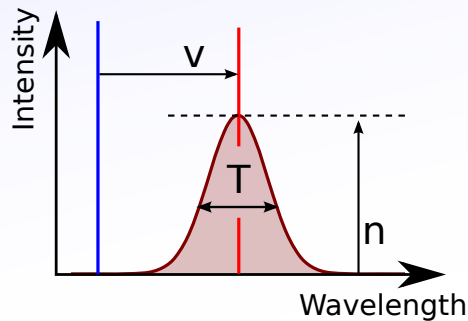


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Doppler broadening --> Temperature  
Intensity --> Particle density

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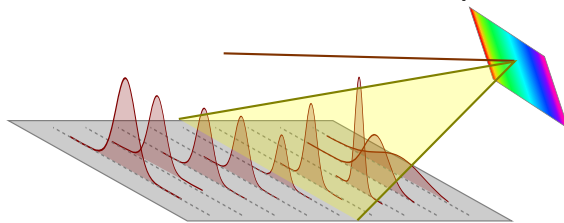
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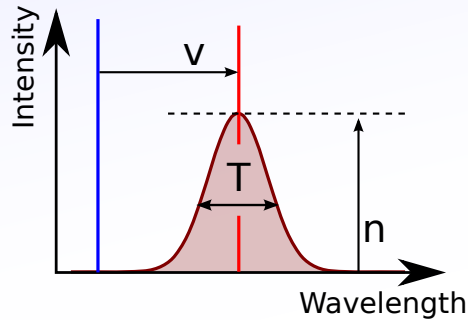


Low light levels. 1D set of points.

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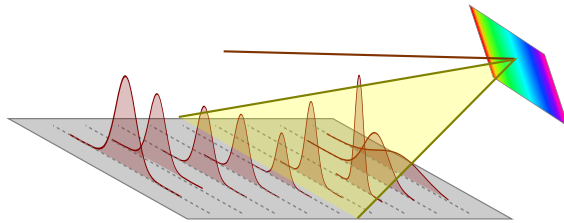
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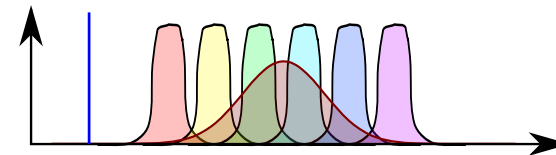
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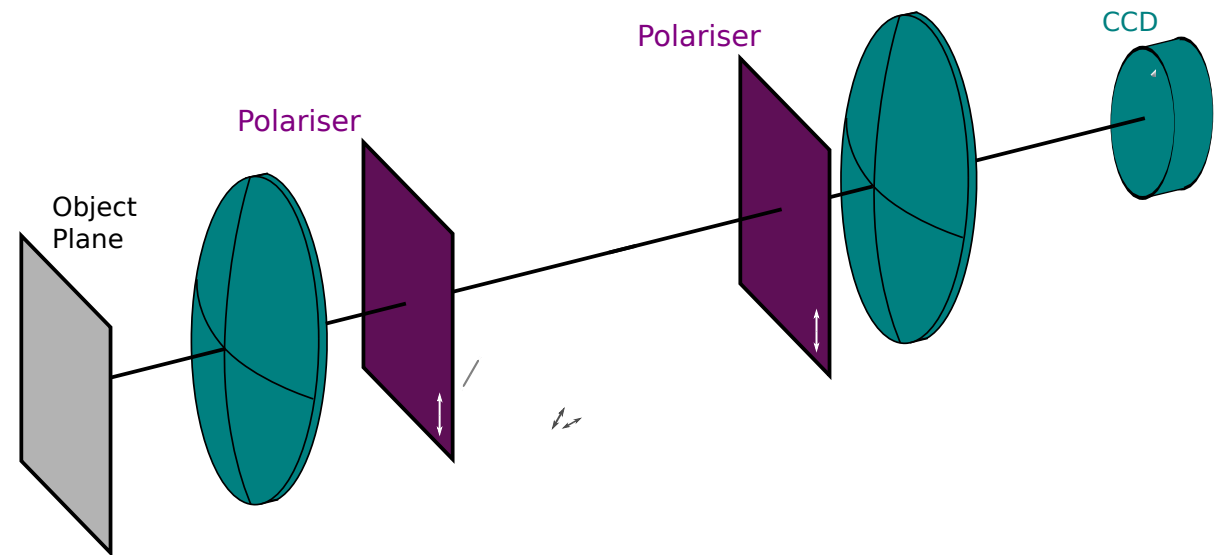
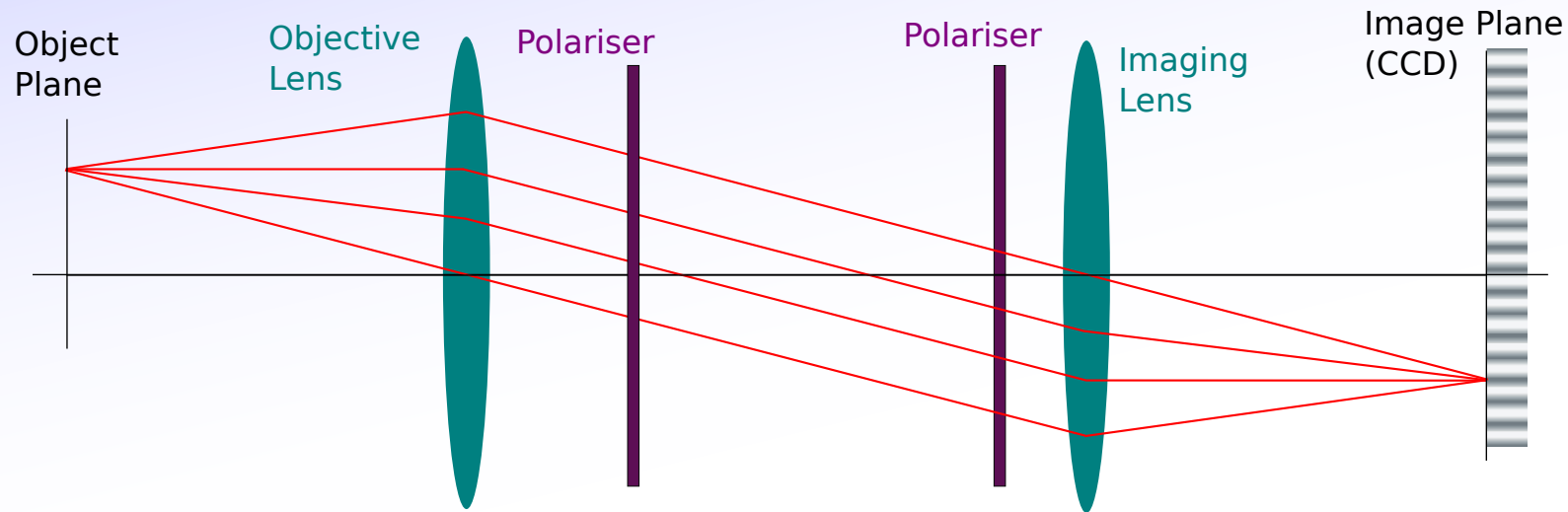
Individual spectral filters and  
fast sensitive detectors.

or



Very complex setup per channel.  
Low spectral resolution.

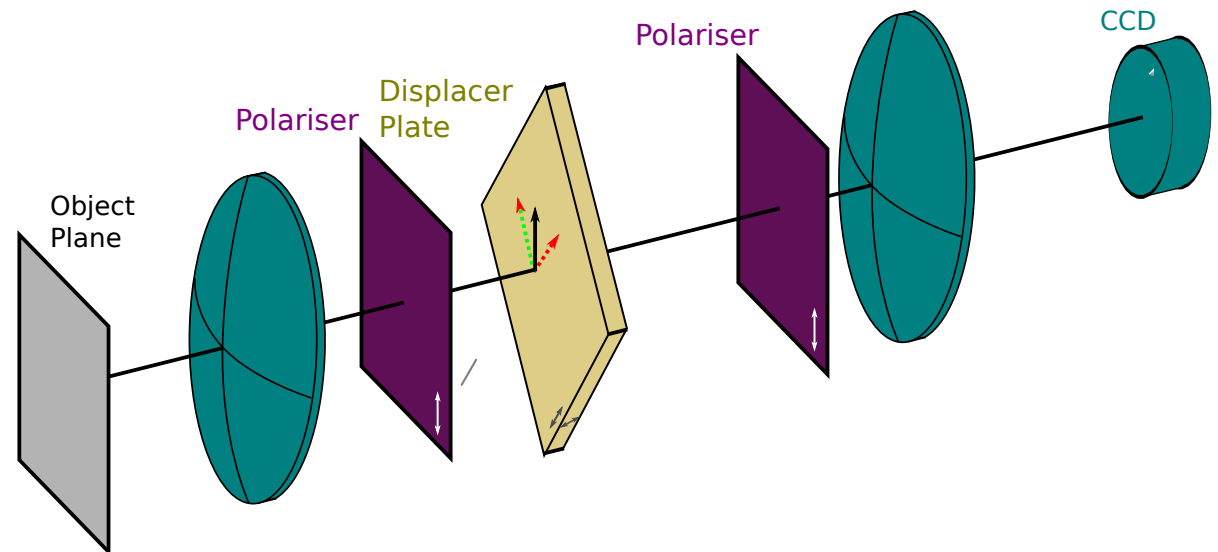
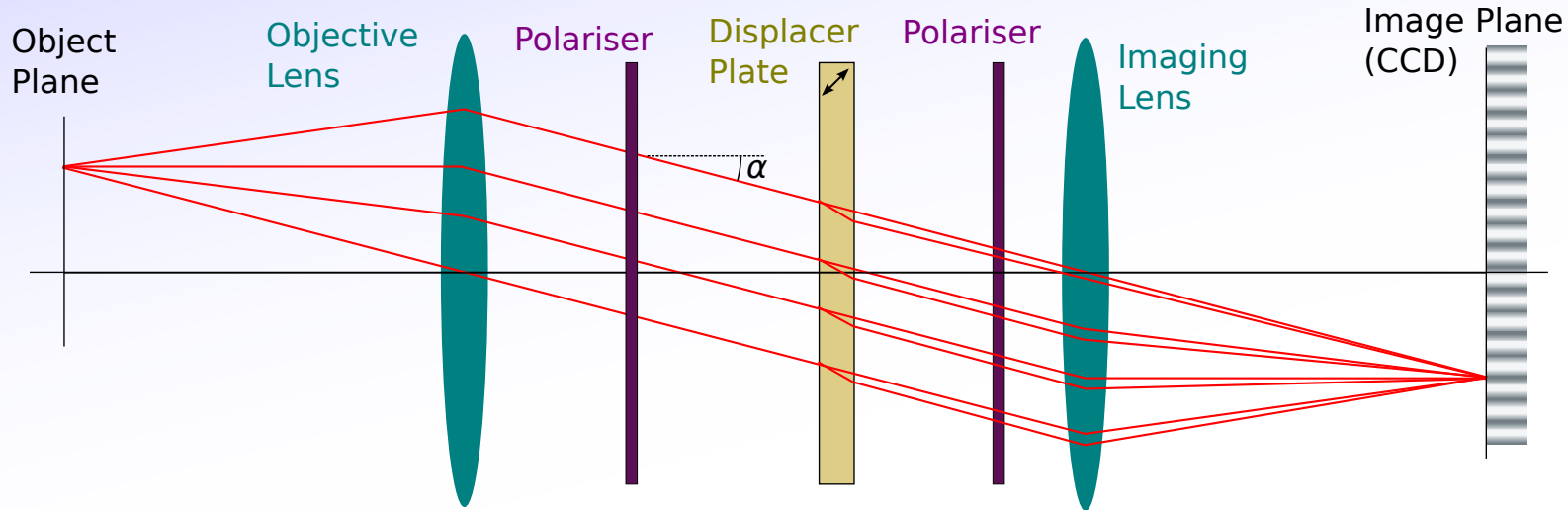
# Coherence Imaging





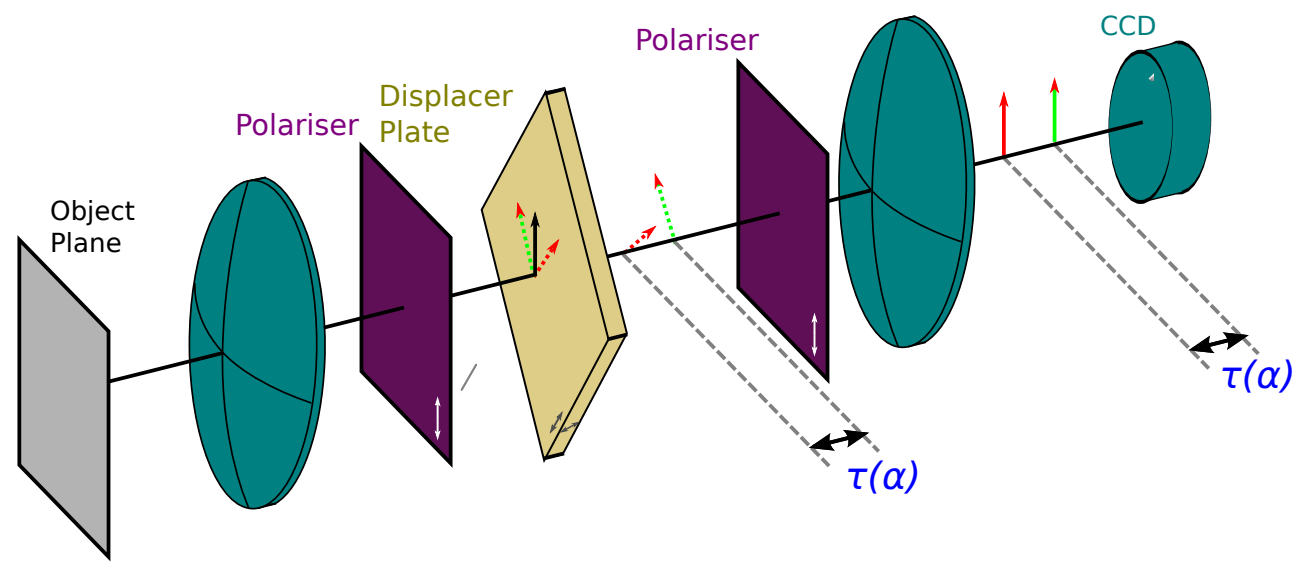
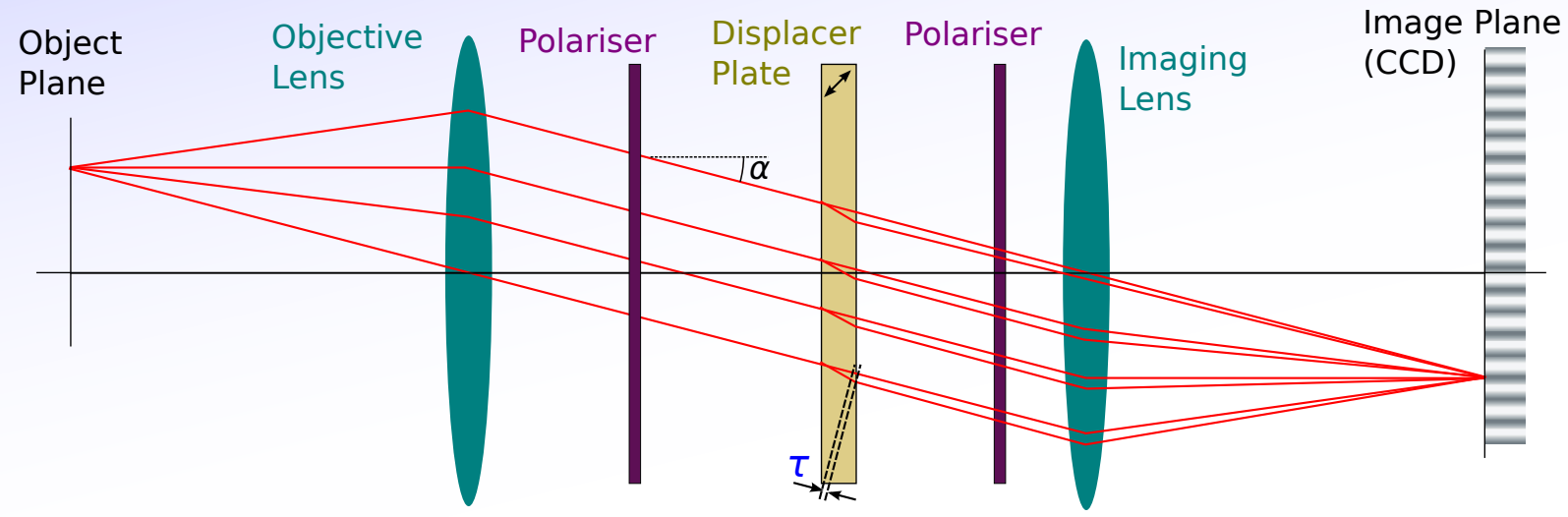
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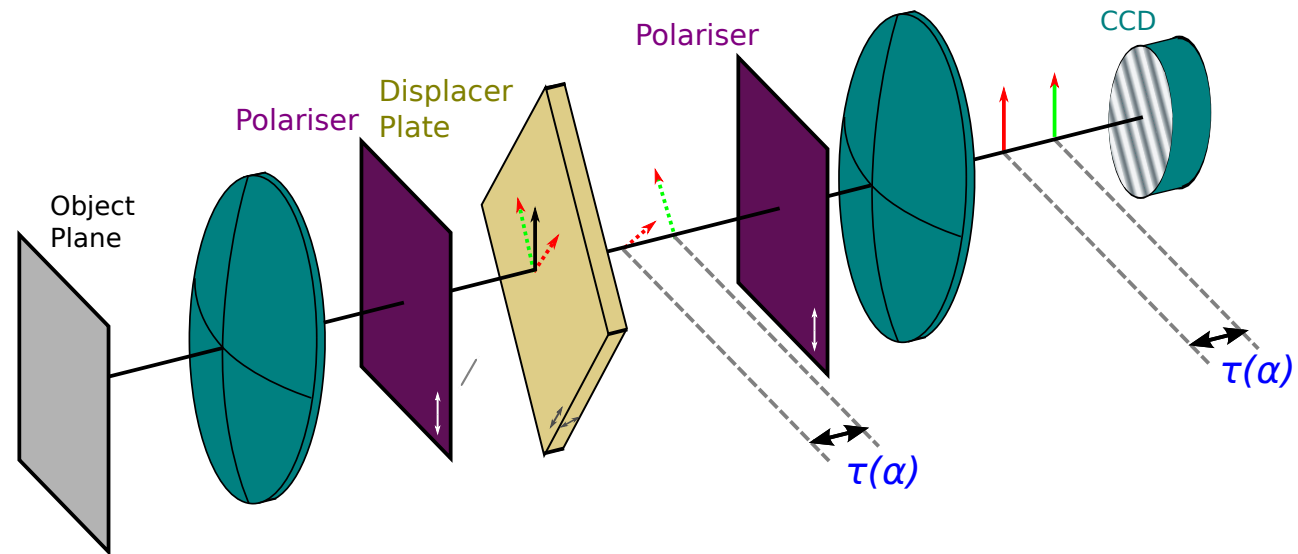
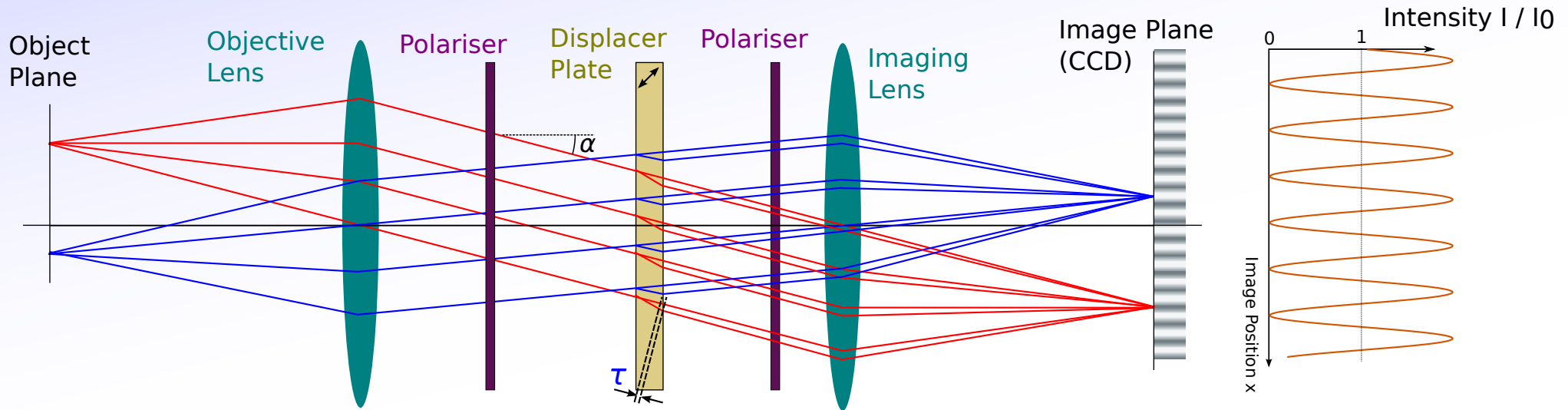
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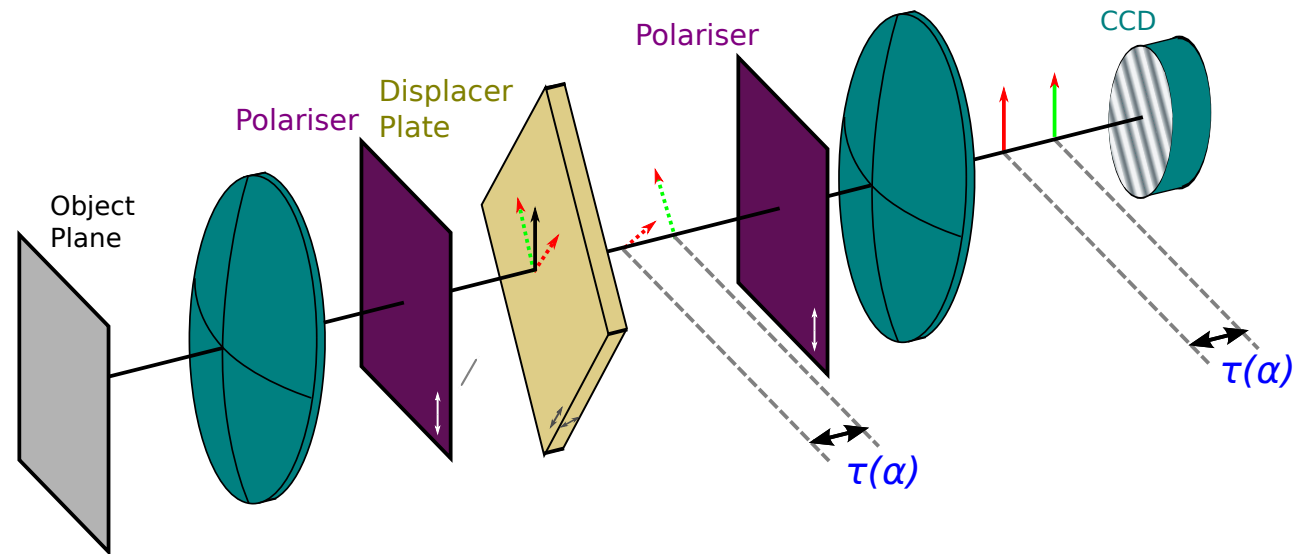
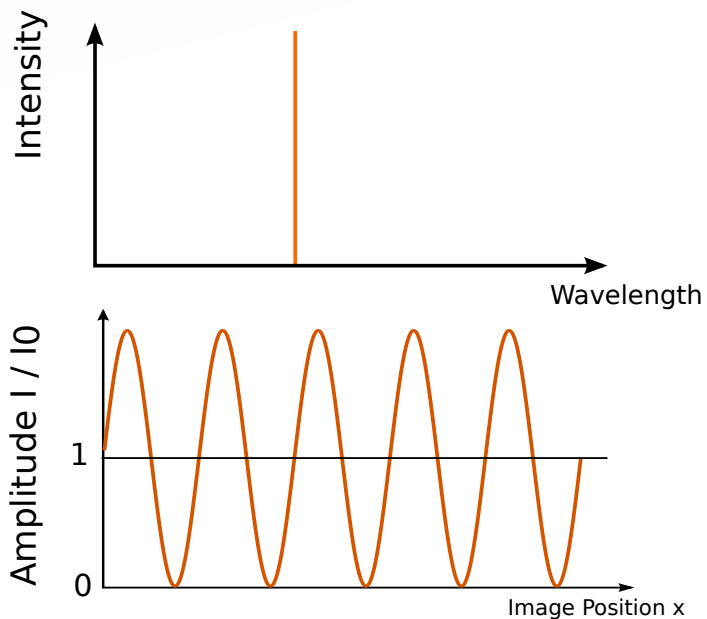
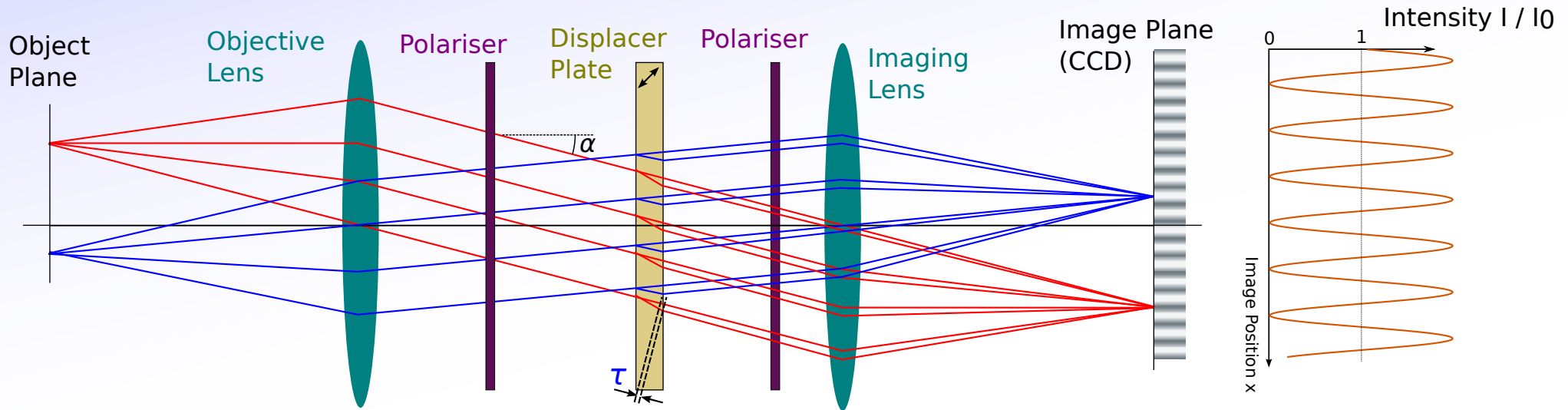
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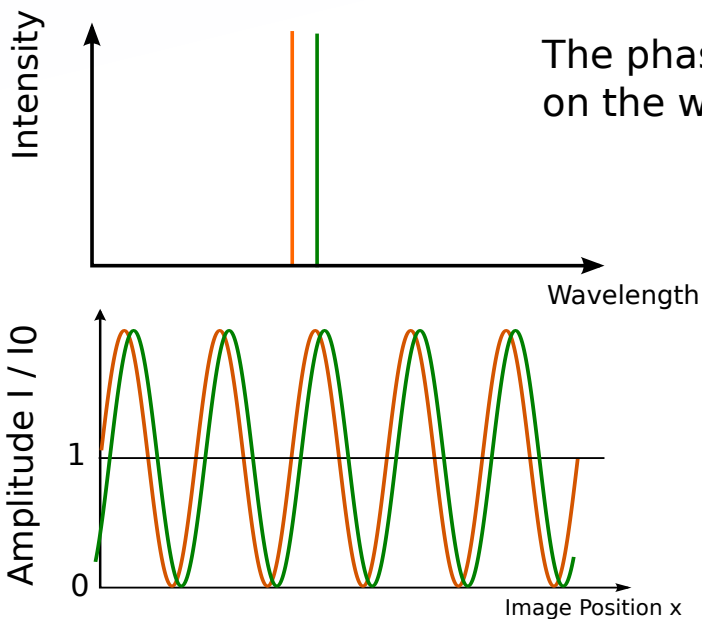
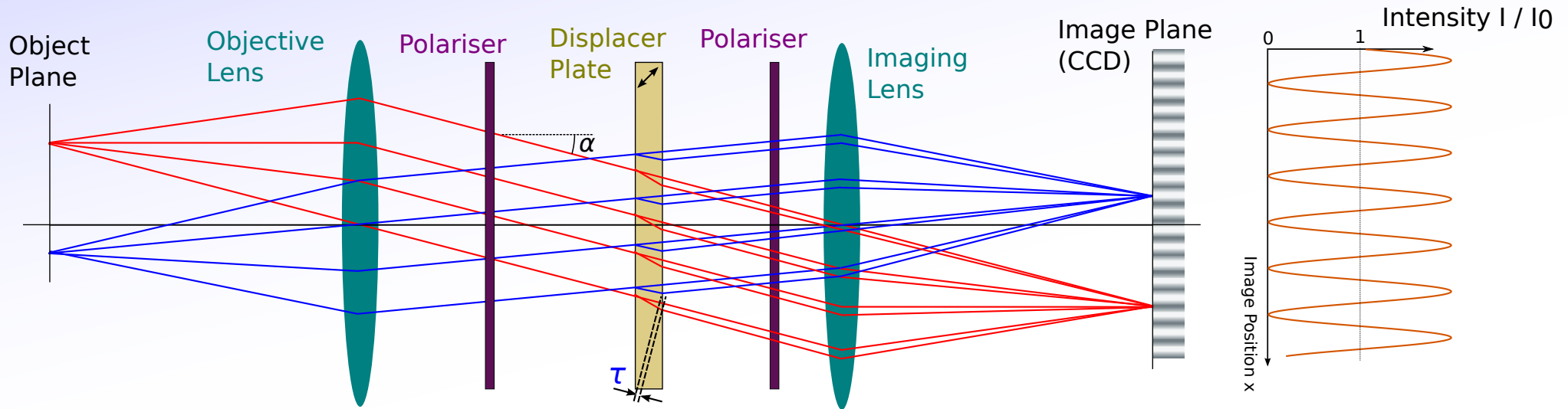
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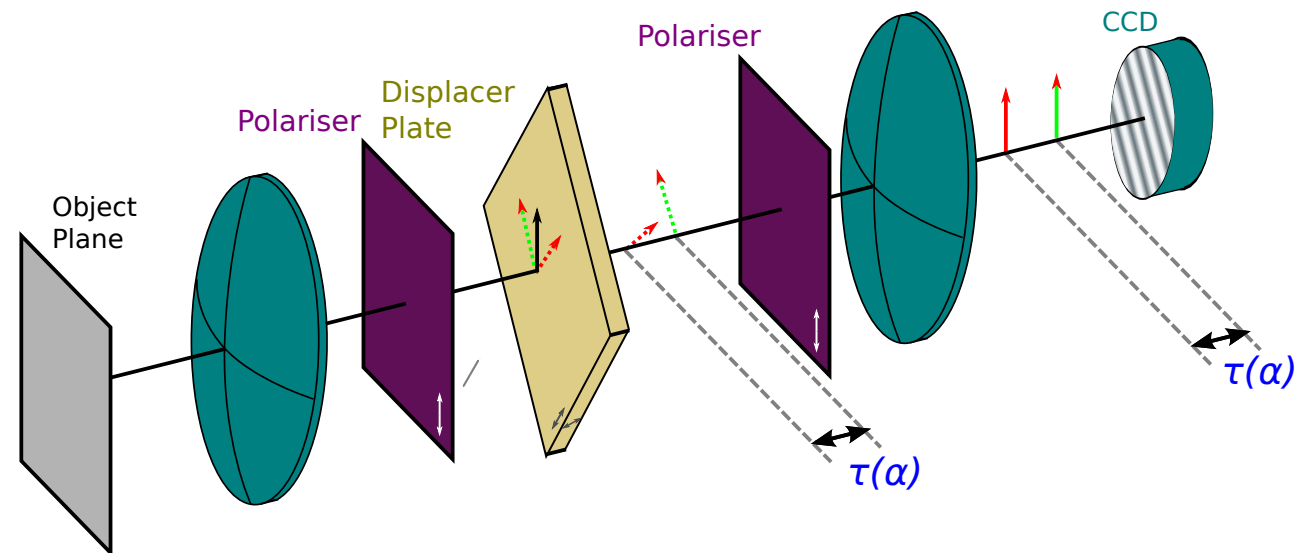


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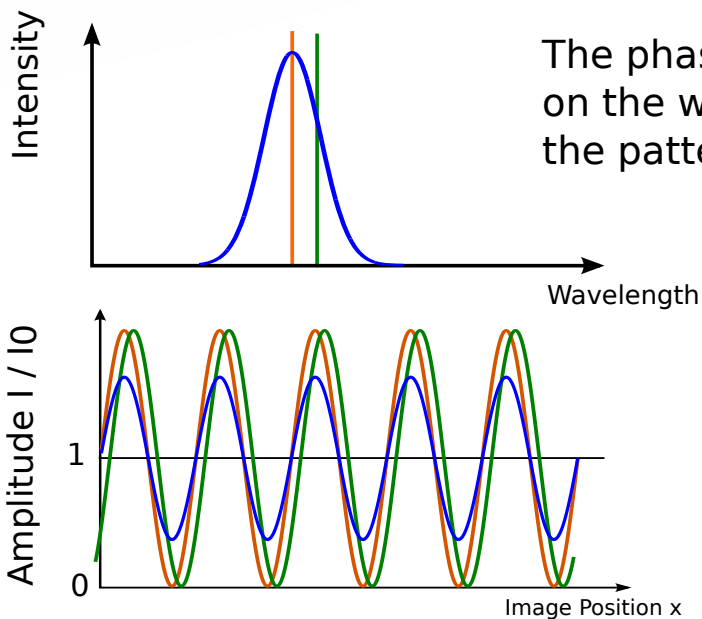
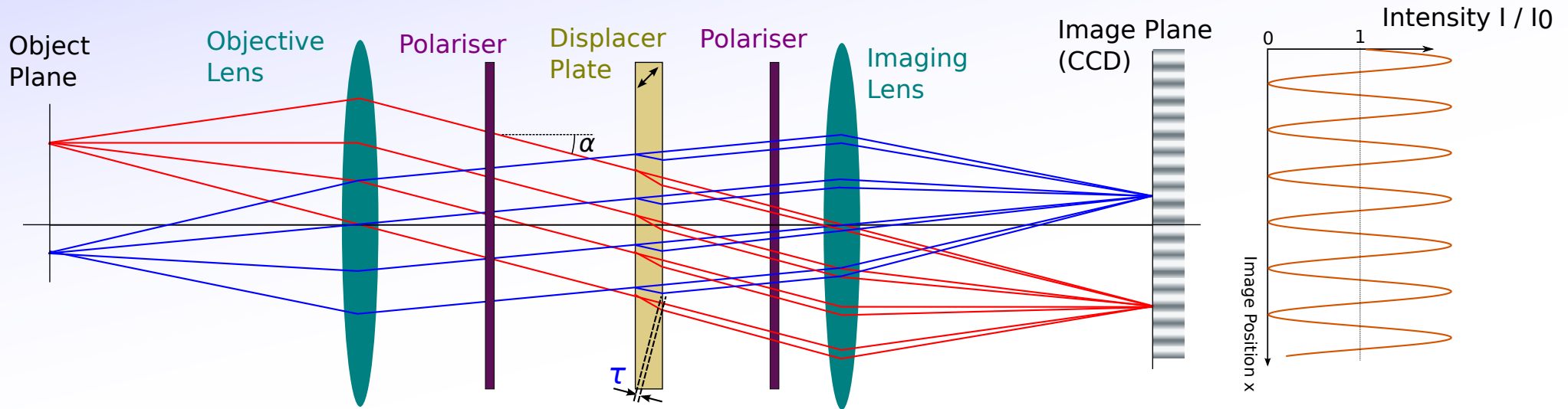


The phase of the interference pattern depends on the wavelength  $\Delta\omega$ .

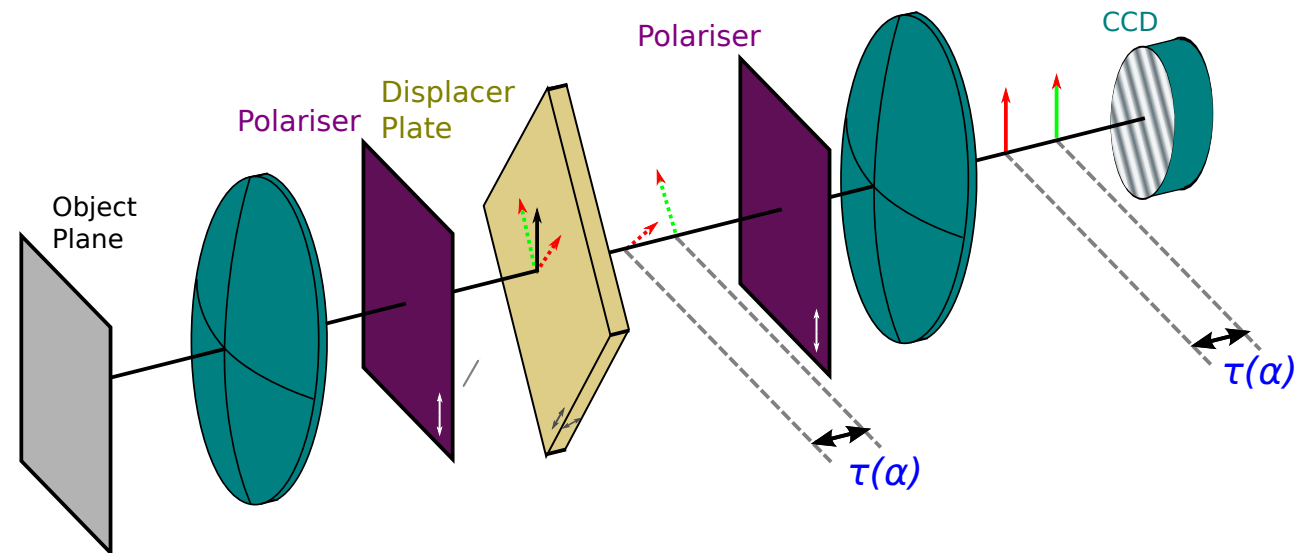


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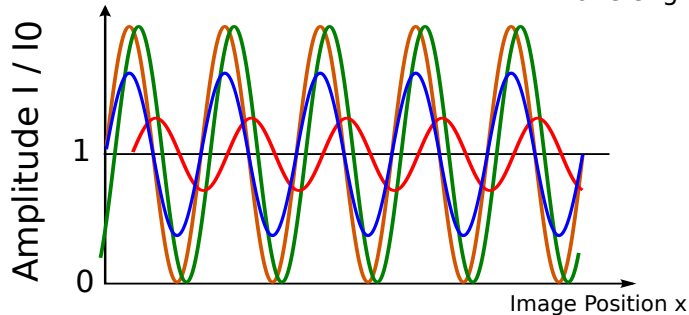
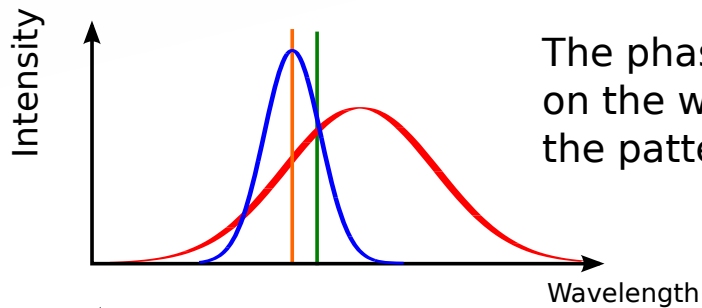
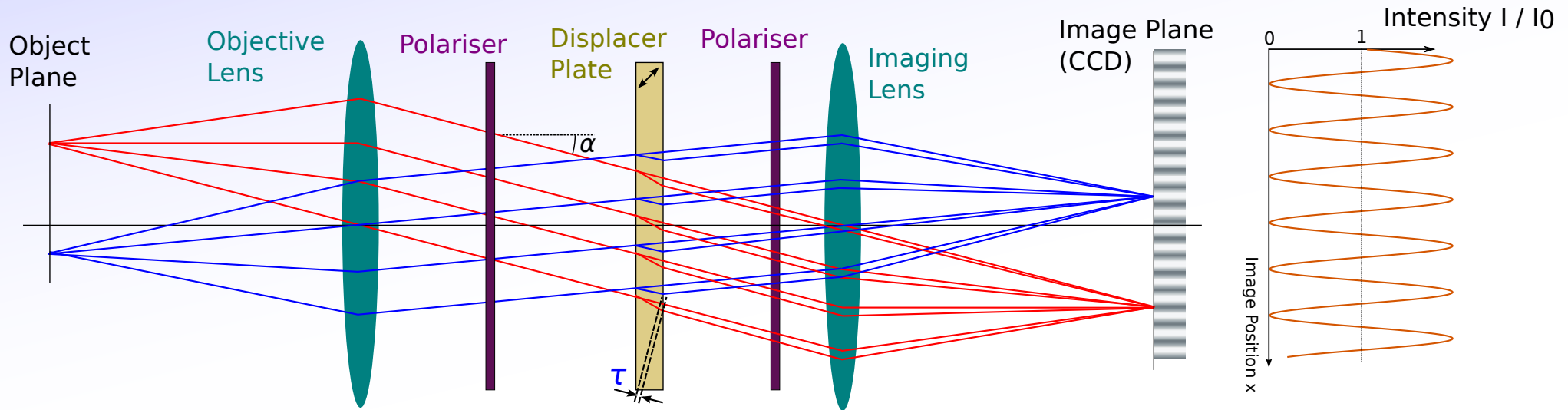


The phase of the interference pattern depends on the wavelength  $\Delta\omega$ . With multiple wavelengths, the pattern contrast  $\zeta$  is reduced.

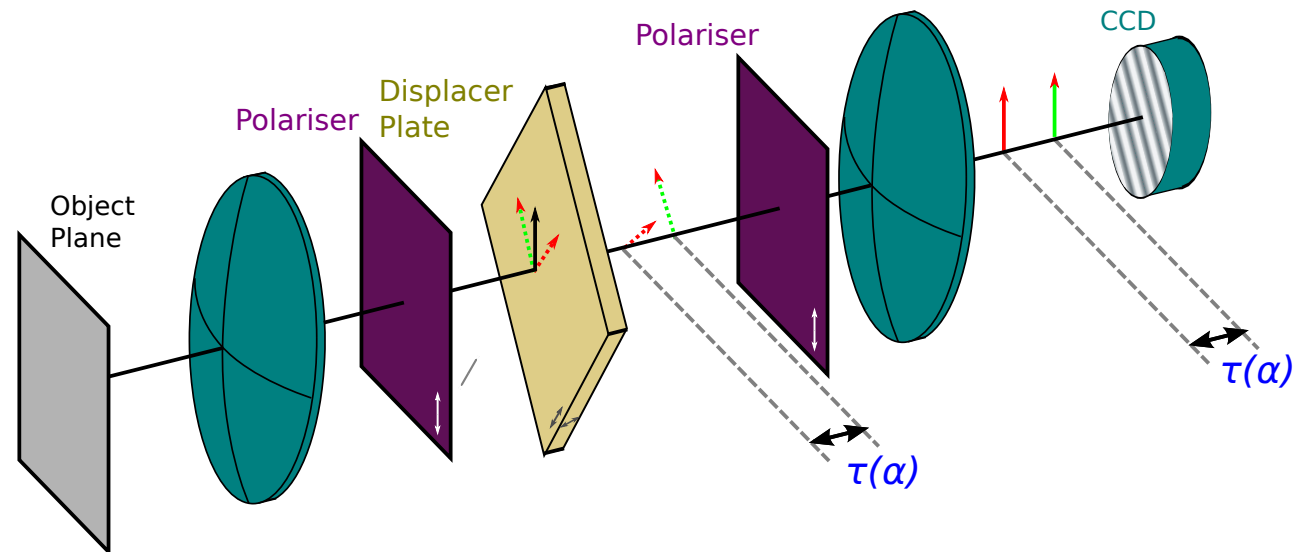


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$$I \propto 1 + \zeta \cos((\omega + \Delta\omega)x)$$

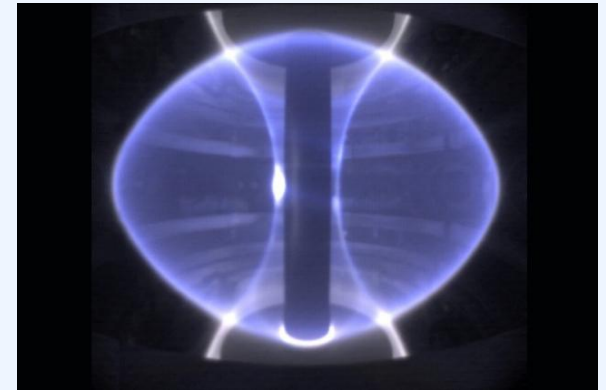


# Doppler Coherence Flow Imaging - MAST

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

## MAST

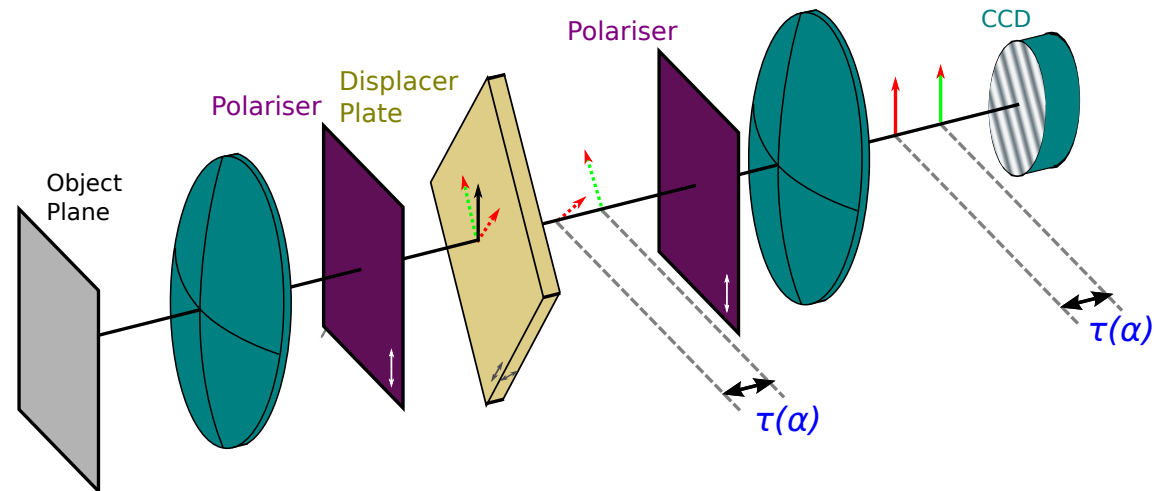
Mega Amp Spherical Tokamak,  
CCFE, Culham, UK



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

And some videos...

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[S. Silburn et. al. 40th EPS Conf. on plasma phys. 2013]



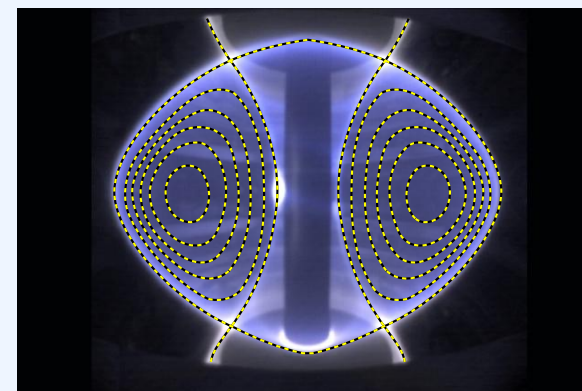


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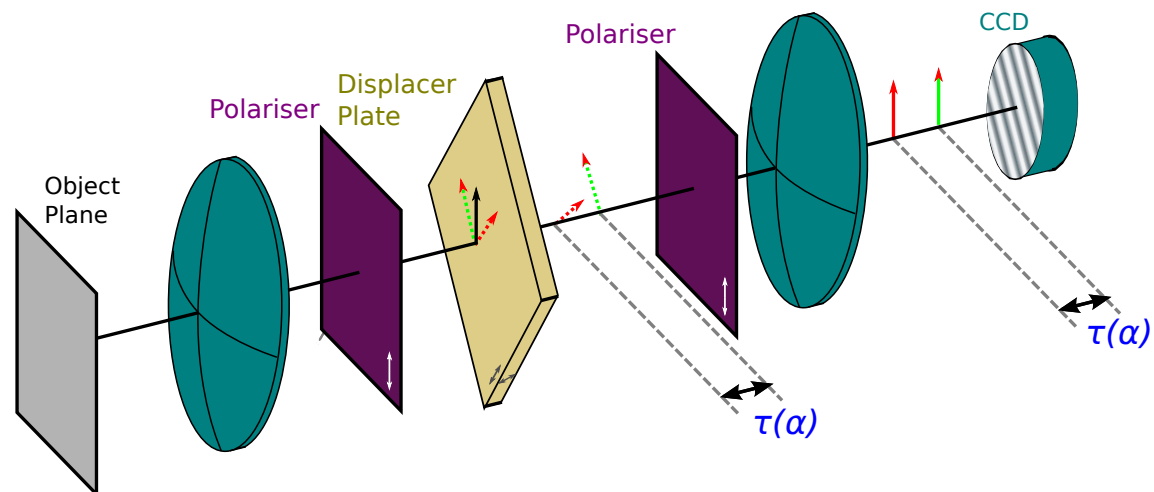
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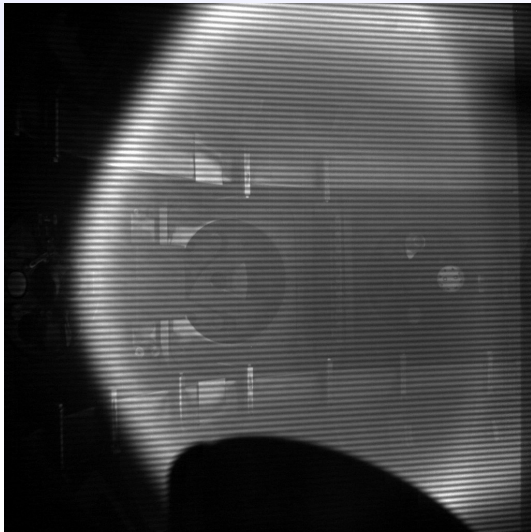
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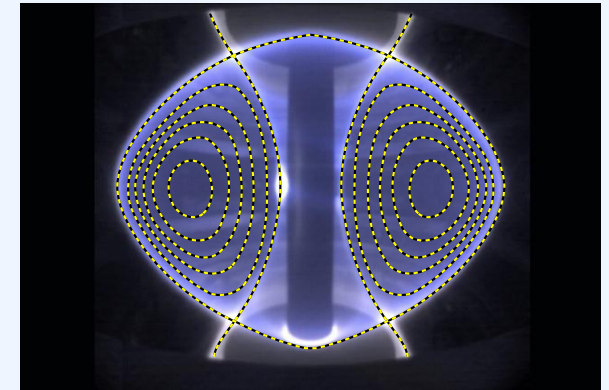
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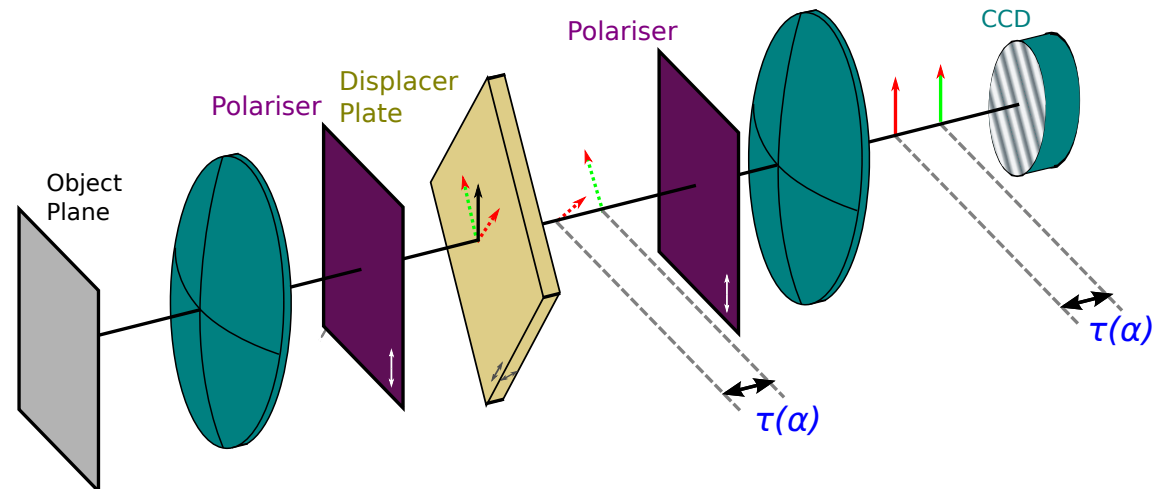
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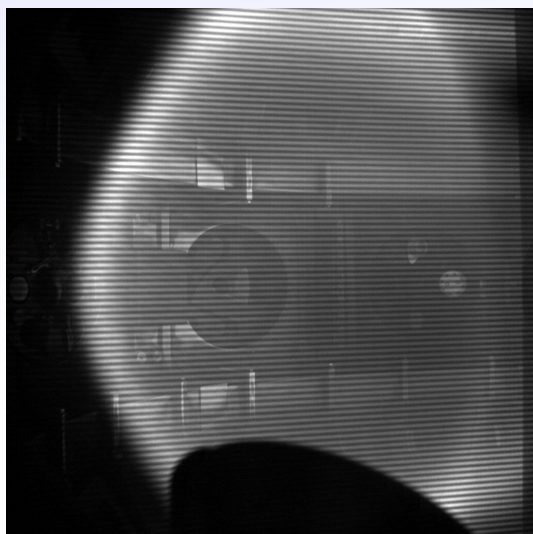
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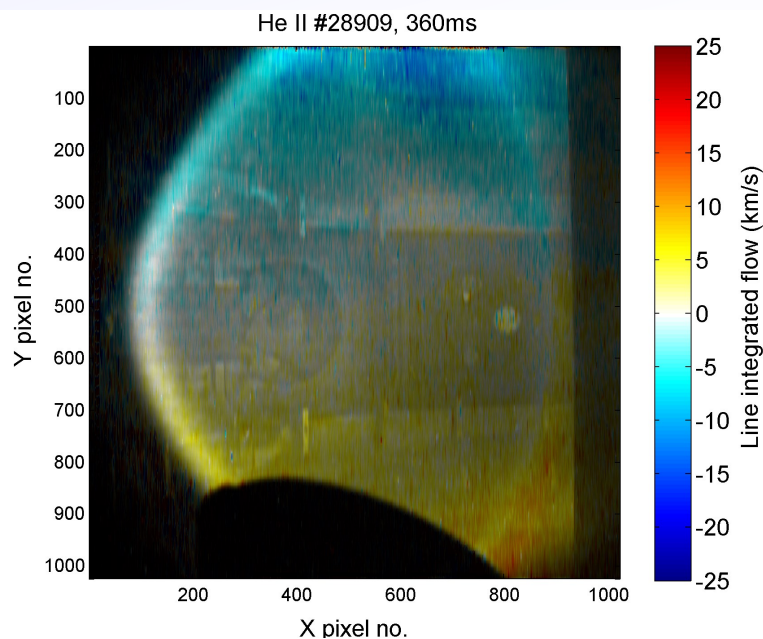
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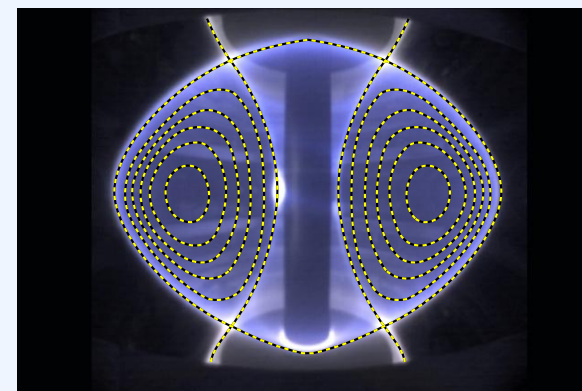


Helium Flow Velocity:



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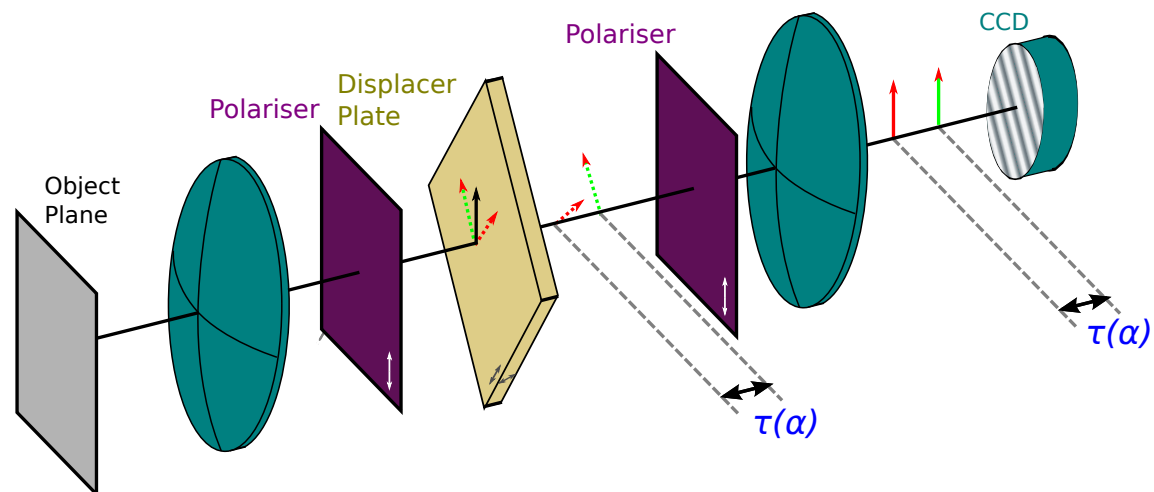


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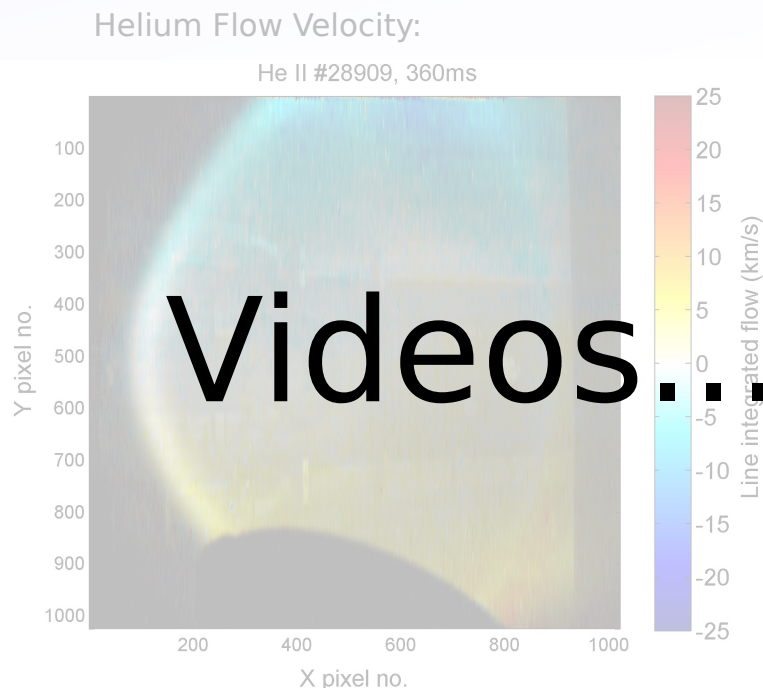
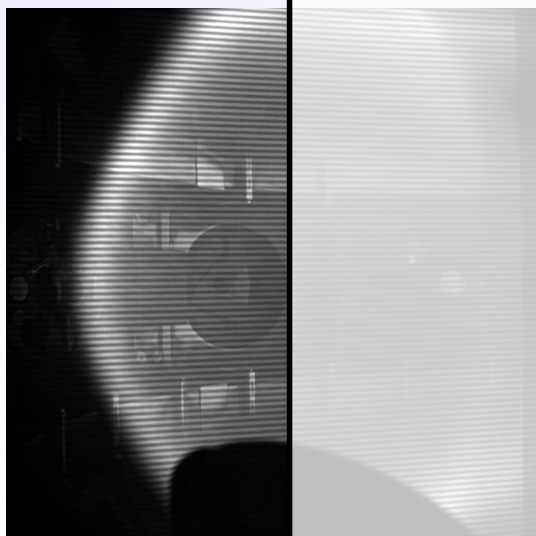




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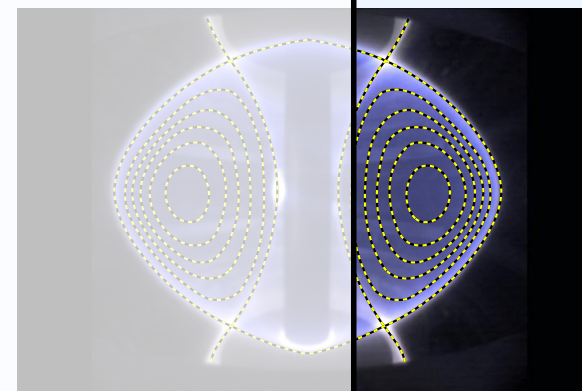
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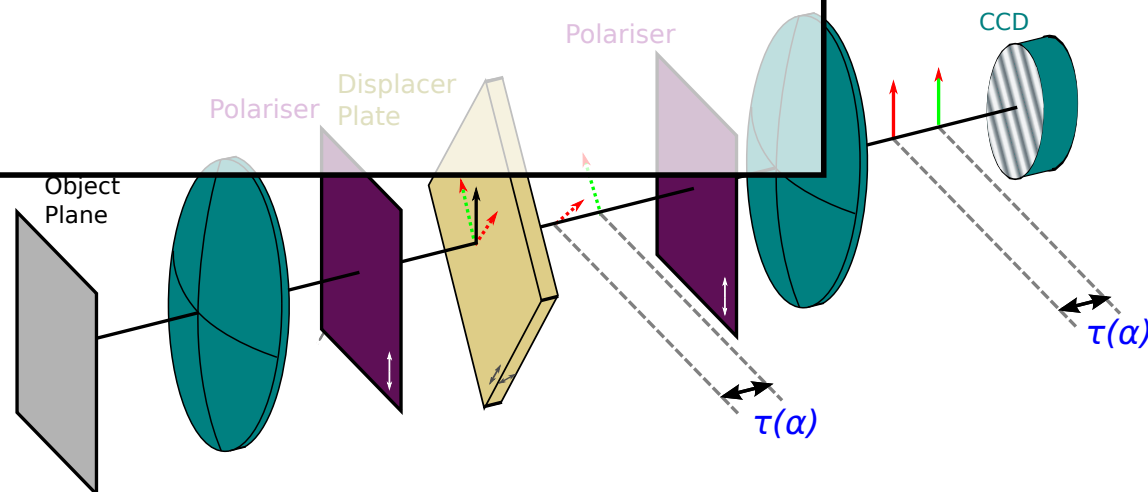
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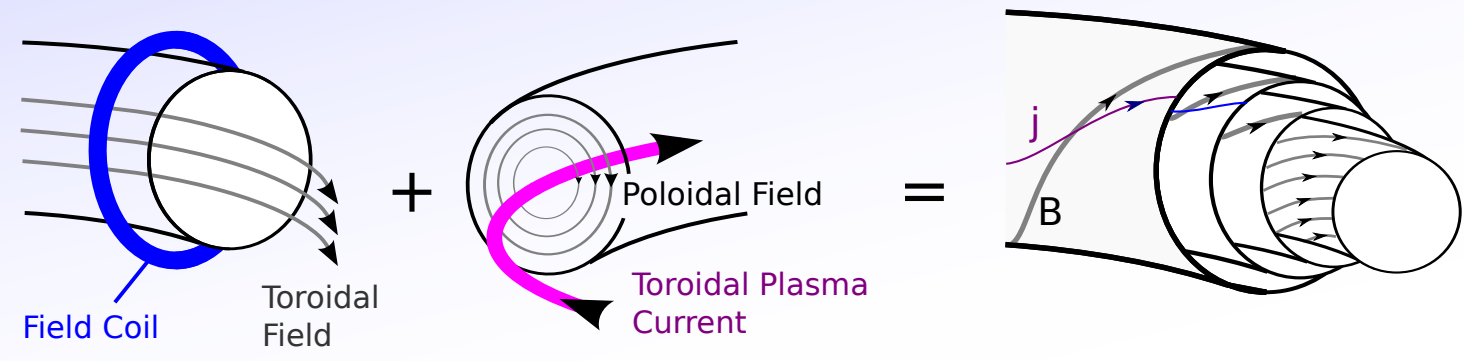
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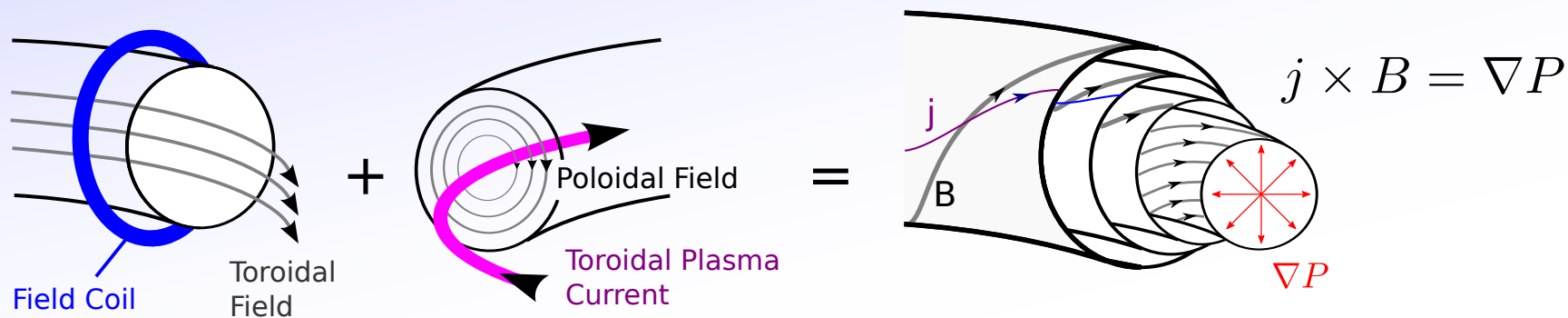
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The Tokamak plasma current and magnetic configuration strongly effects the stability and confinement properties of the plasma. Measurements of the internal magnetic pitch angles highly desirable.



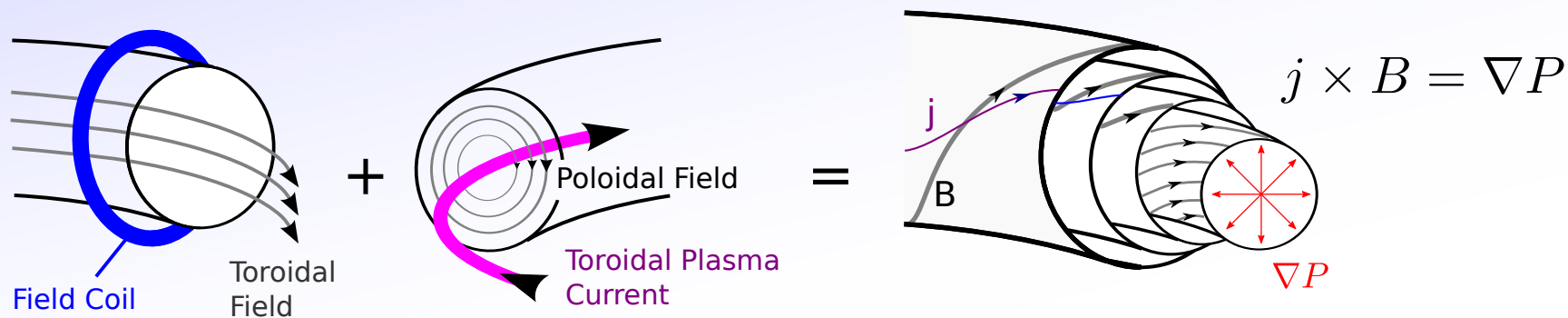
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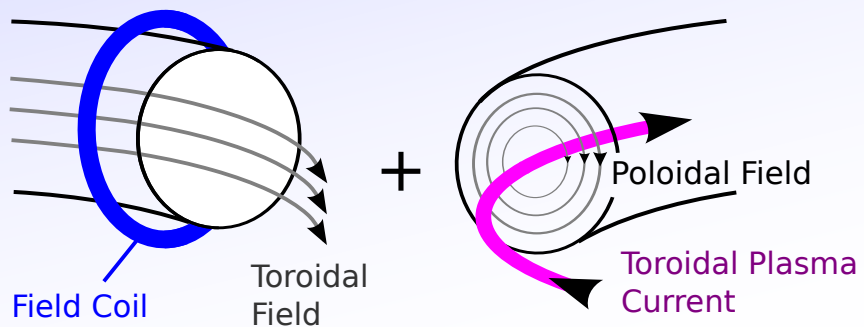
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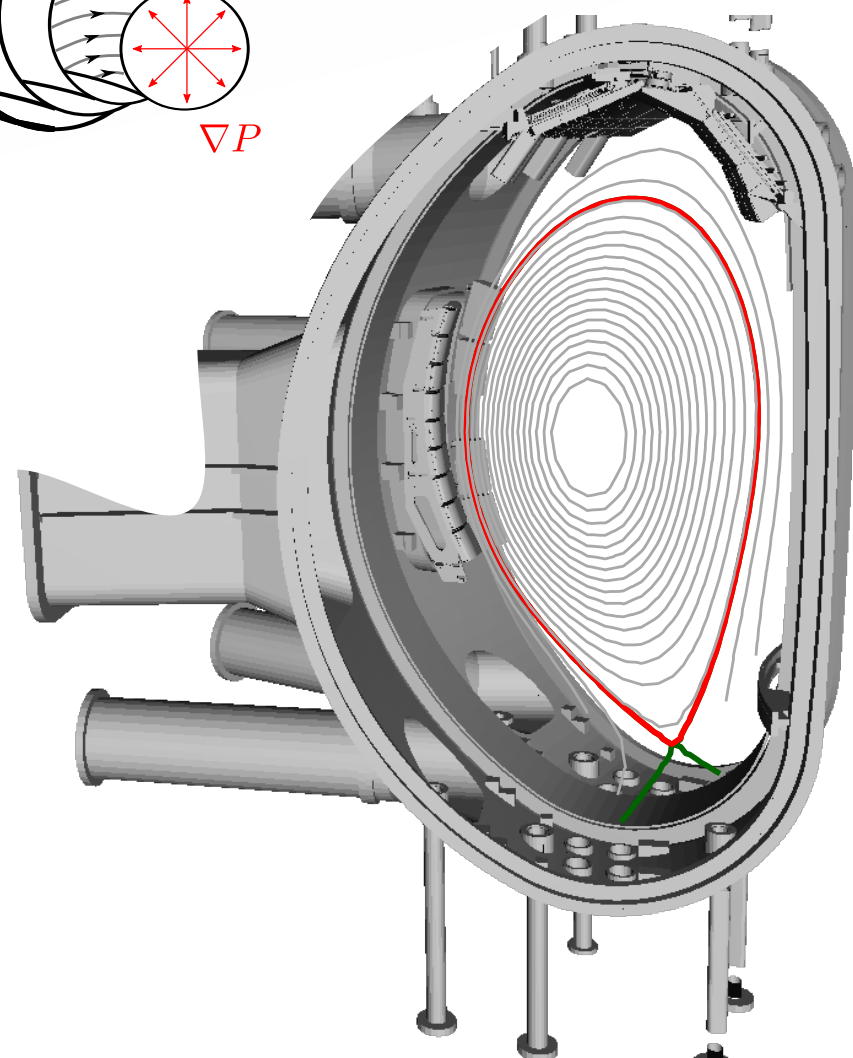
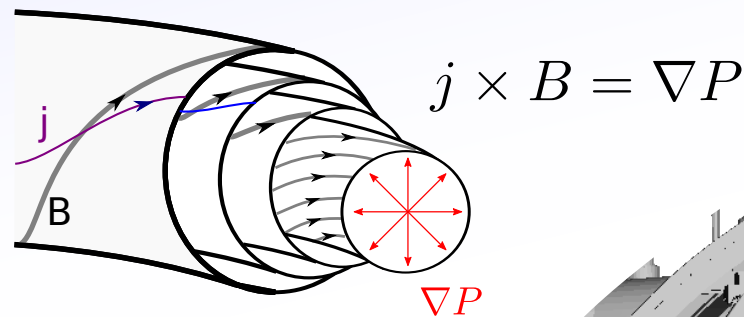
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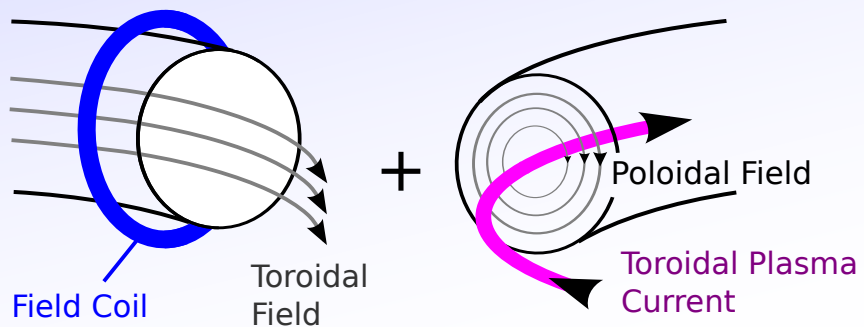
ASDEX Upgrade Vacuum Vessel

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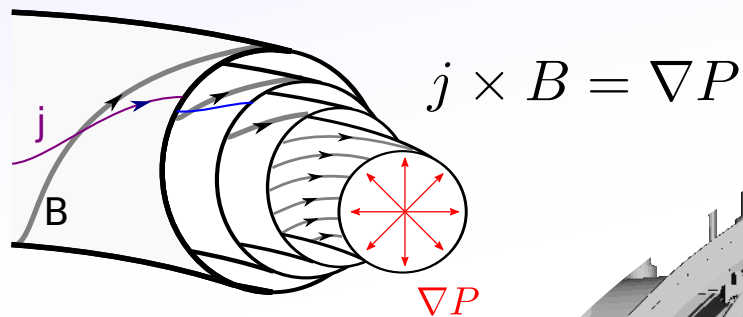


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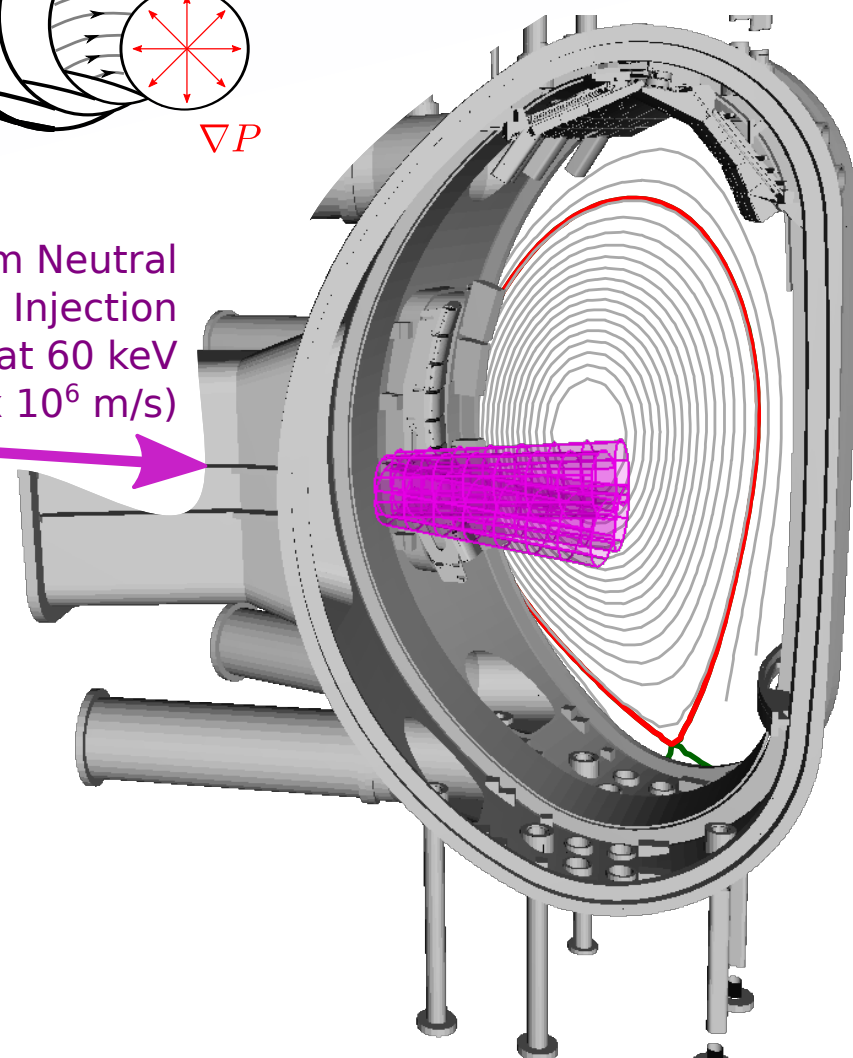


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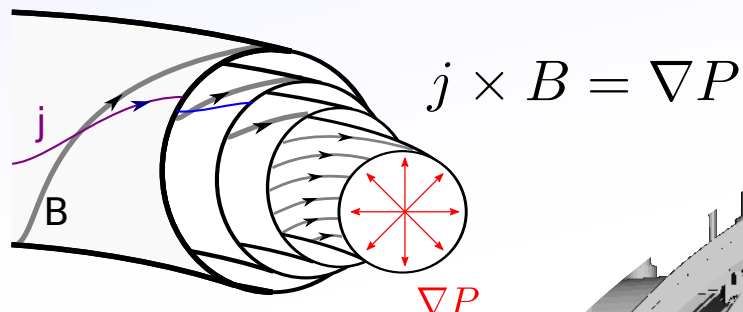
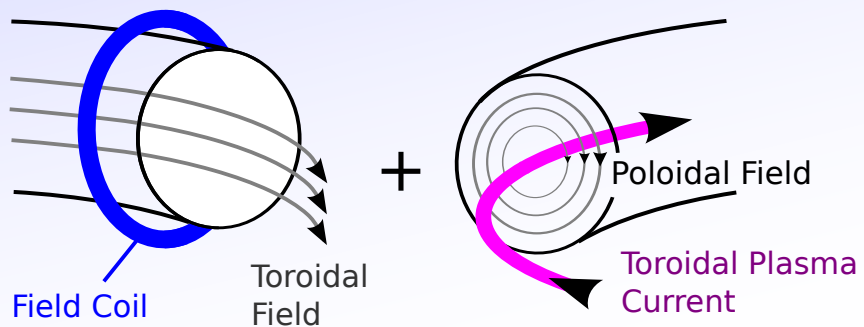
Deuterium Neutral Beam Injection  
 5MW at 60 keV  
 ( $3 \times 10^6$  m/s)



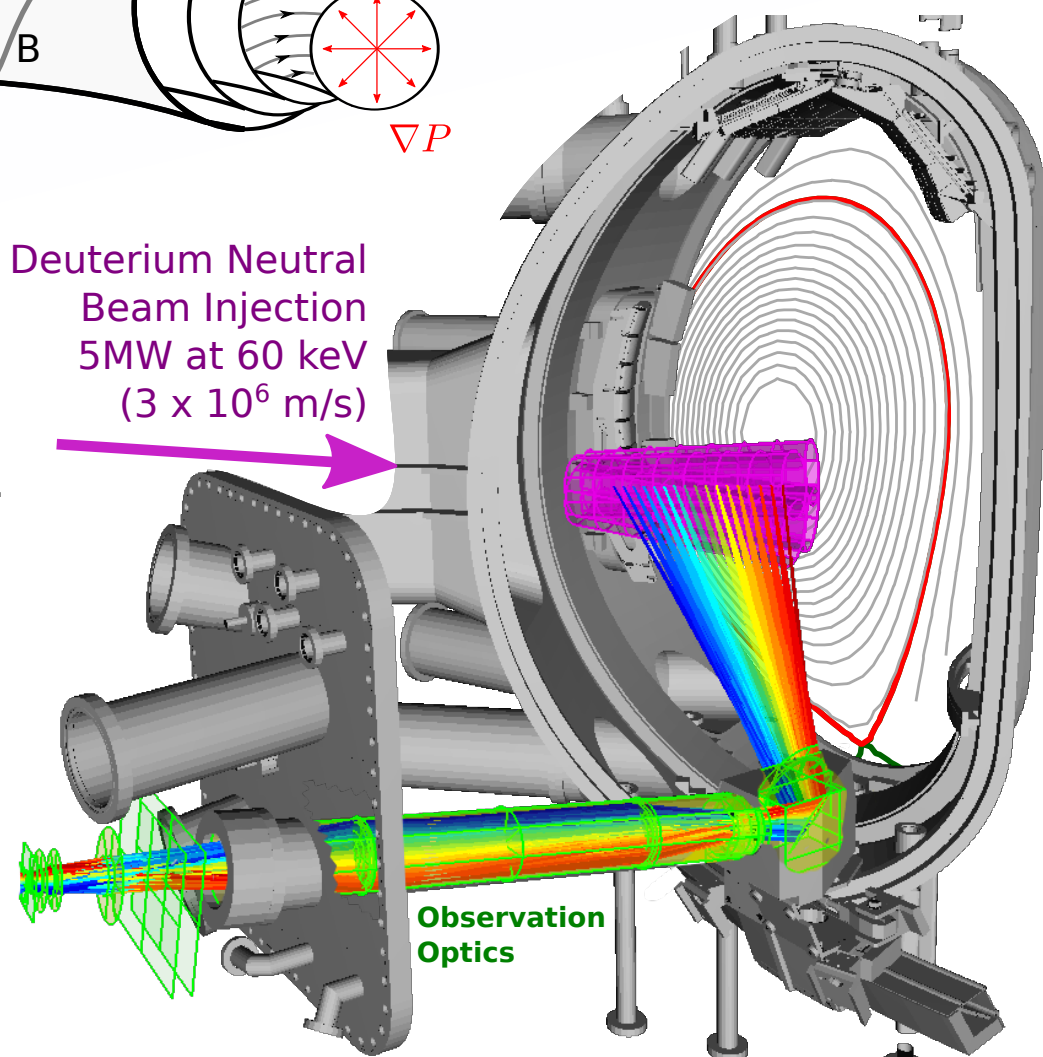
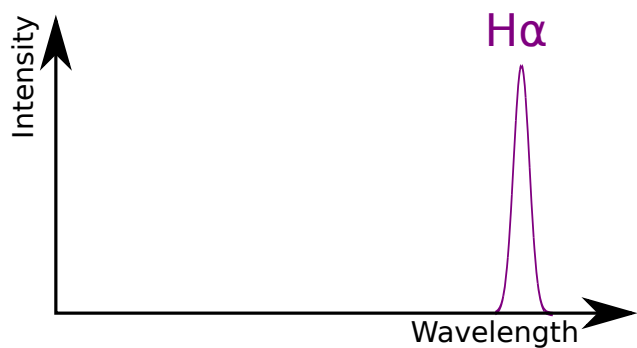
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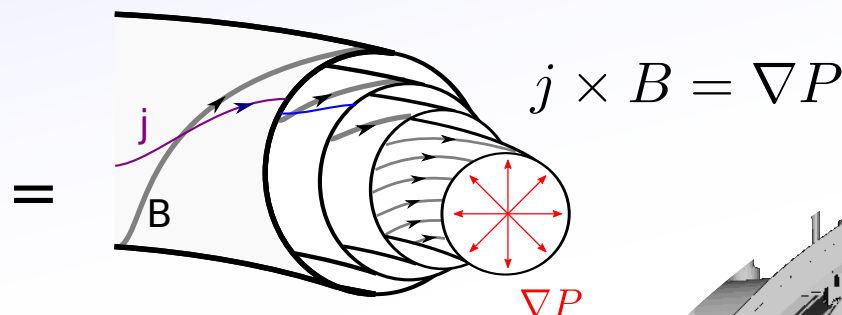
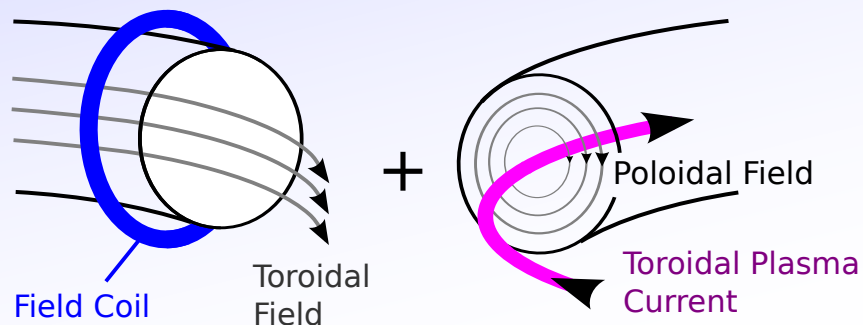
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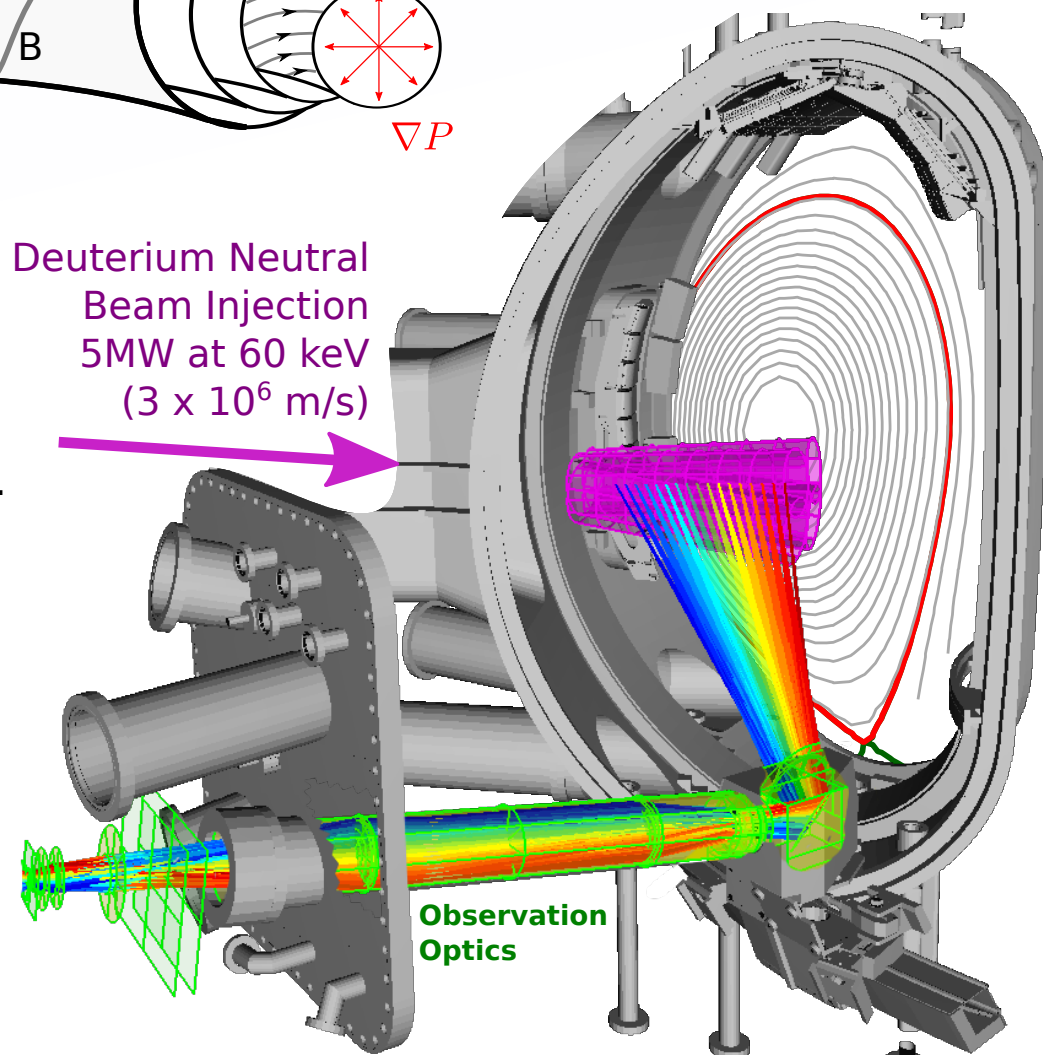
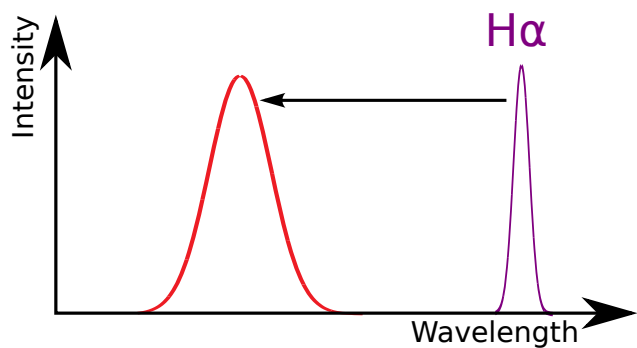
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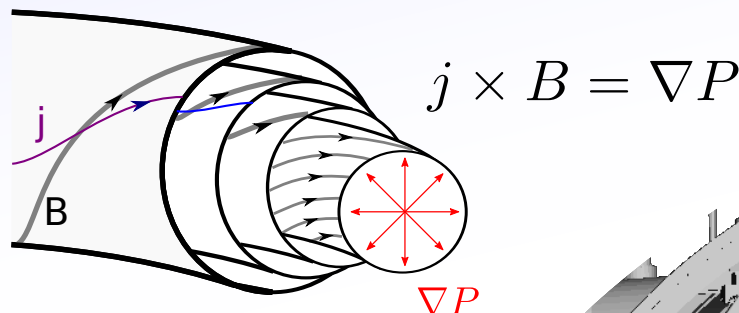
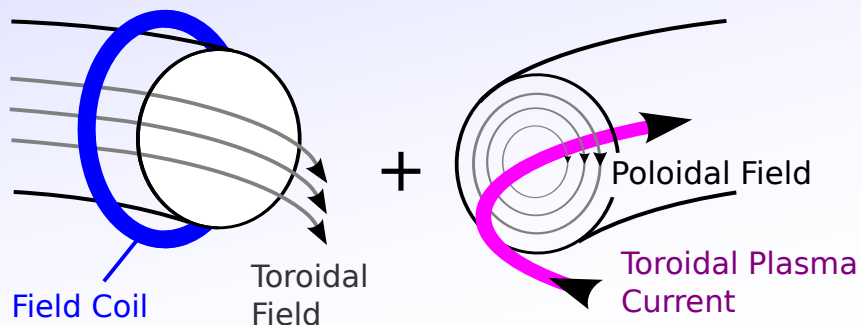
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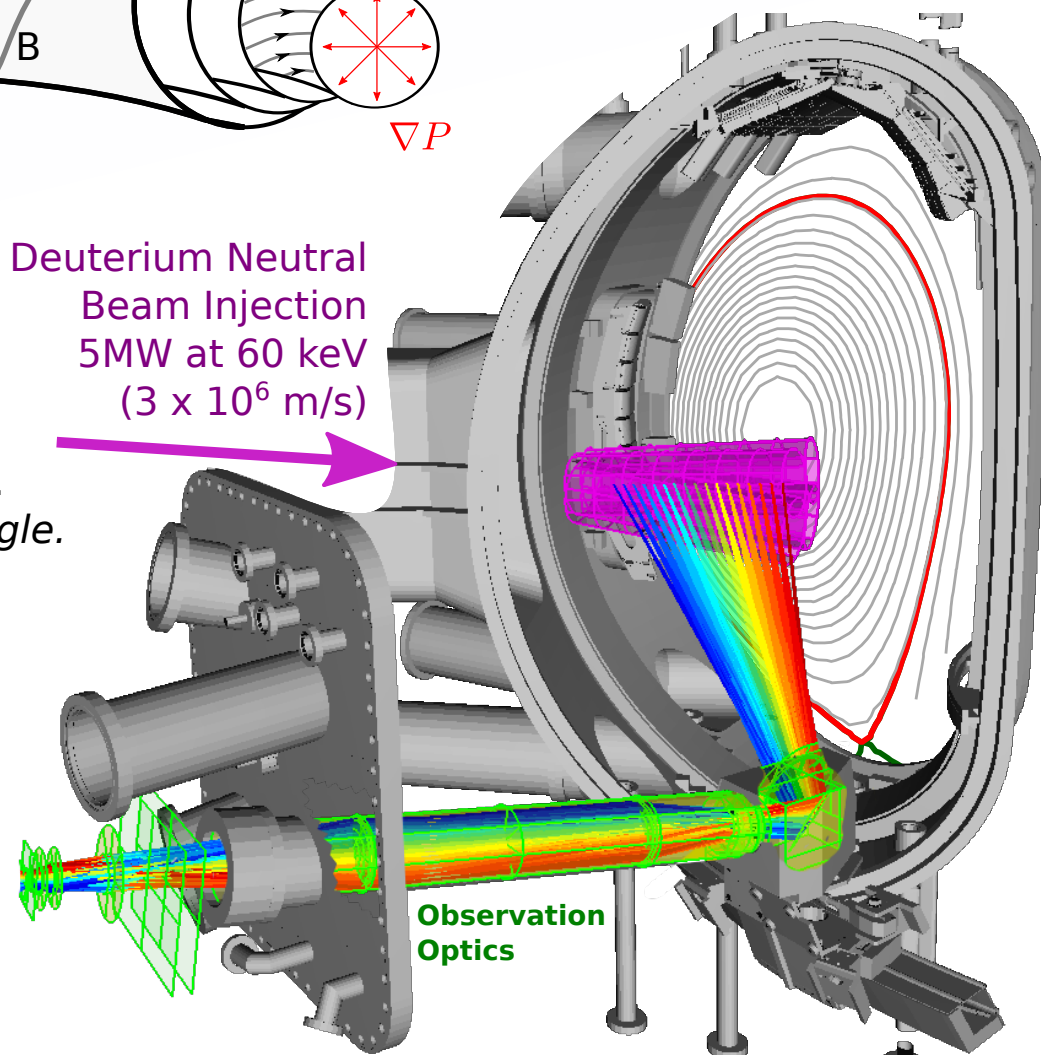
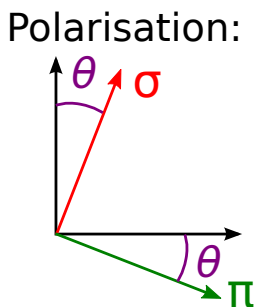
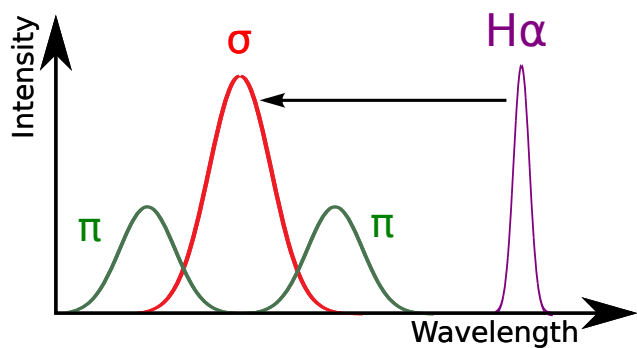
ASDEX Upgrade Vacuum Vessel

# 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.



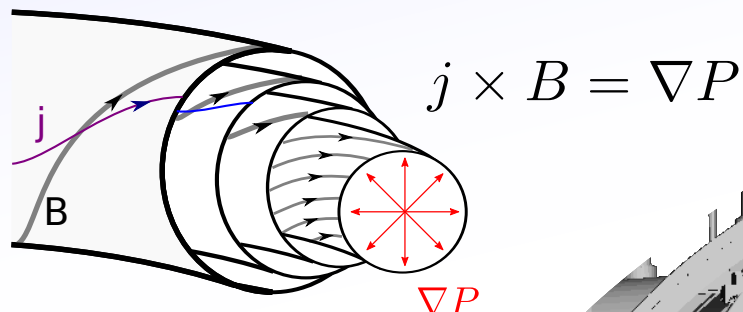
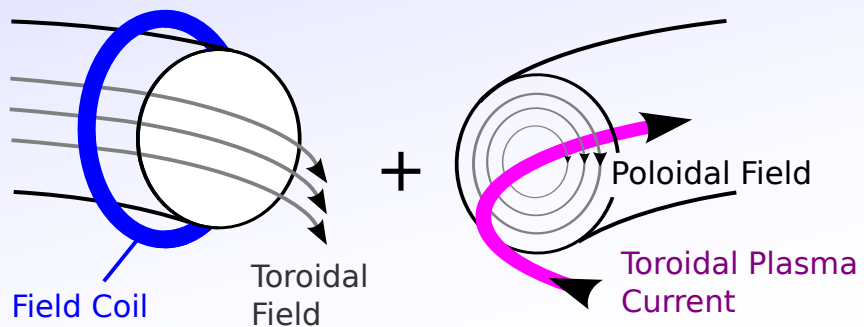
Typical is usually done with polarimetry.  
Spectral lines are split and polarised by E/M fields:  
Zeeman Effect: Magnetic field.  
Stark Effect: Electric field.  
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Polarisation  $\theta$  gives information about the field *pitch angle*.



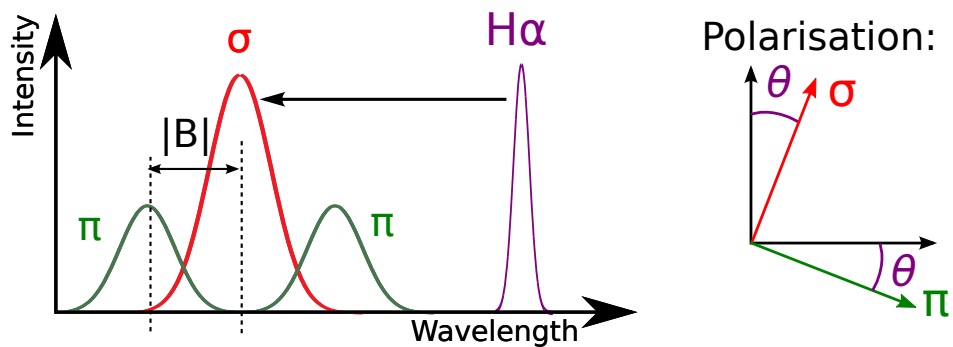
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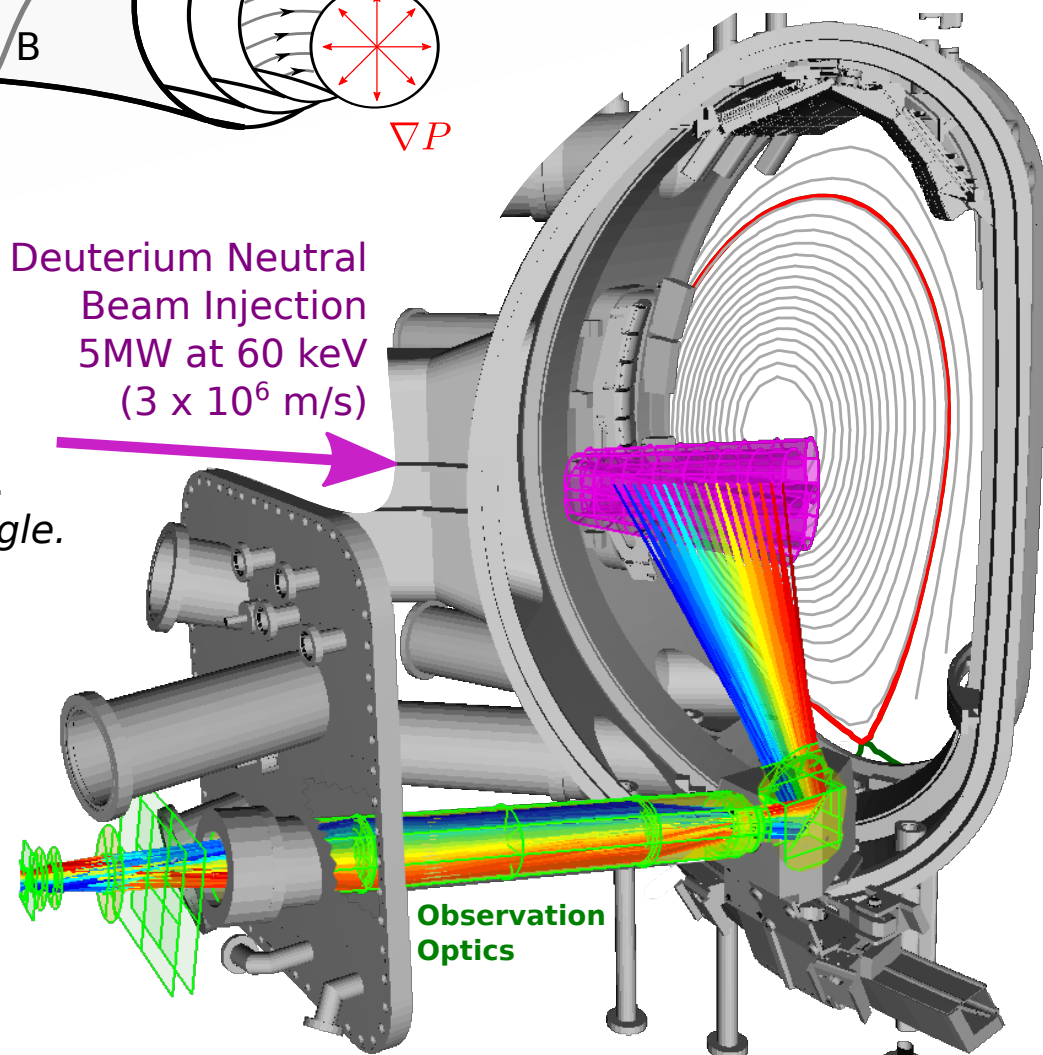
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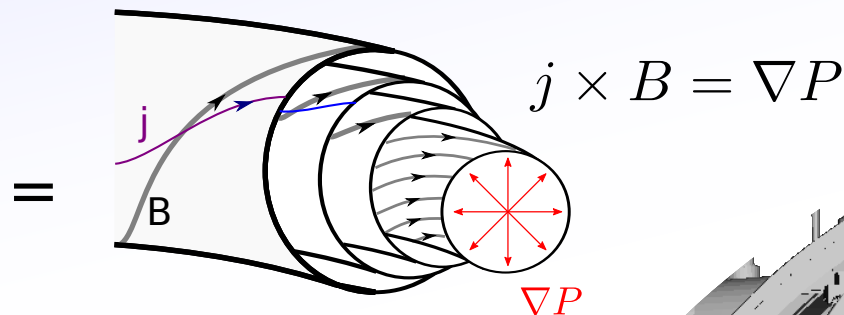
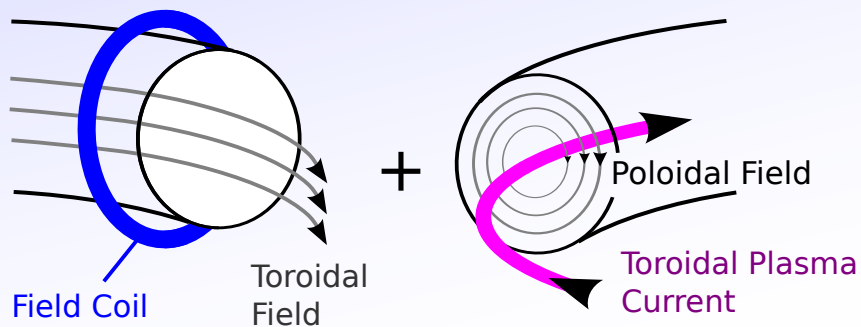
Deuterium Neutral Beam Injection  
 5MW at 60 keV  
 ( $3 \times 10^6$  m/s)



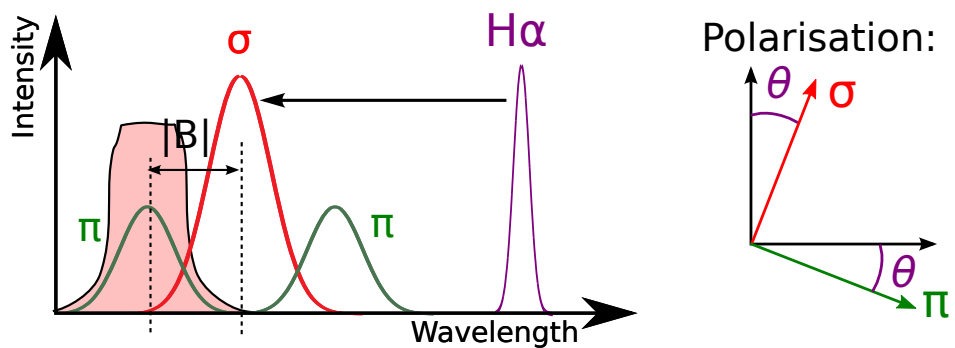
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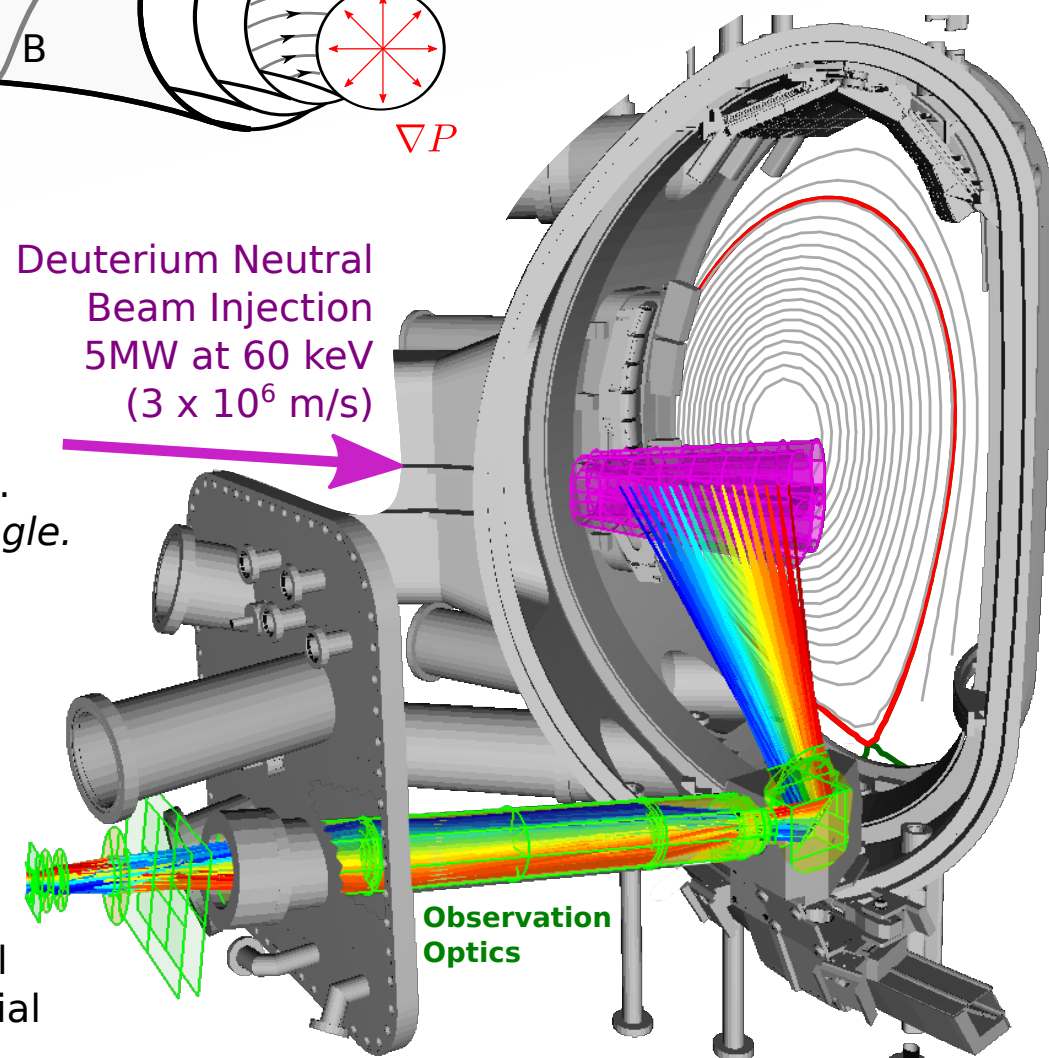
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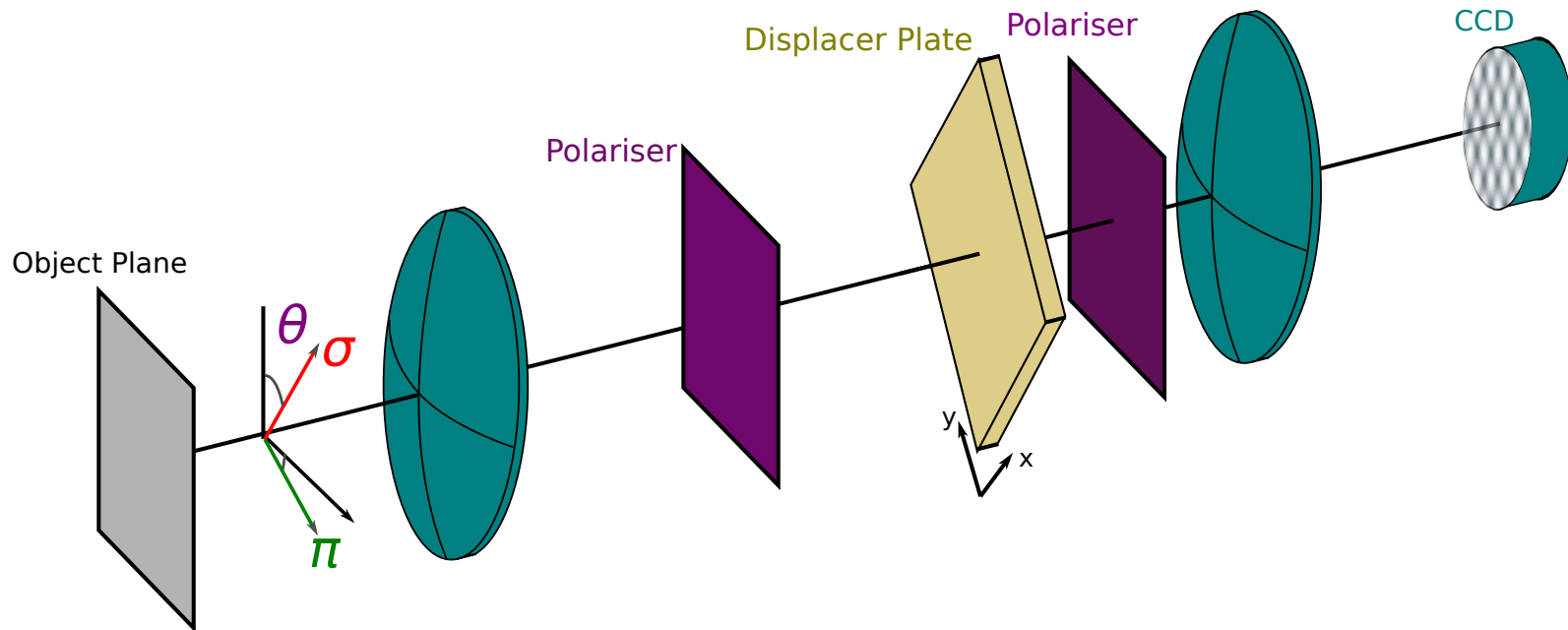
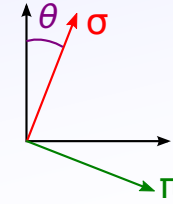


Typically, complex hardware is required, with individual filters for each spatial position. Up to a few 10s of spatial positions usually measured.



# Multiplet Polarisation Coherence Imaging

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

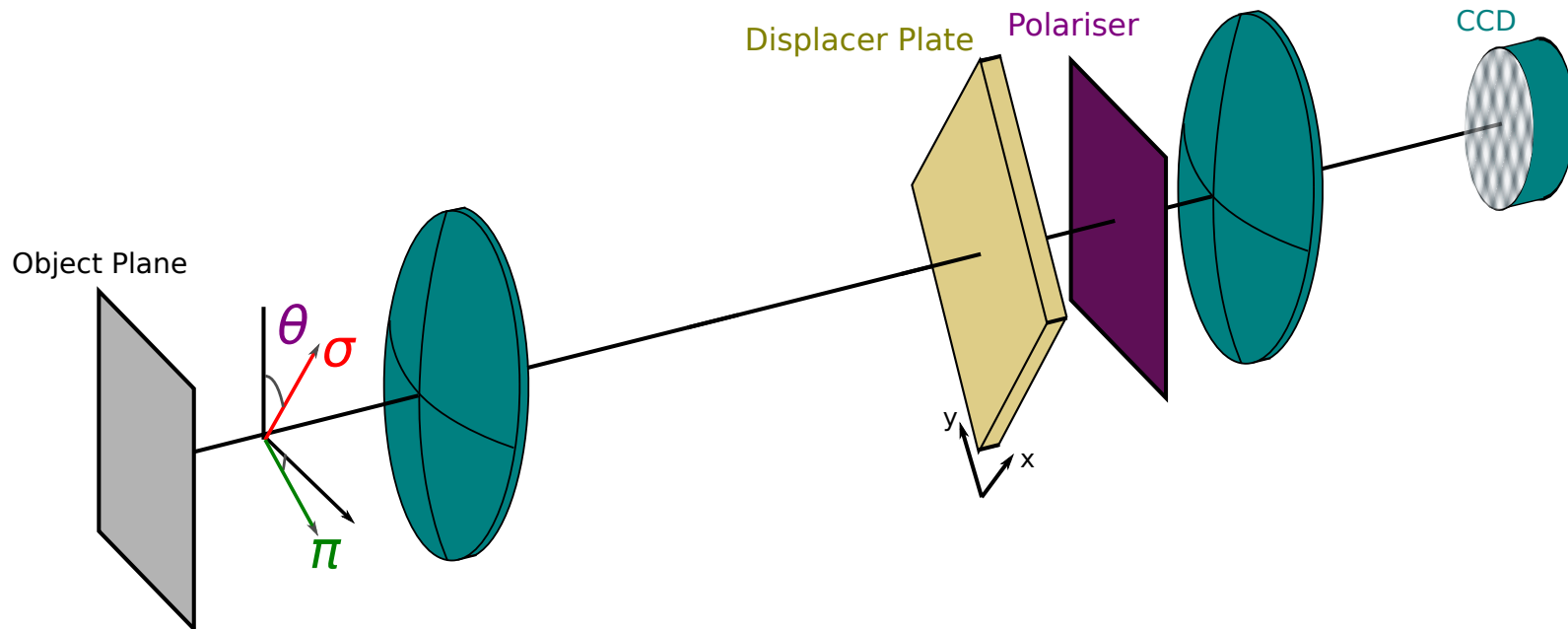
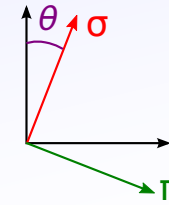


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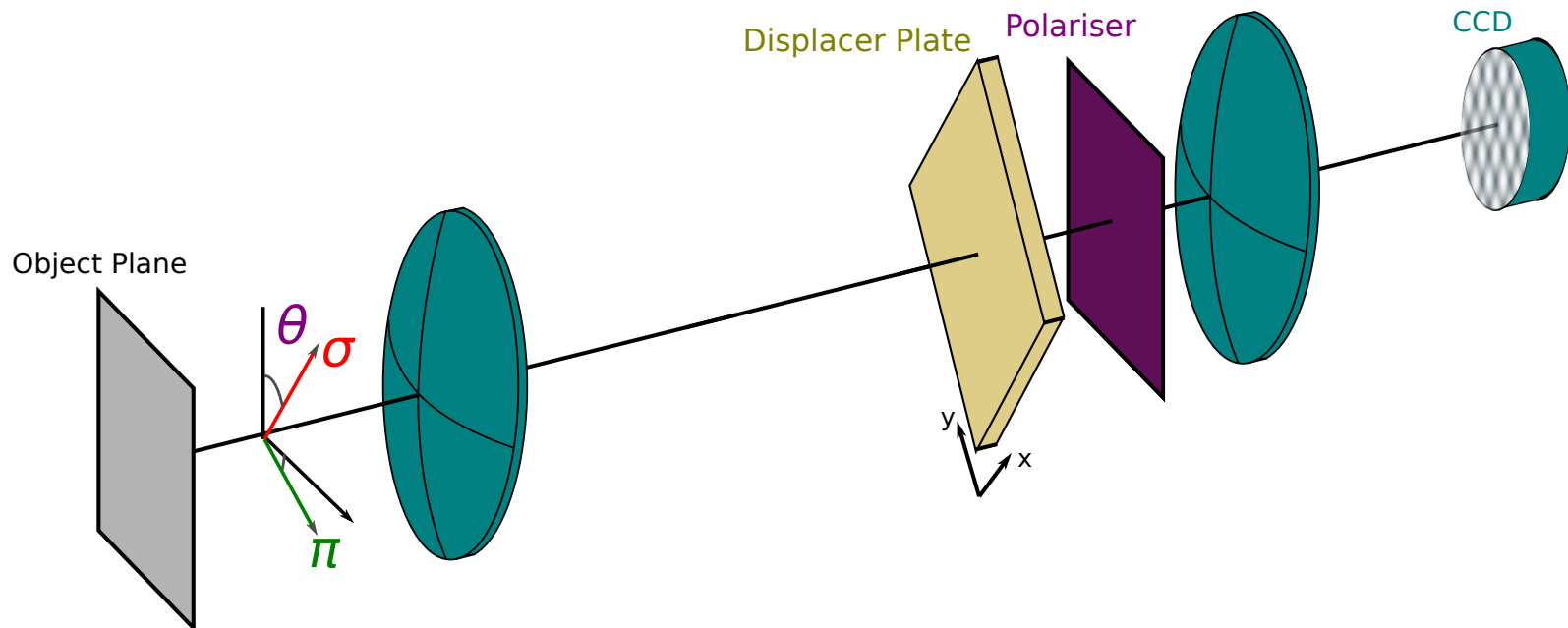
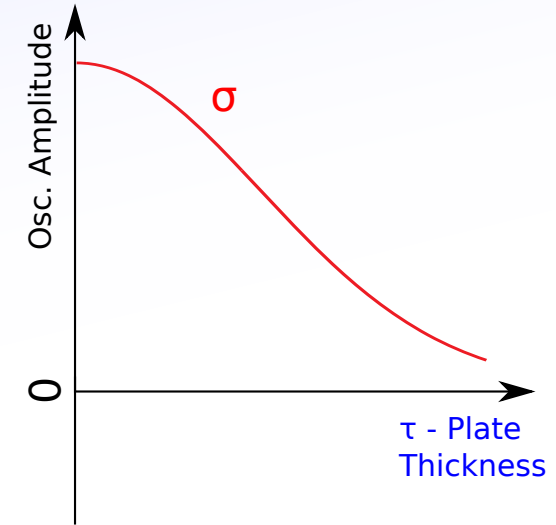
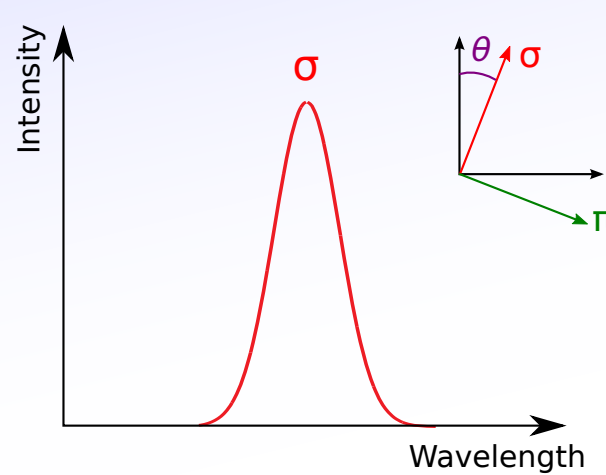


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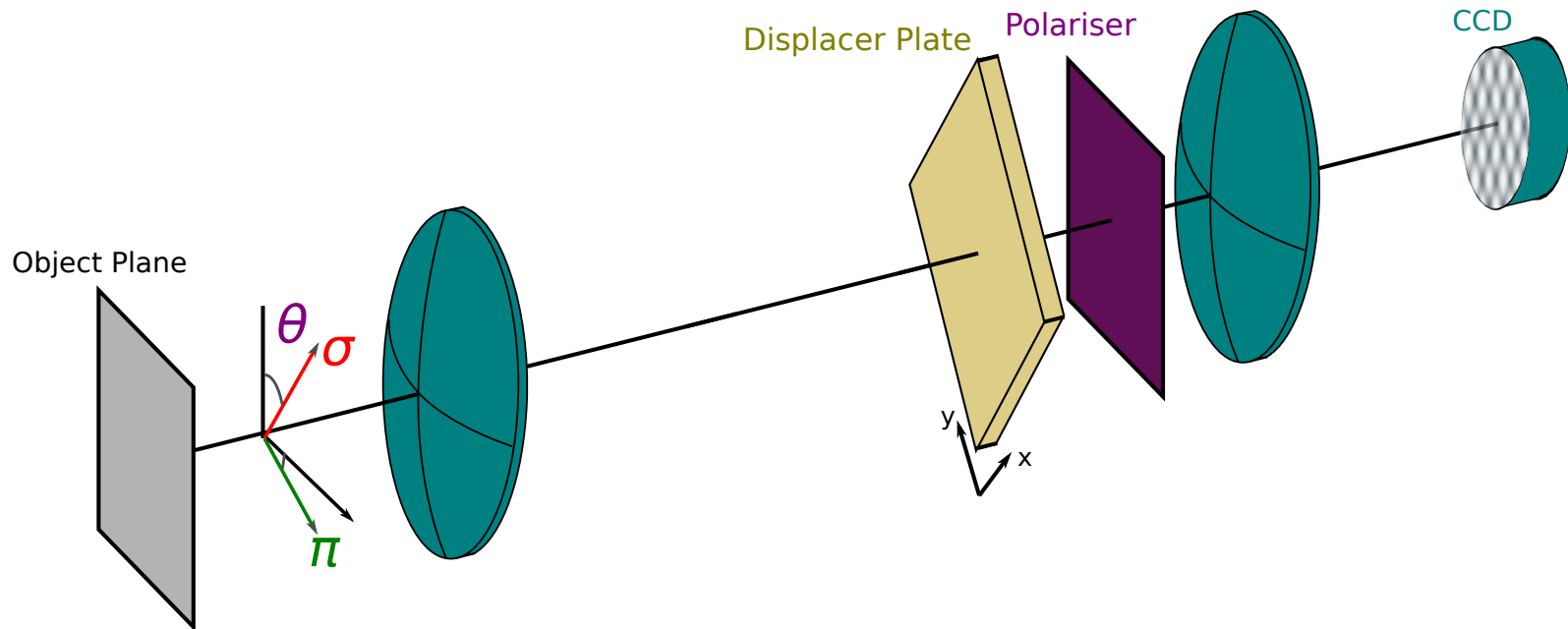
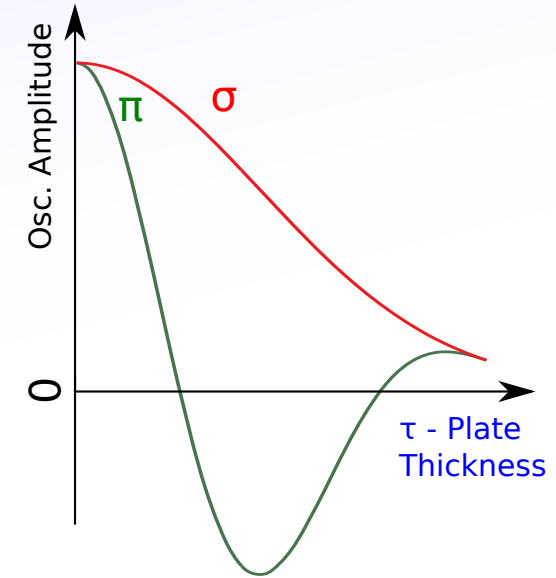
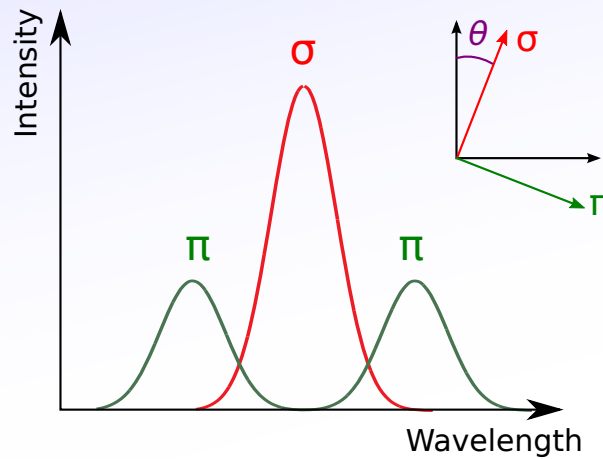
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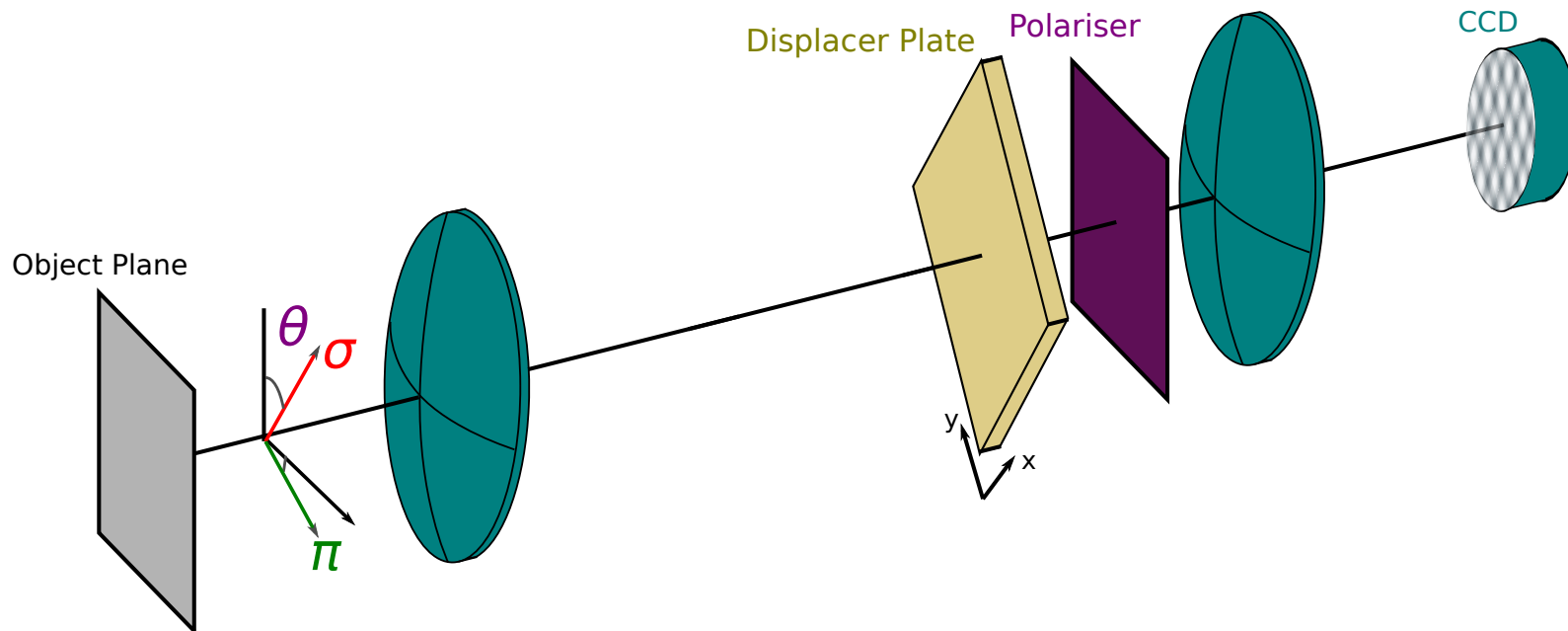
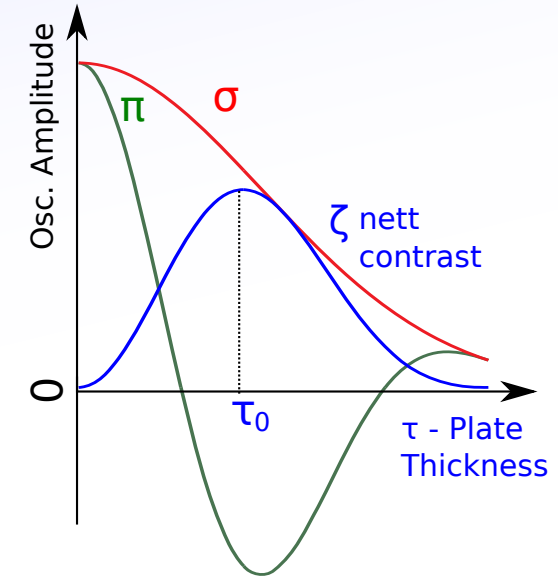
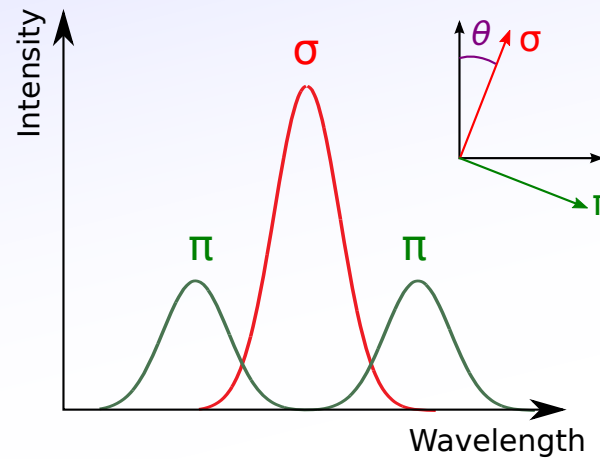
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# Multiplet Polarisation Coherence Imaging

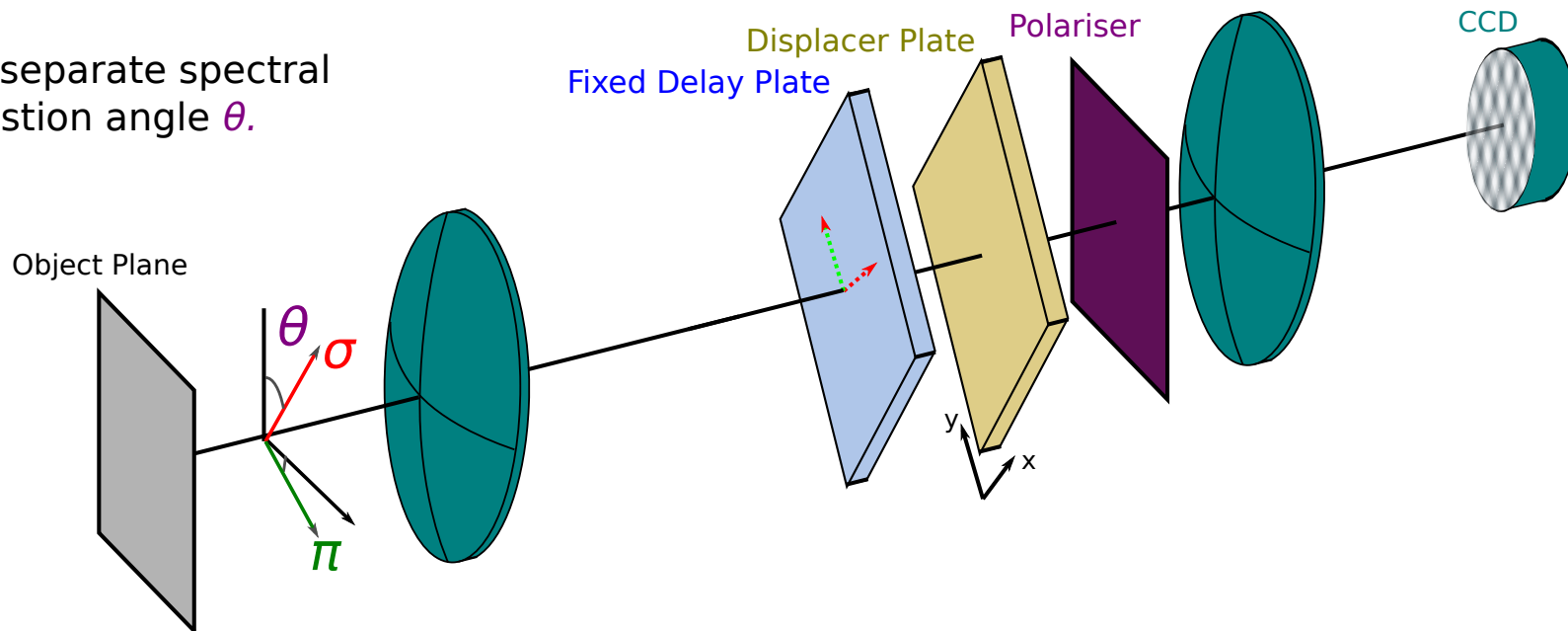
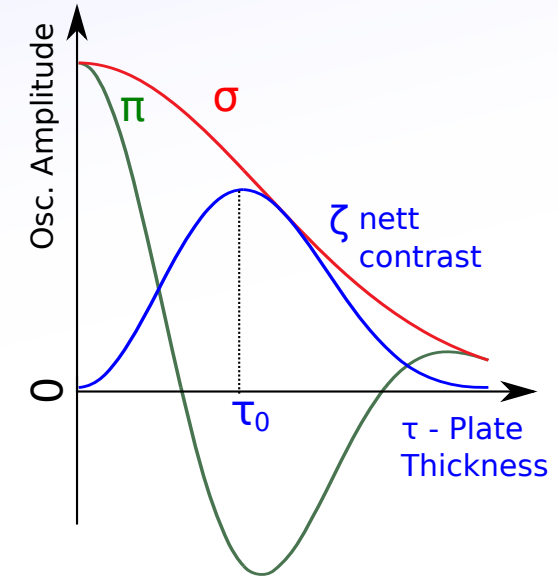
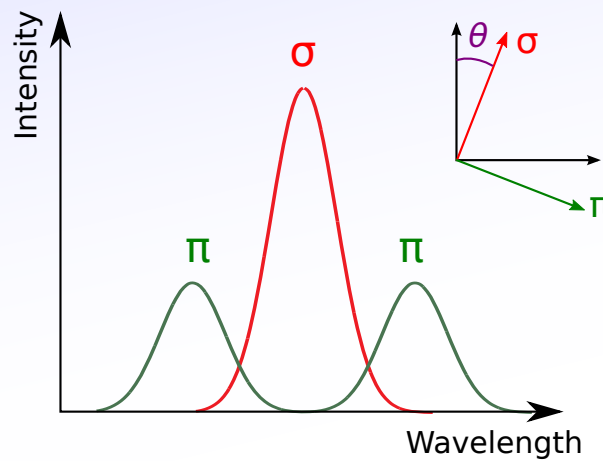
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However, we now need to separate spectral contrast  $\zeta$  from the polarisation angle  $\theta$ .



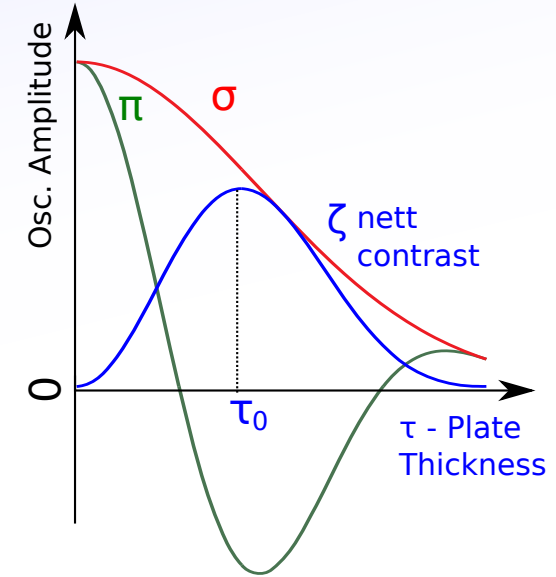
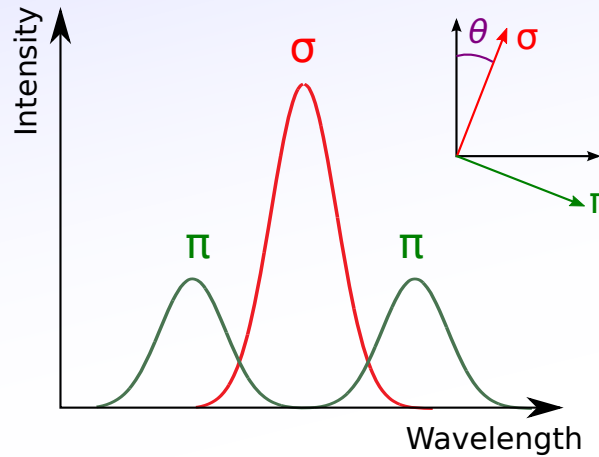
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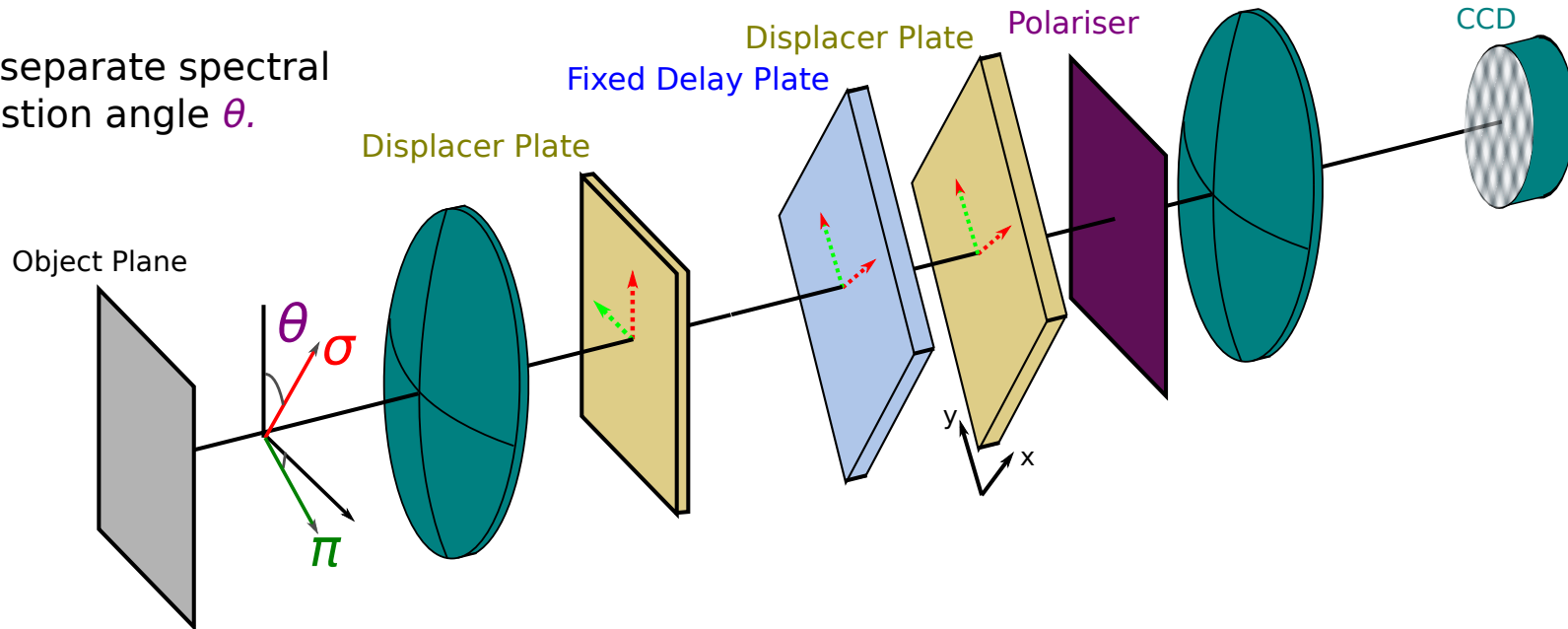
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However, we now need to separate spectral contrast  $\zeta$  from the polarisation angle  $\theta$ .



add another displacer at  $45^\circ$ . Combined effect adds 2 extra terms:

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



# 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  $\theta$ :

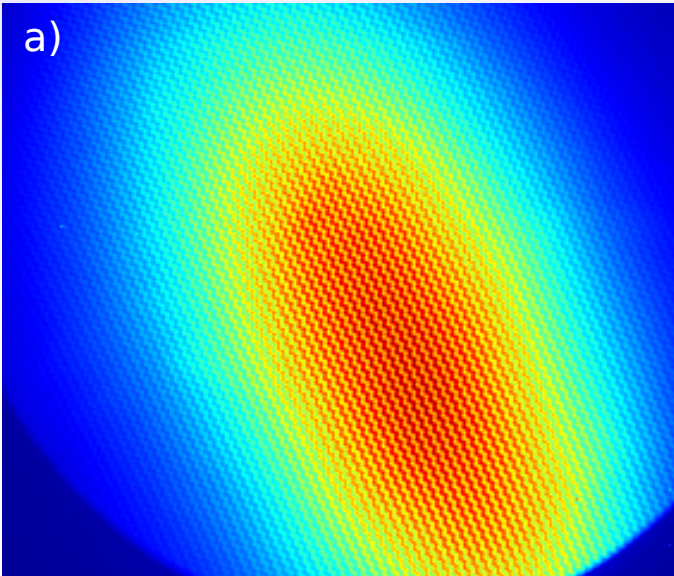
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a)

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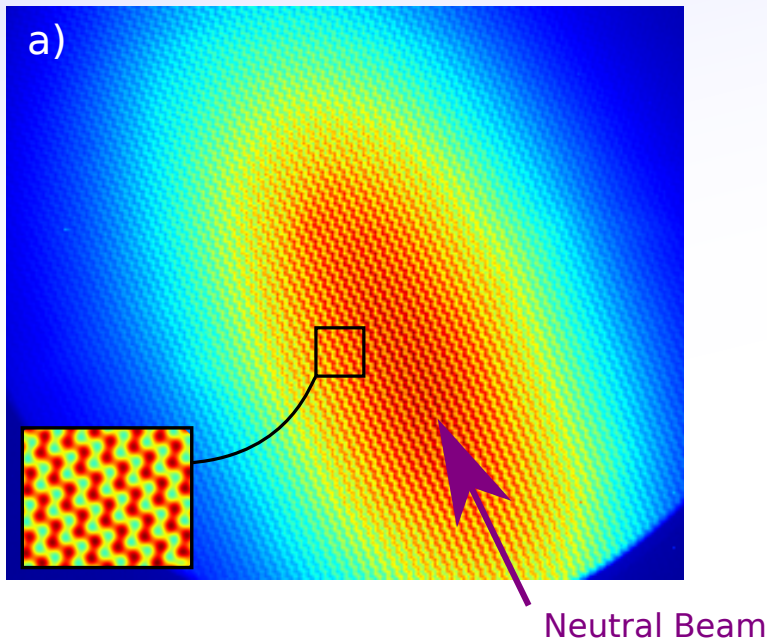
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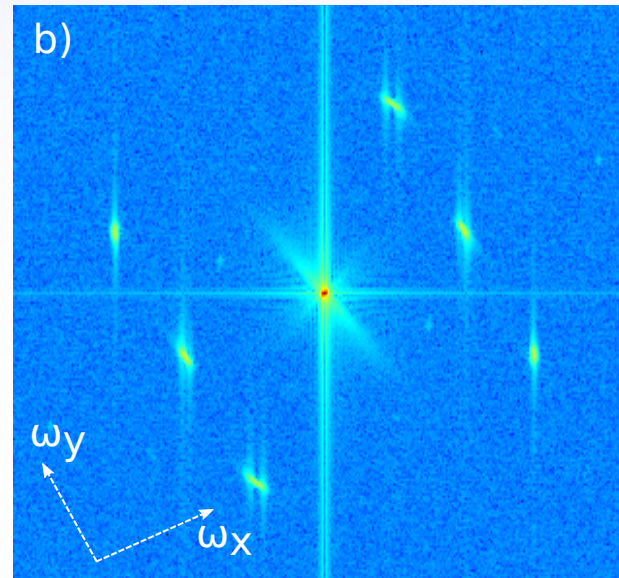
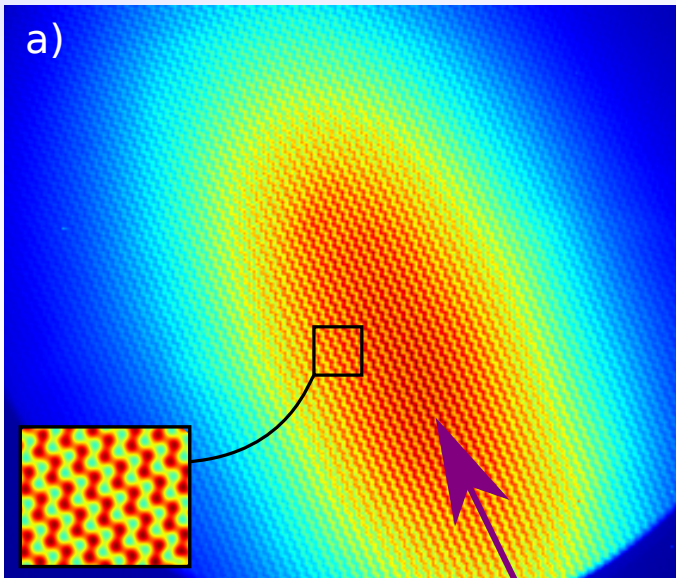




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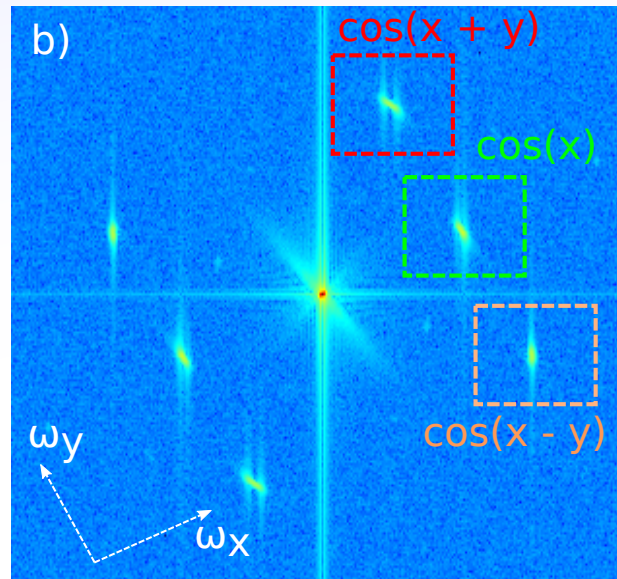
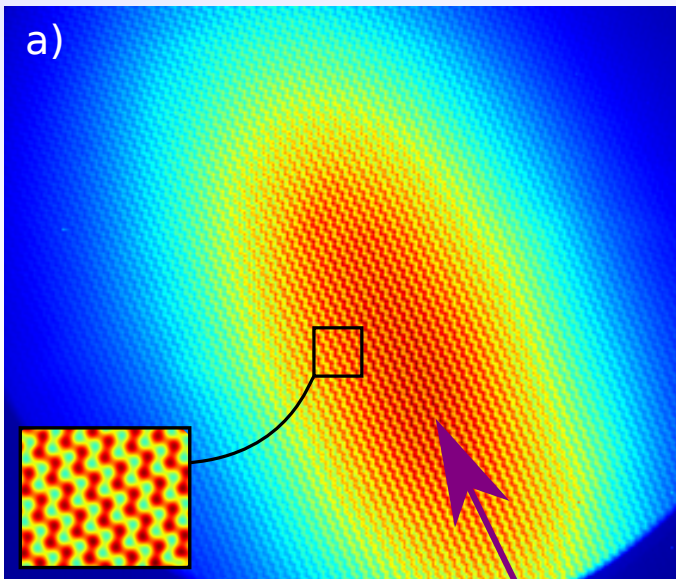


Neutral Beam

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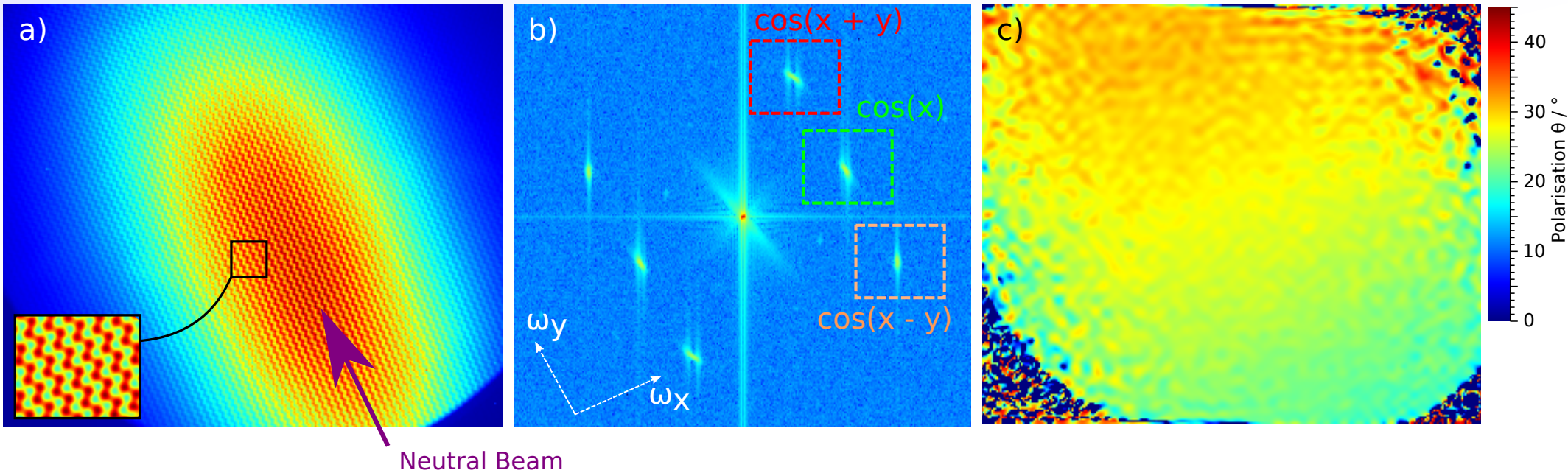


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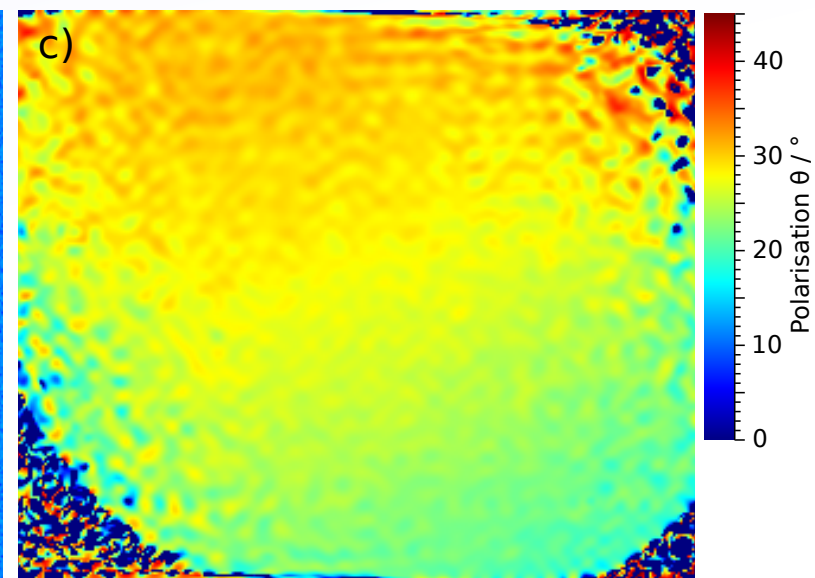
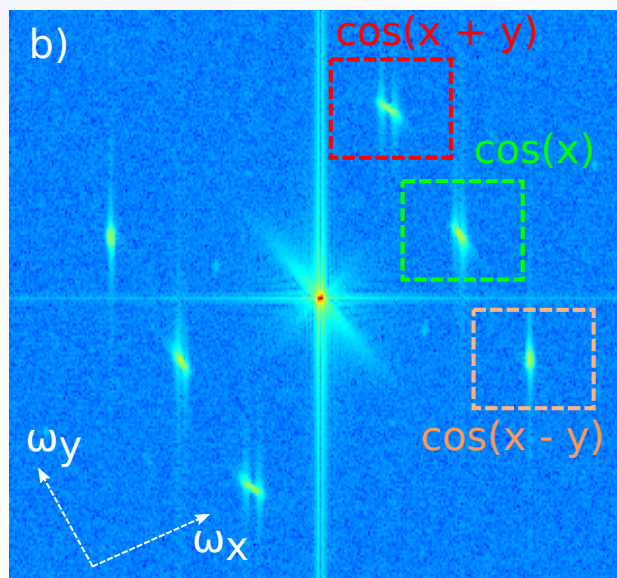
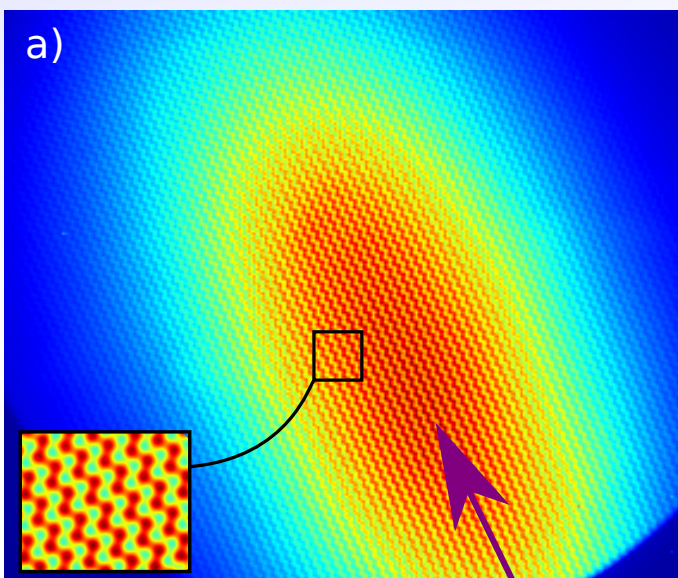
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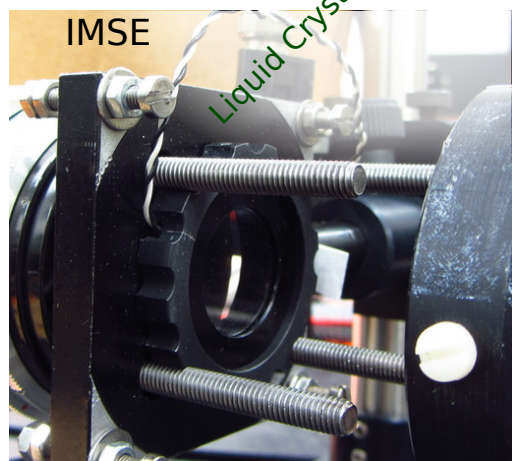
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The hardware:

Neutral Beam

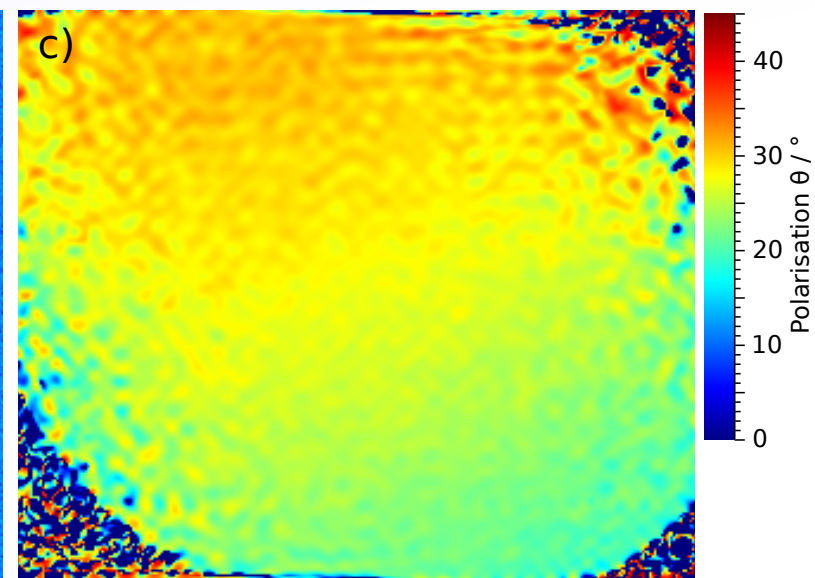
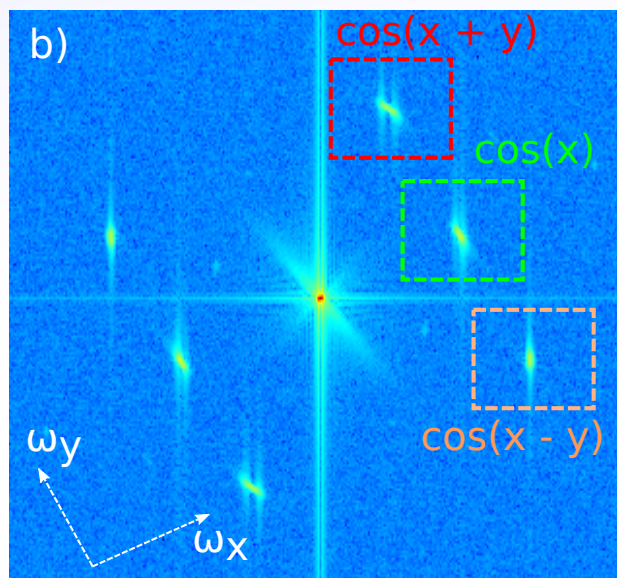
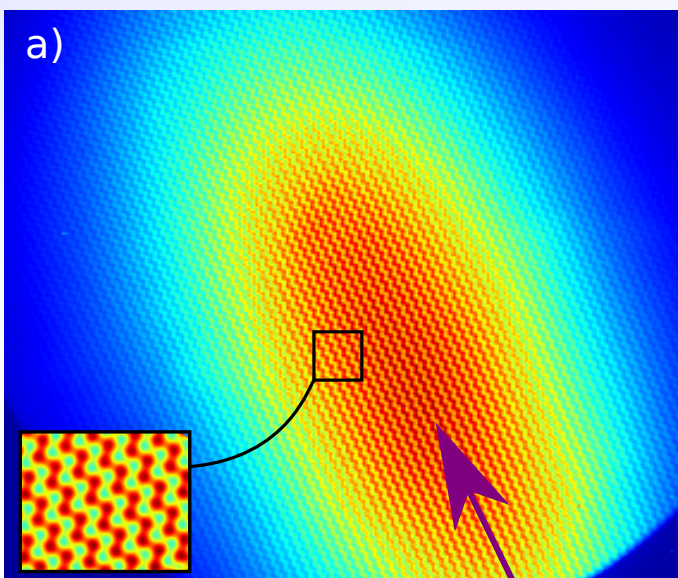
IMSE: 100x100 data points



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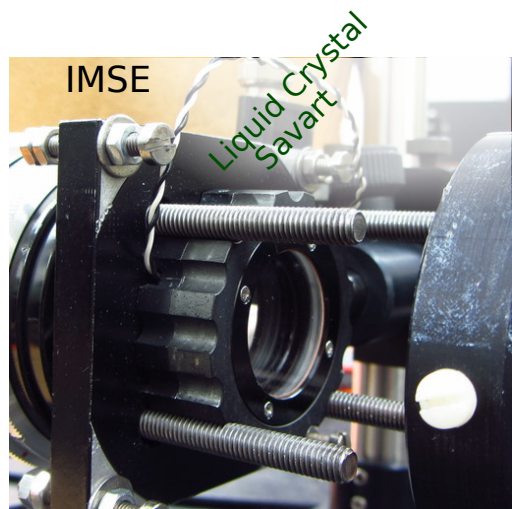
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Neutral Beam

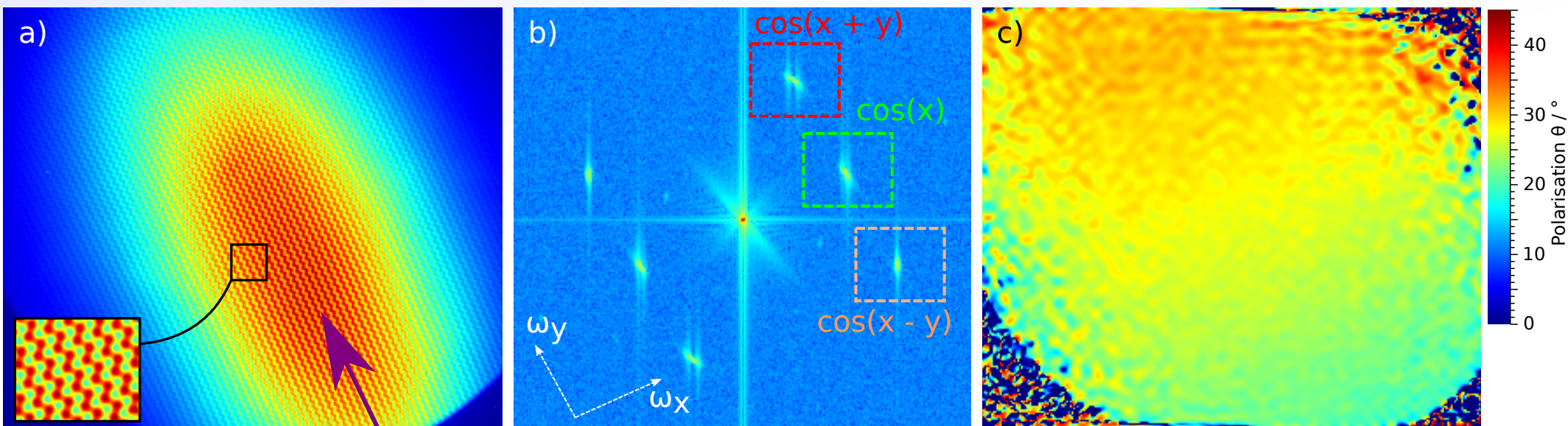
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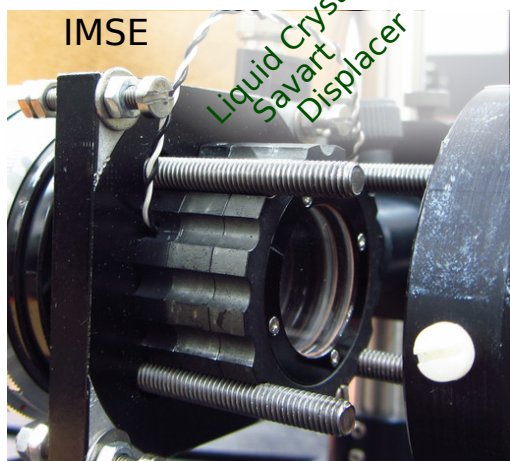
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Neutral Beam

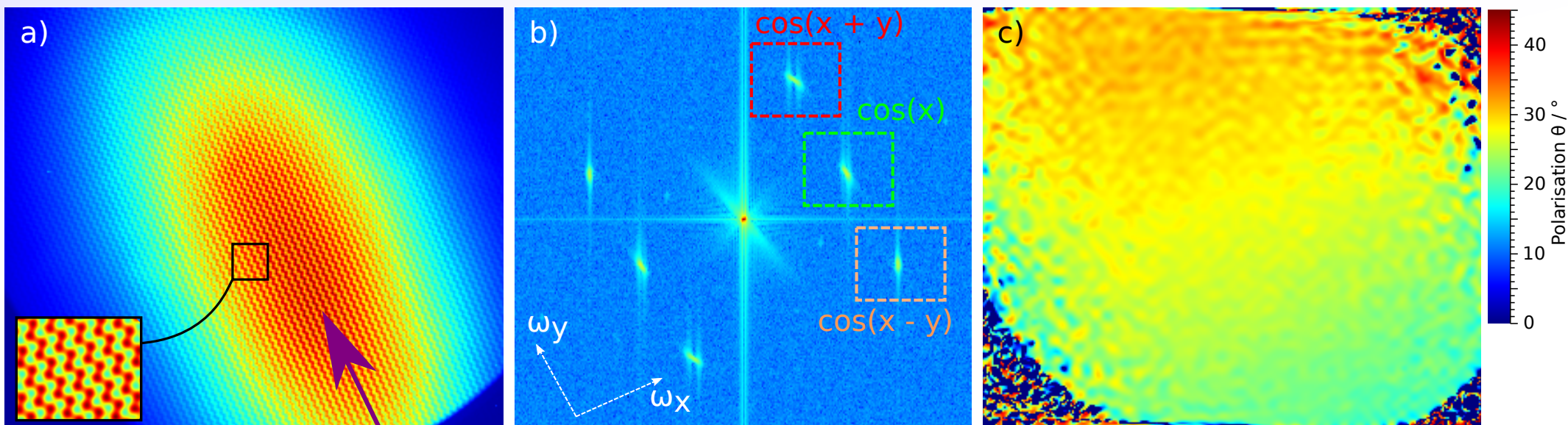
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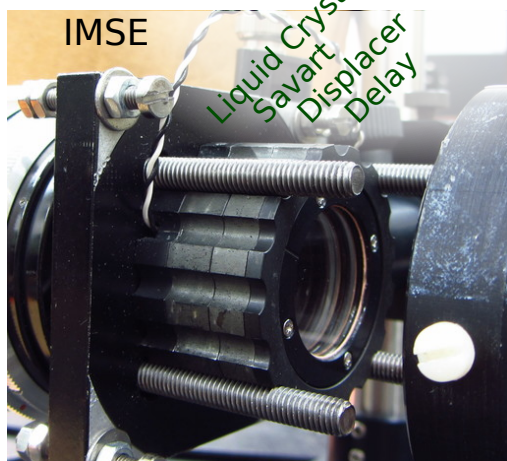
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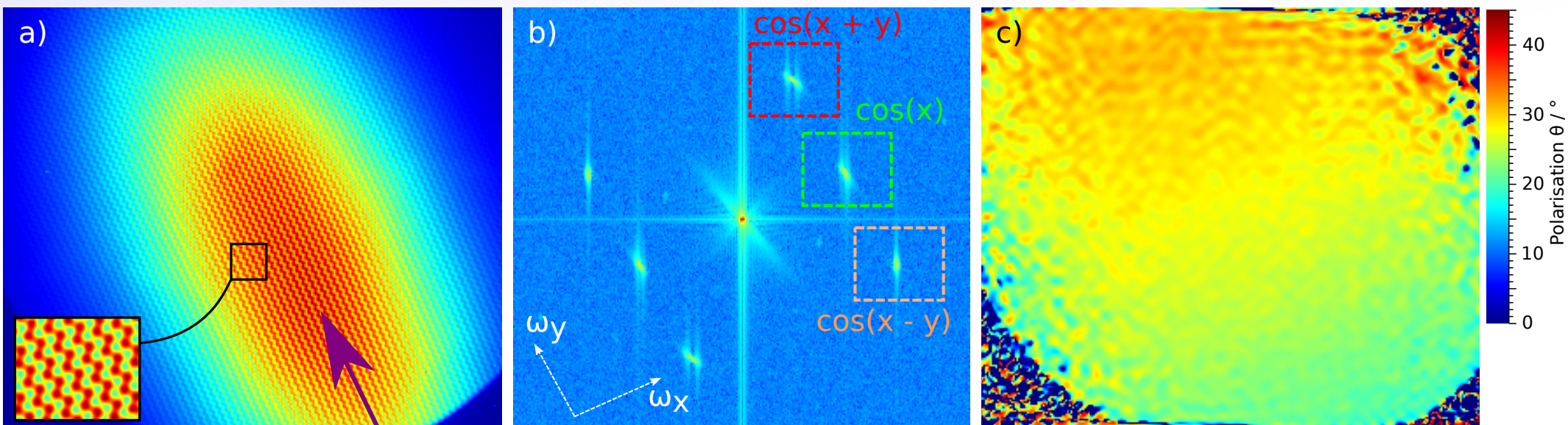


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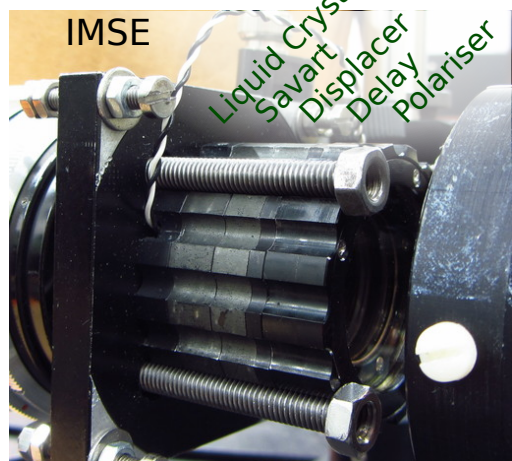
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Neutral Beam

IMSE: 100x100 data points

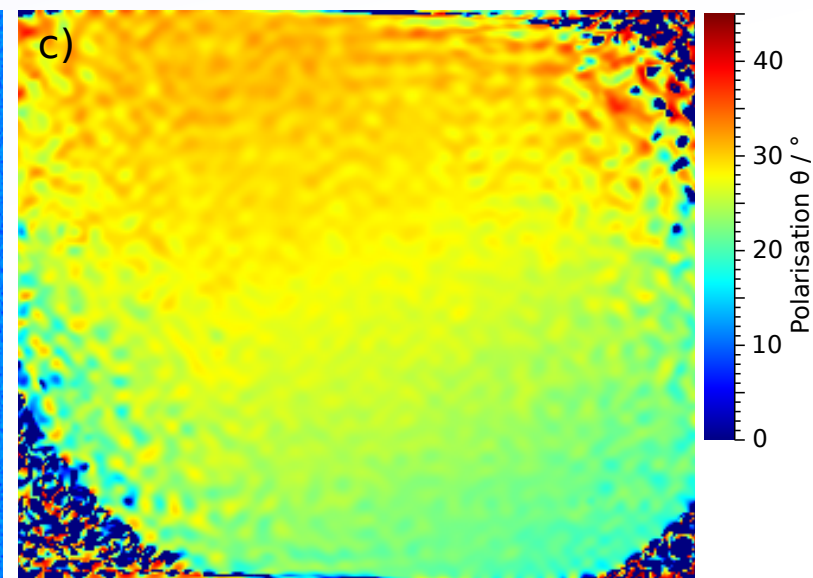
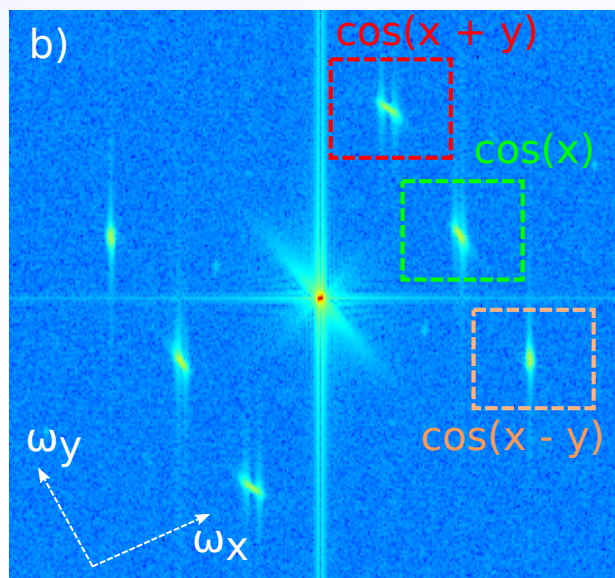
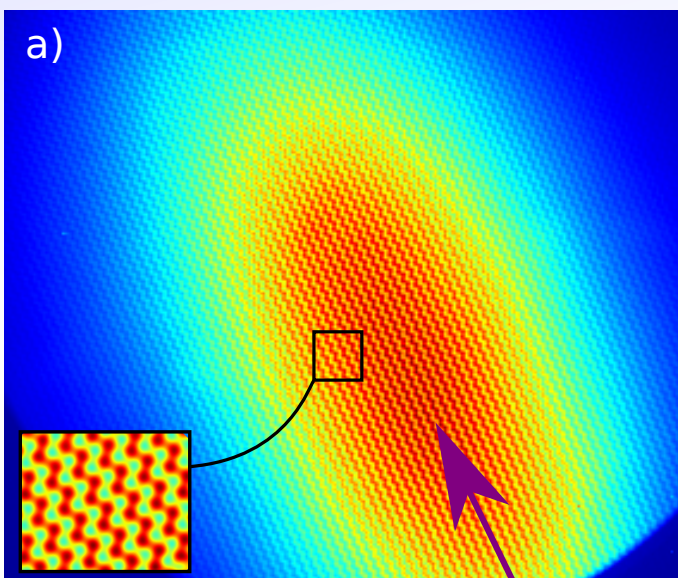




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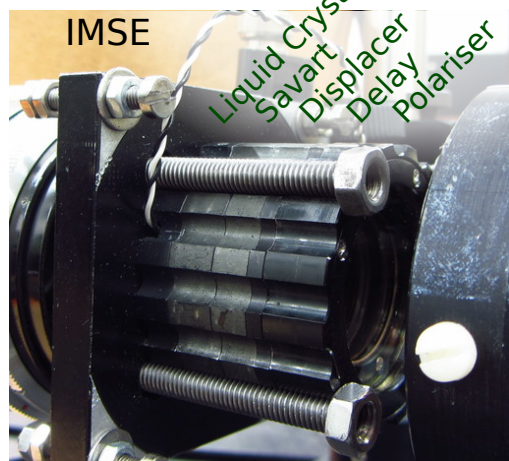
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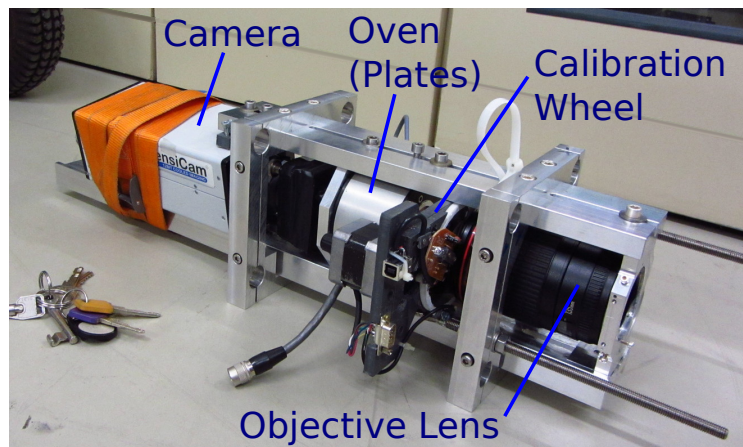


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Neutral Beam



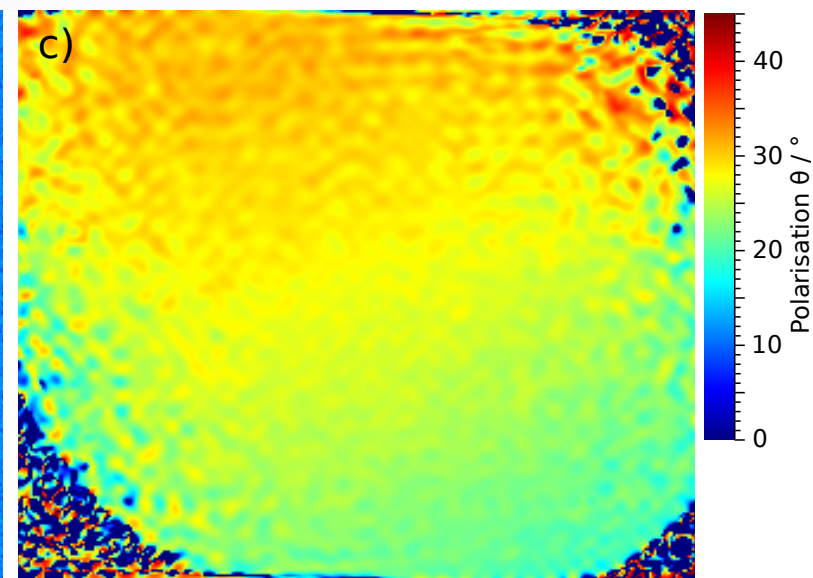
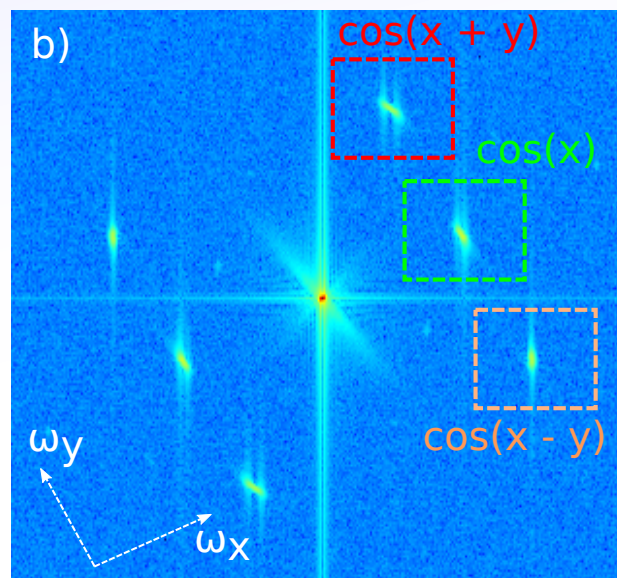
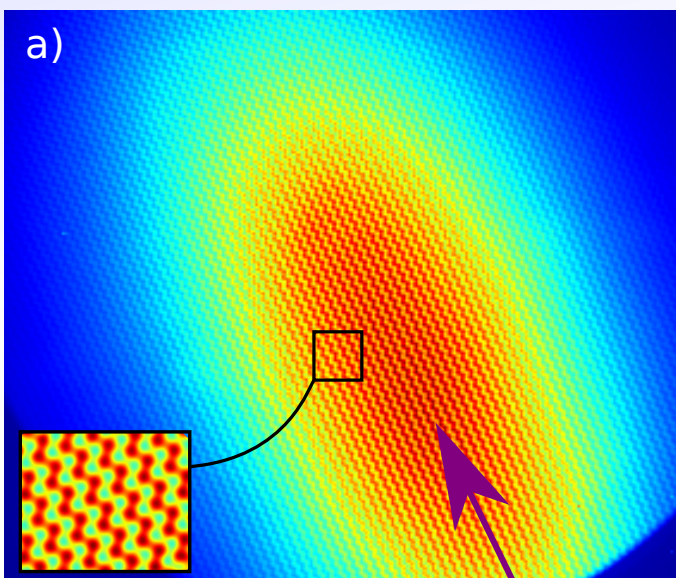
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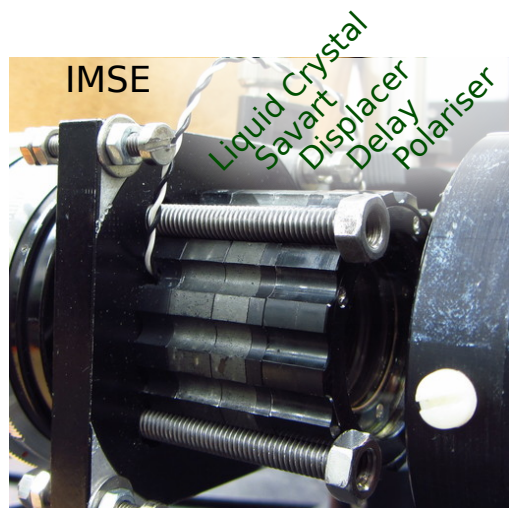
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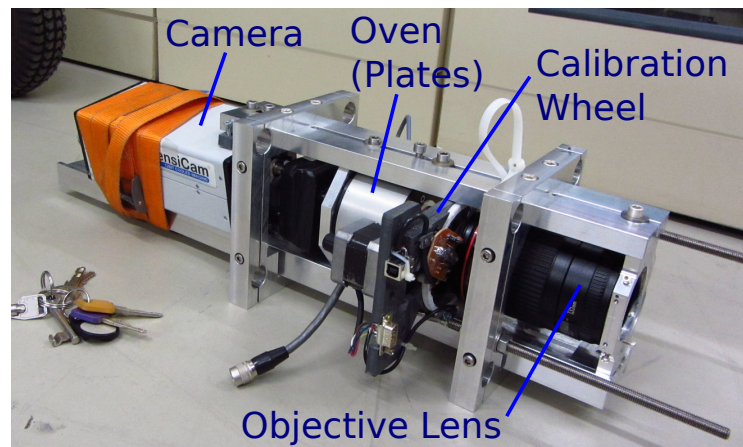


The hardware:

Neutral Beam



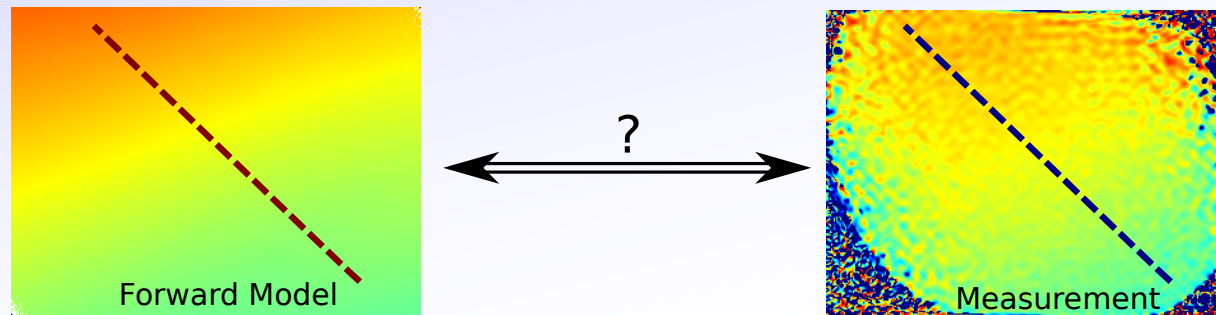
IMSE: 100x100 data points



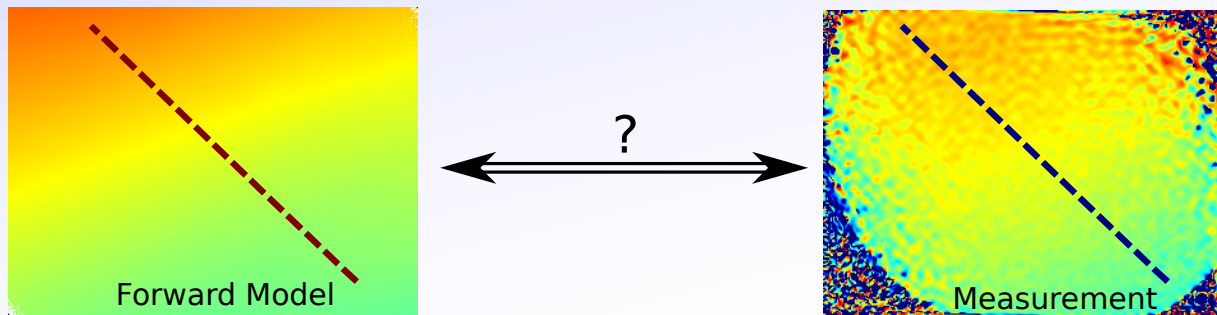
MSE Polarimeter: 12 data points



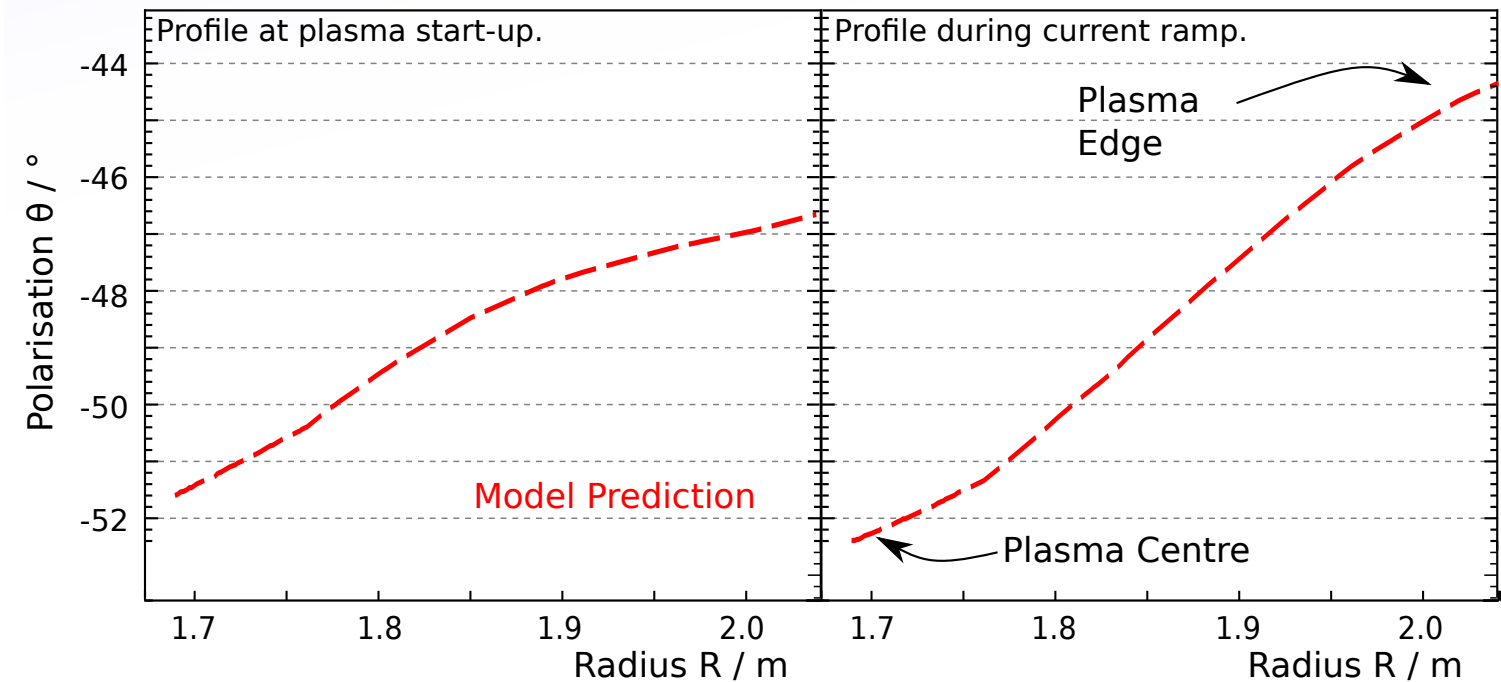
# Preliminary comparison with Forward Model



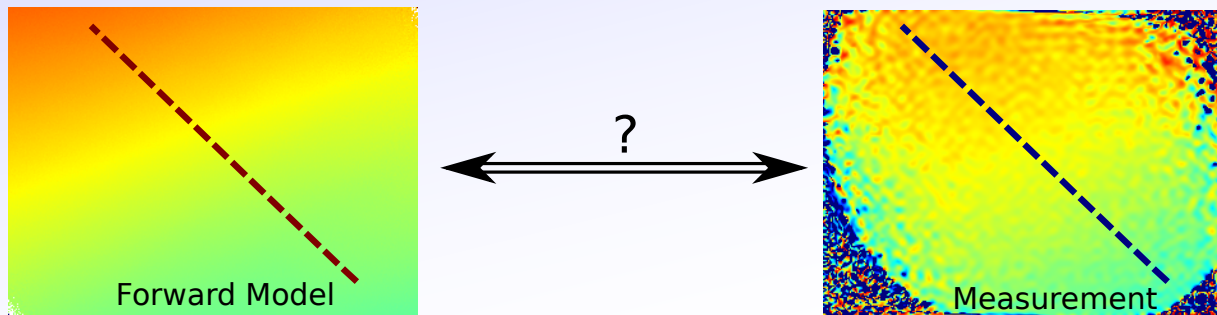
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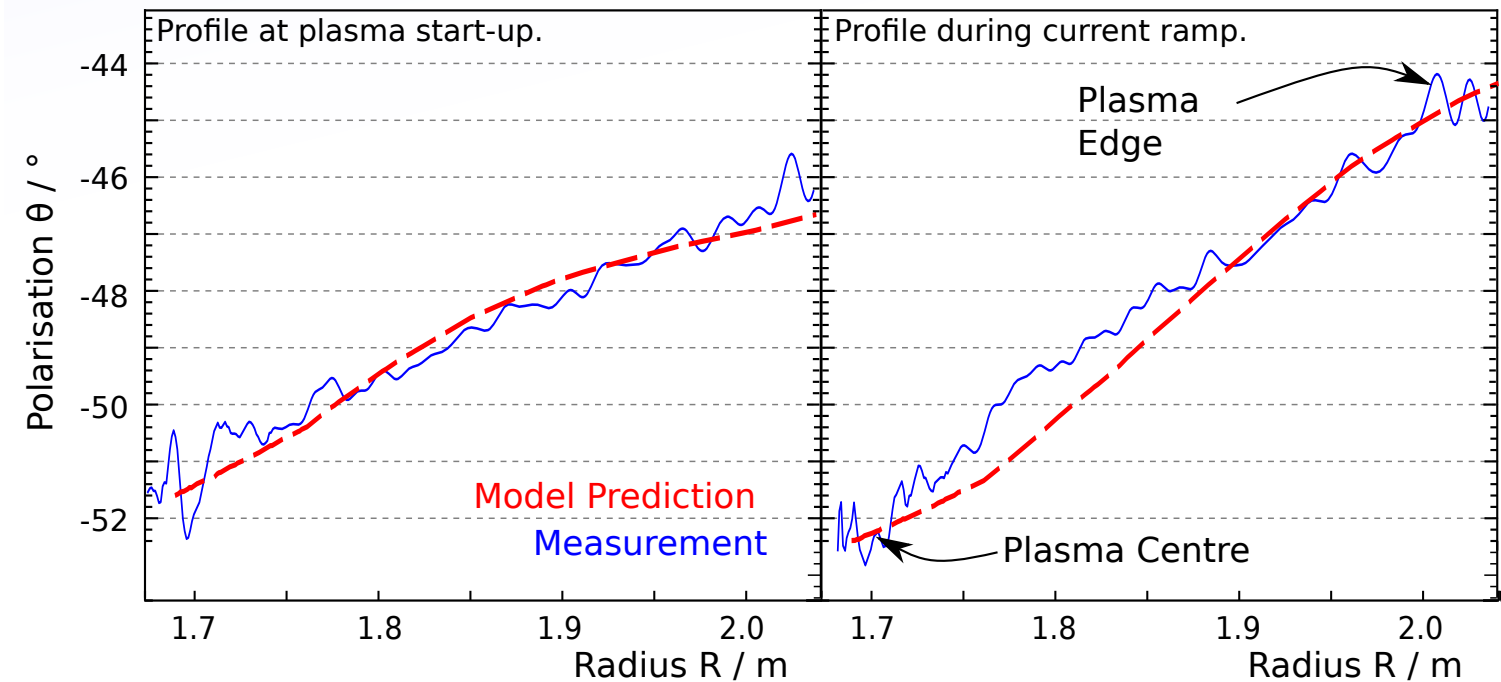
Except for a  $0.7^\circ$  offset, the results agree with the modelling where what we already know from other diagnostics is expected to be correct. The difference is the new information that the IMSE provides:



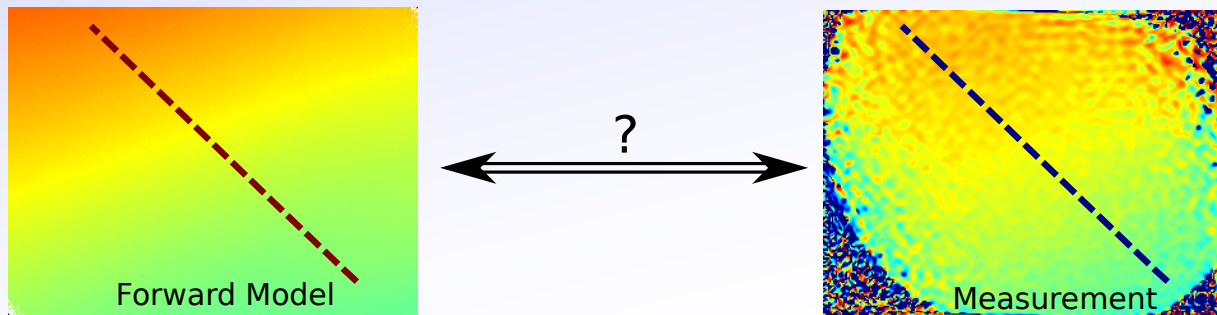
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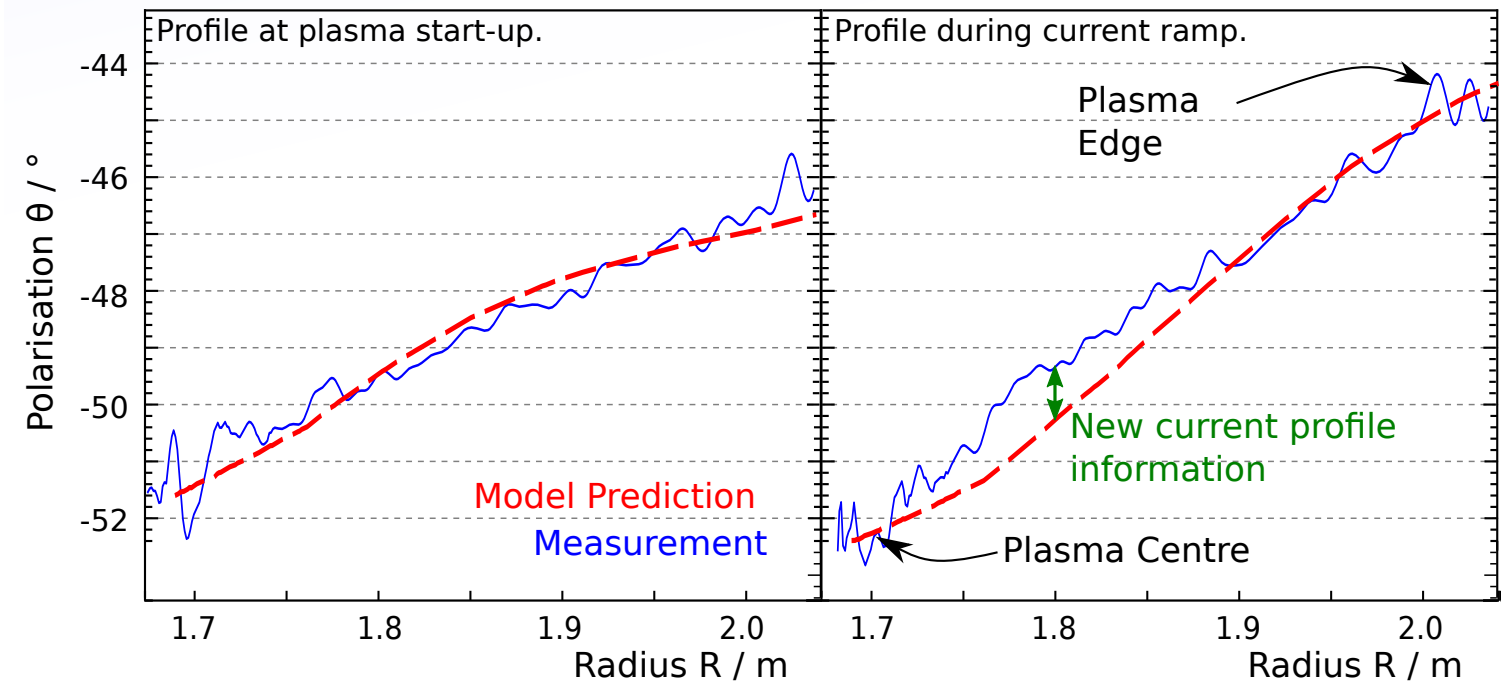
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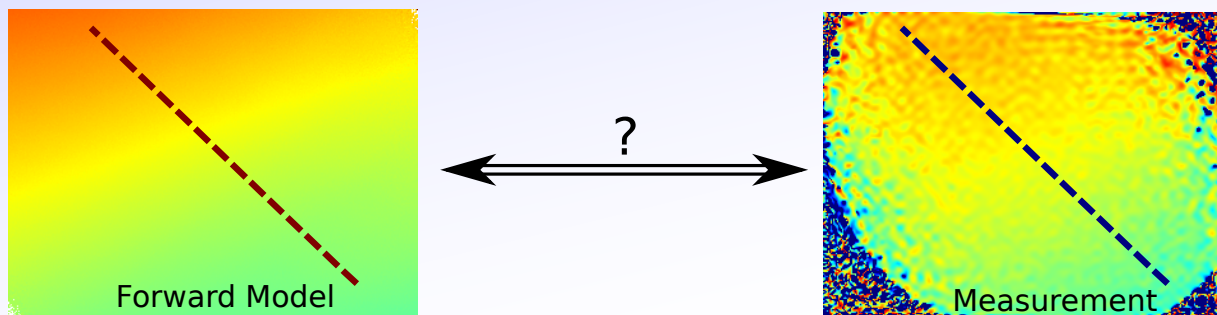
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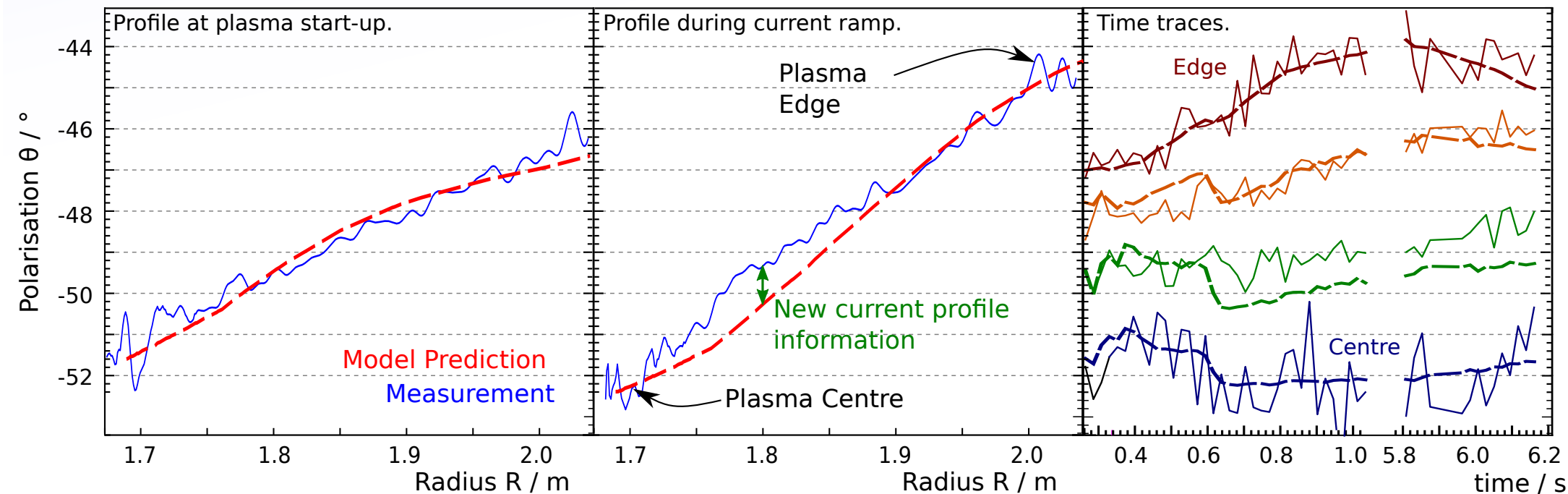
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Inferring the plasma current and q-profiles from the polarisation is far from trivial and the analysis work is still on-going.



## 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.





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- ✓ An new Imaging Motional Stark Effect diagnostic has been designed, constructed and operated on ASDEX Upgrade.
  - It has many advantages, including:
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    - Over 100x more data.
    - Automatic positional calibration.
    - Relatively insensitive to the spectrum (no finely tuned filters)
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- ✓ 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.

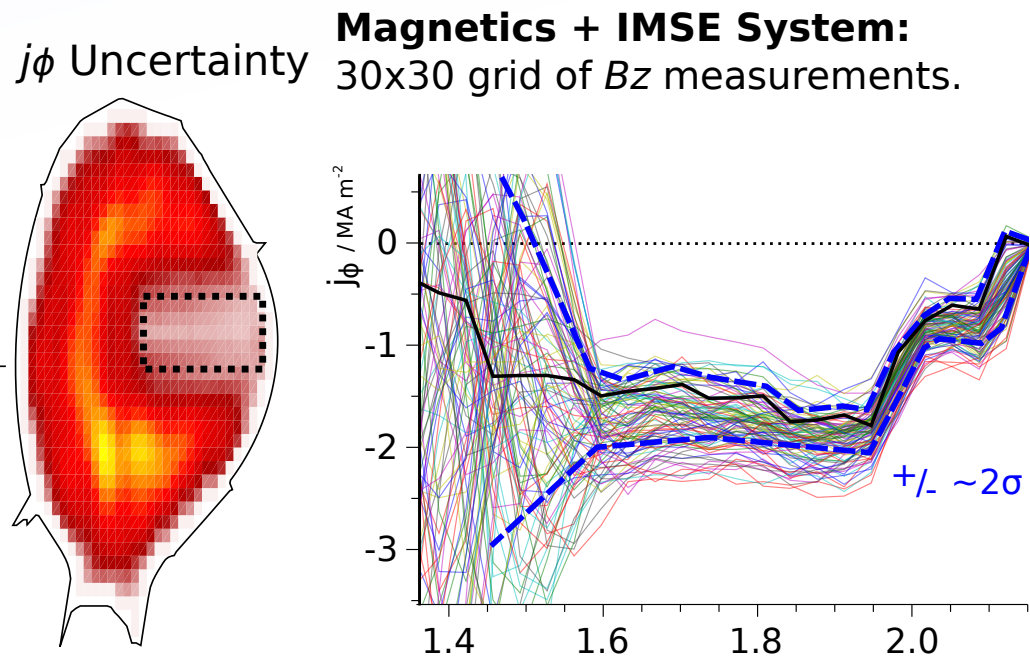
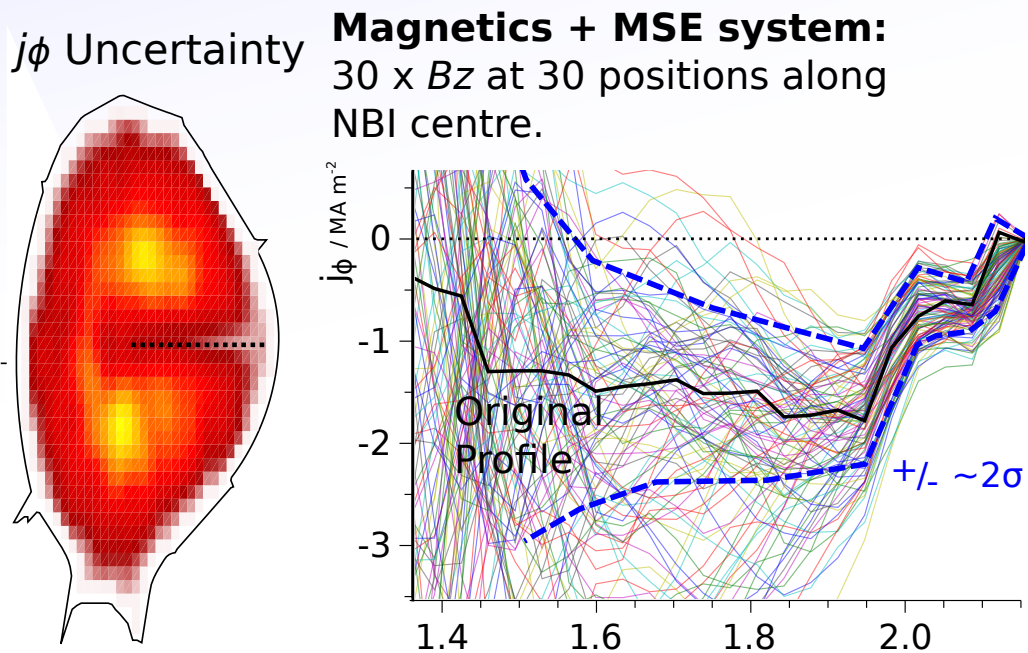


(Additional)

# 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.



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.