Bochum University Colloquium, June 2015

Two-dimensional magnetic field measurements of fusion plasmas using coherence imaging.

- The (prototype) ASDEX Upgrade IMSE diagnostic.
- Doppler coherence imaging.
- Future prospects

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J.Howard[2], A. Burckhart[1], M. Reich[1], R.Wolf[1]

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2: Australian National University, Canberra, Australia

Magnetic Confinement Fusion

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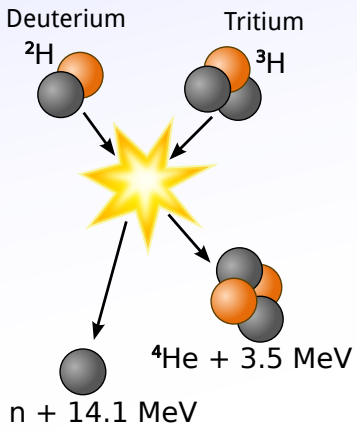
One solution is to confine the plasma in a closed magnetic field.



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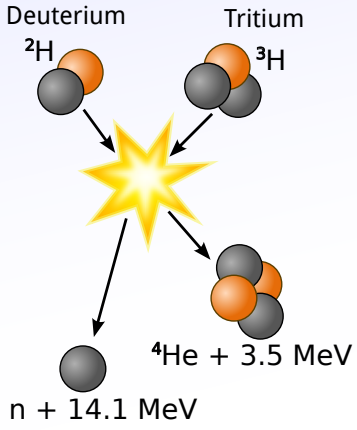

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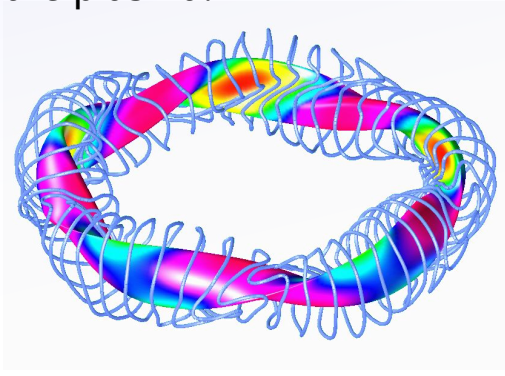

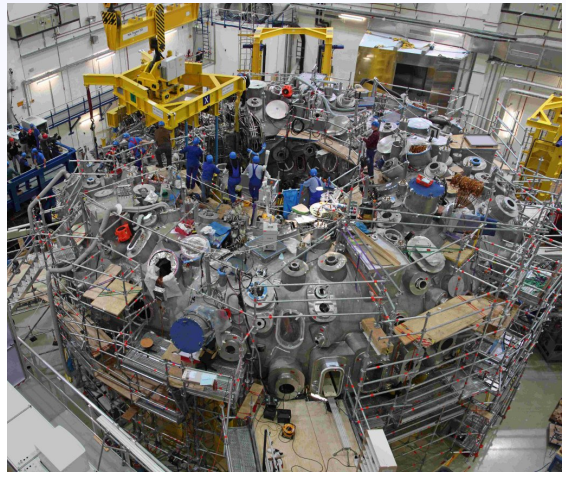

Wendelstein-7X (IPP Greifswald)

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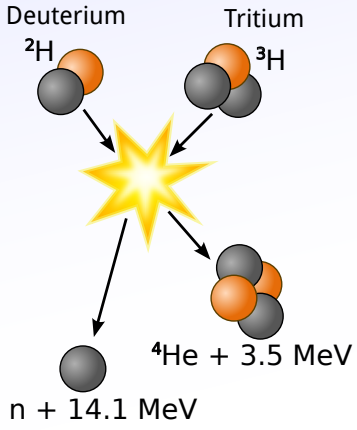

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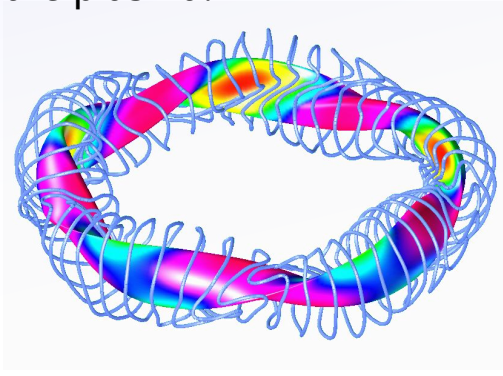

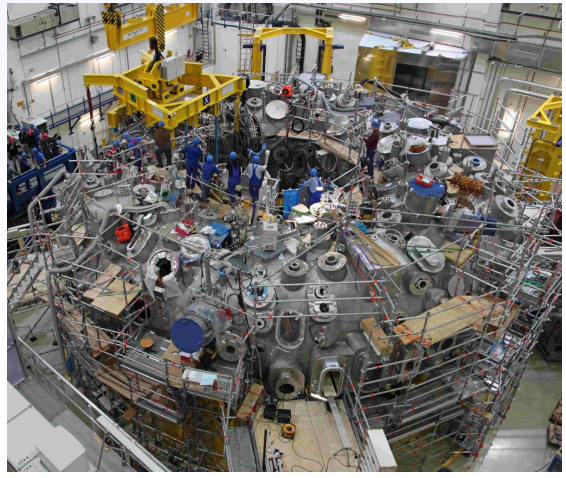

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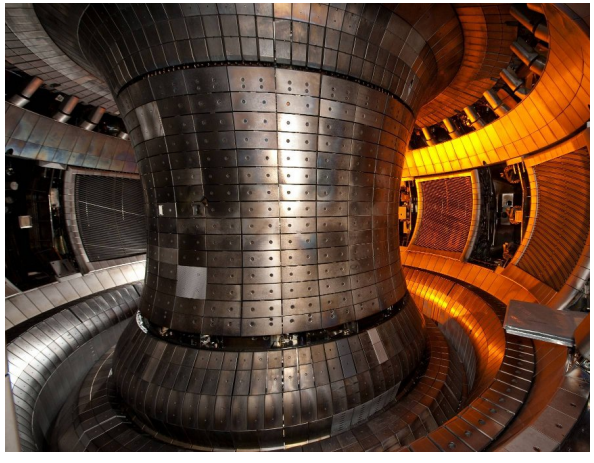

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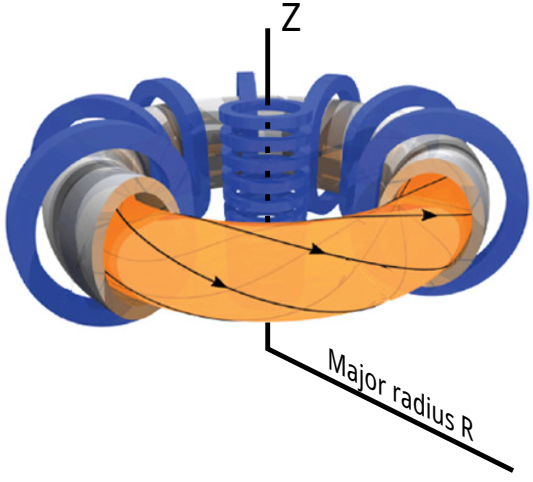

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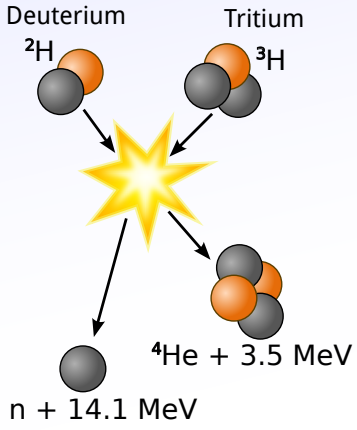

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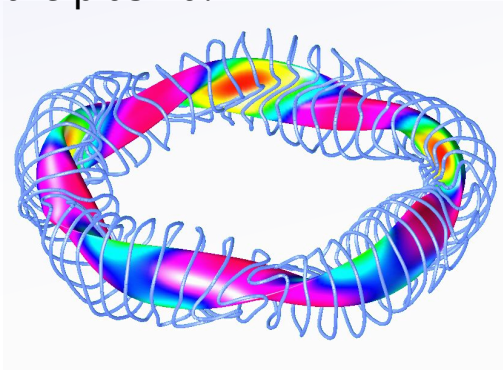

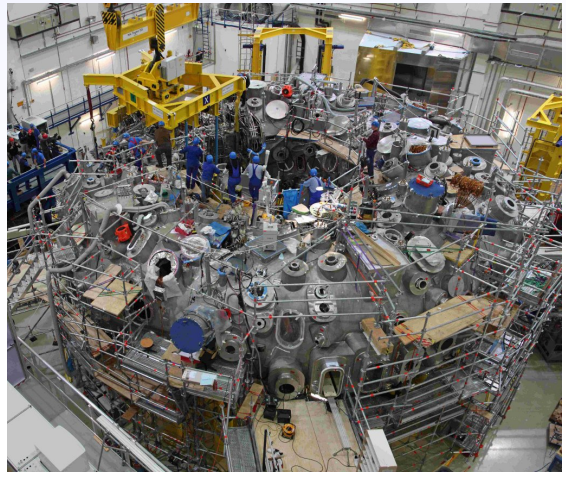

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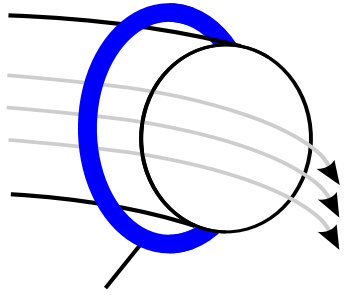
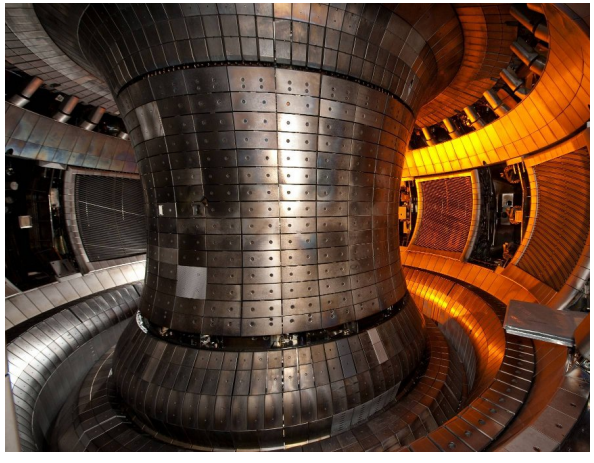


Toroidal Field Coil



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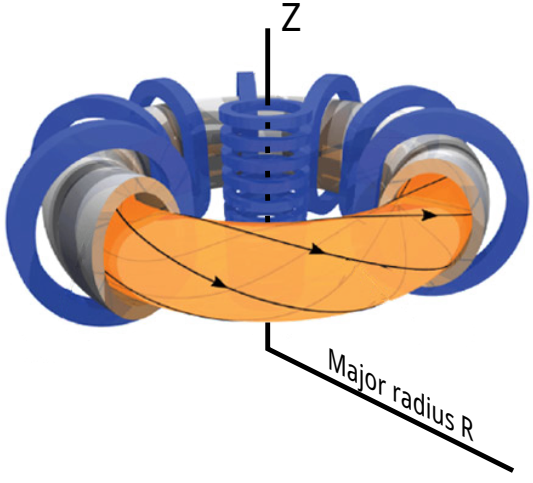

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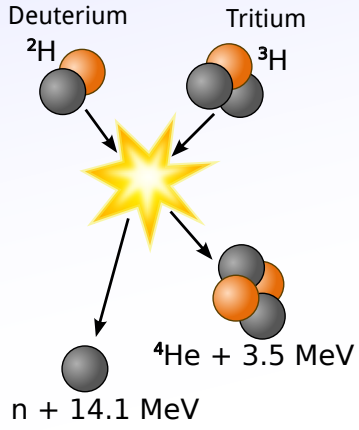

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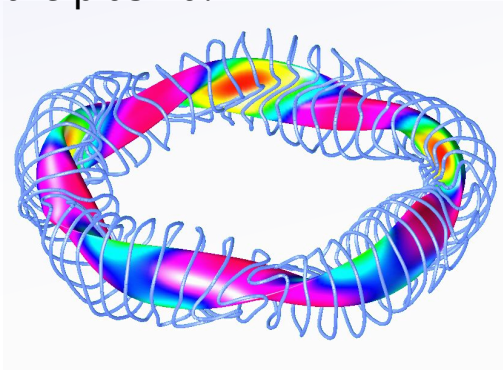

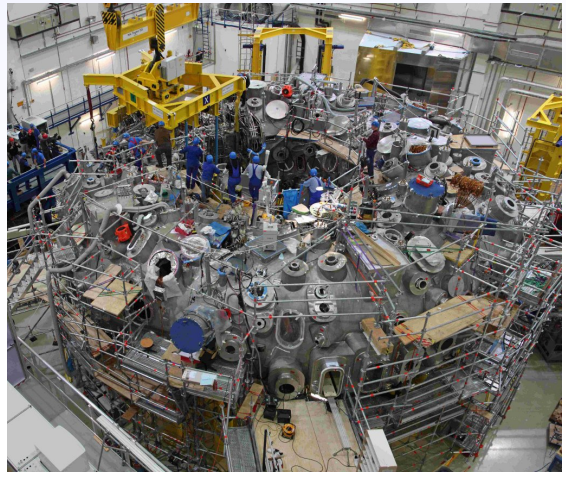

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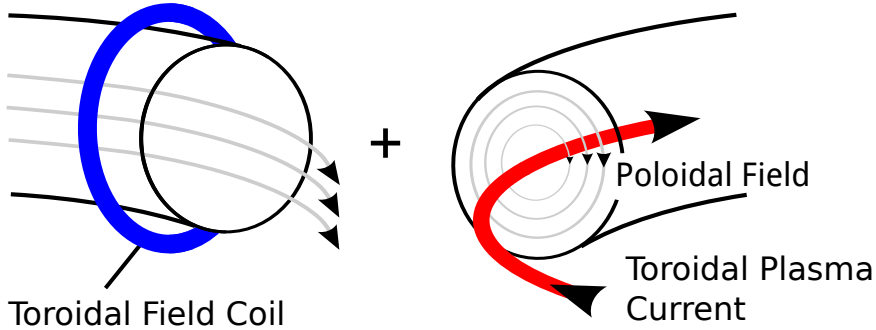

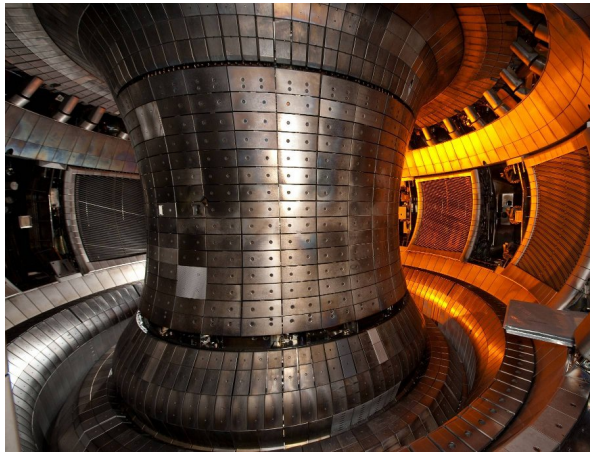

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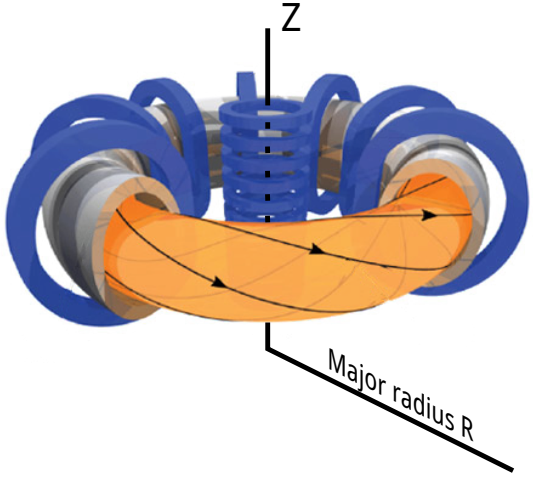

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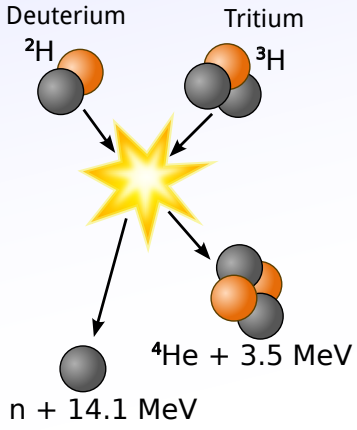

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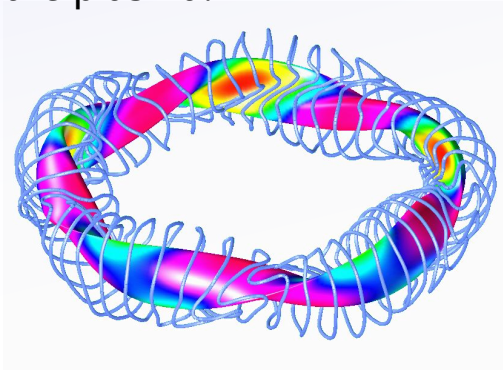

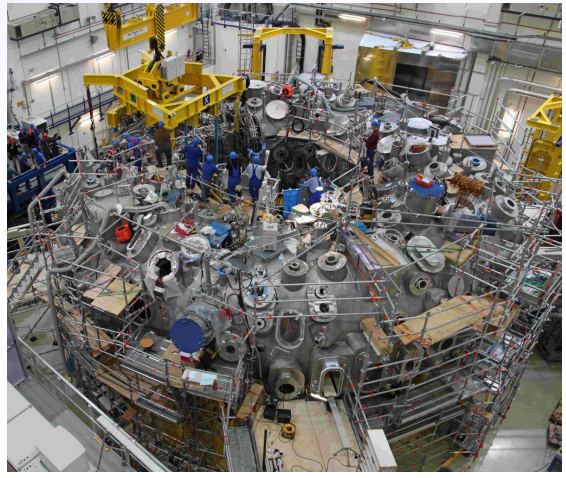

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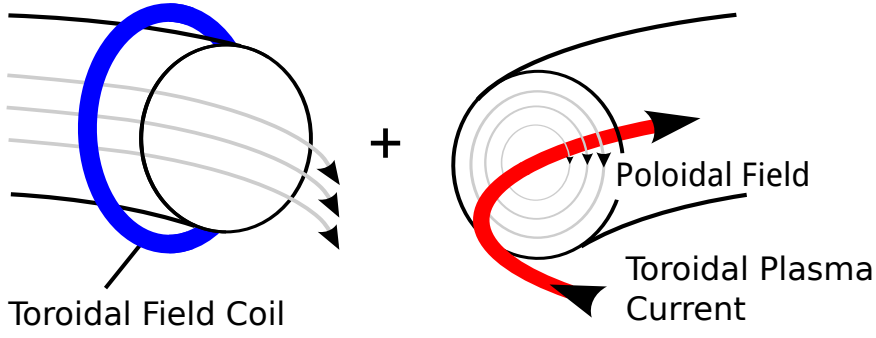

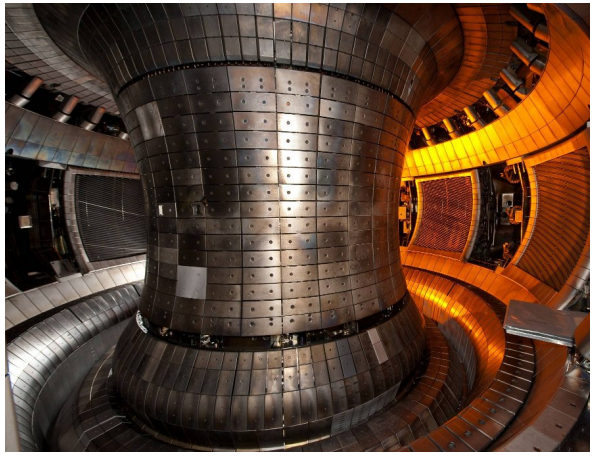

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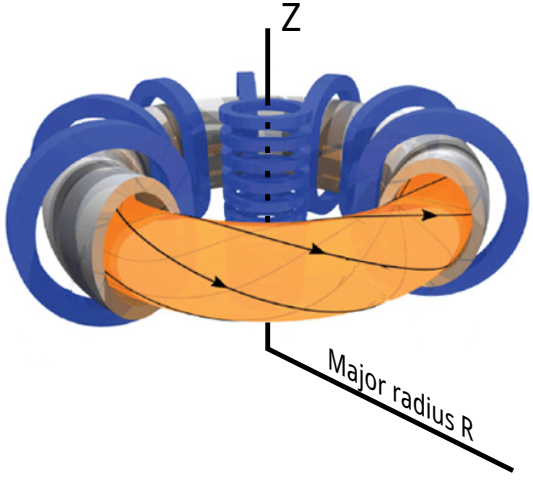

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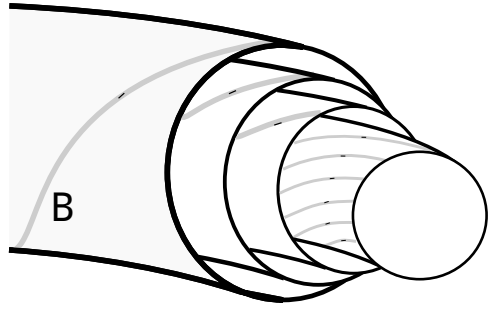

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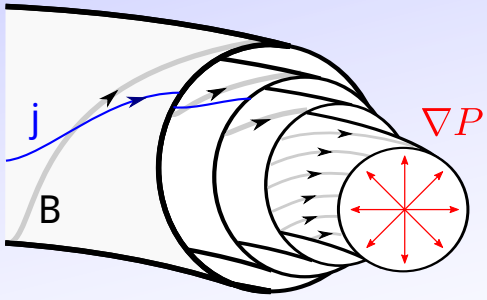

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The current in the plasma is flowing through this field, and the Lorenz force must balance the pressure from the high temperature we are trying to confine, forming a stable equilibrium.

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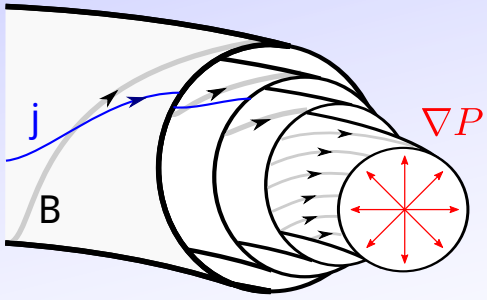

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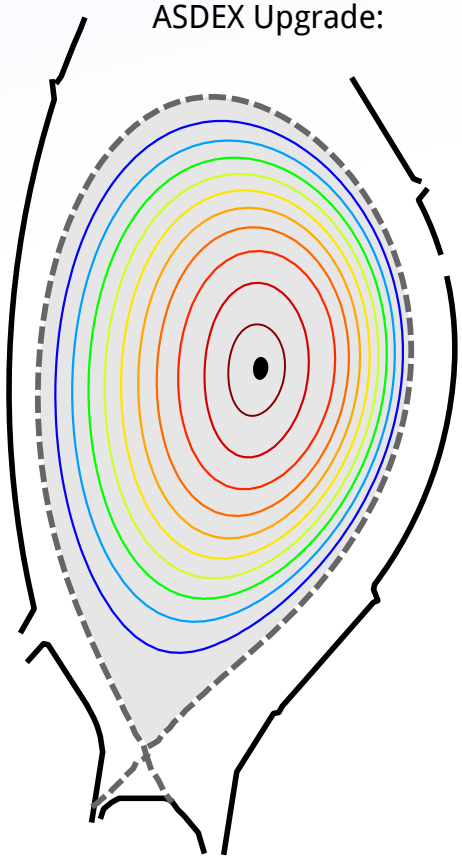

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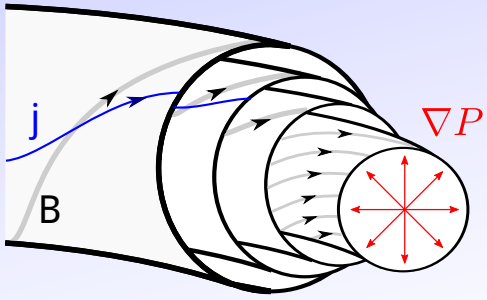

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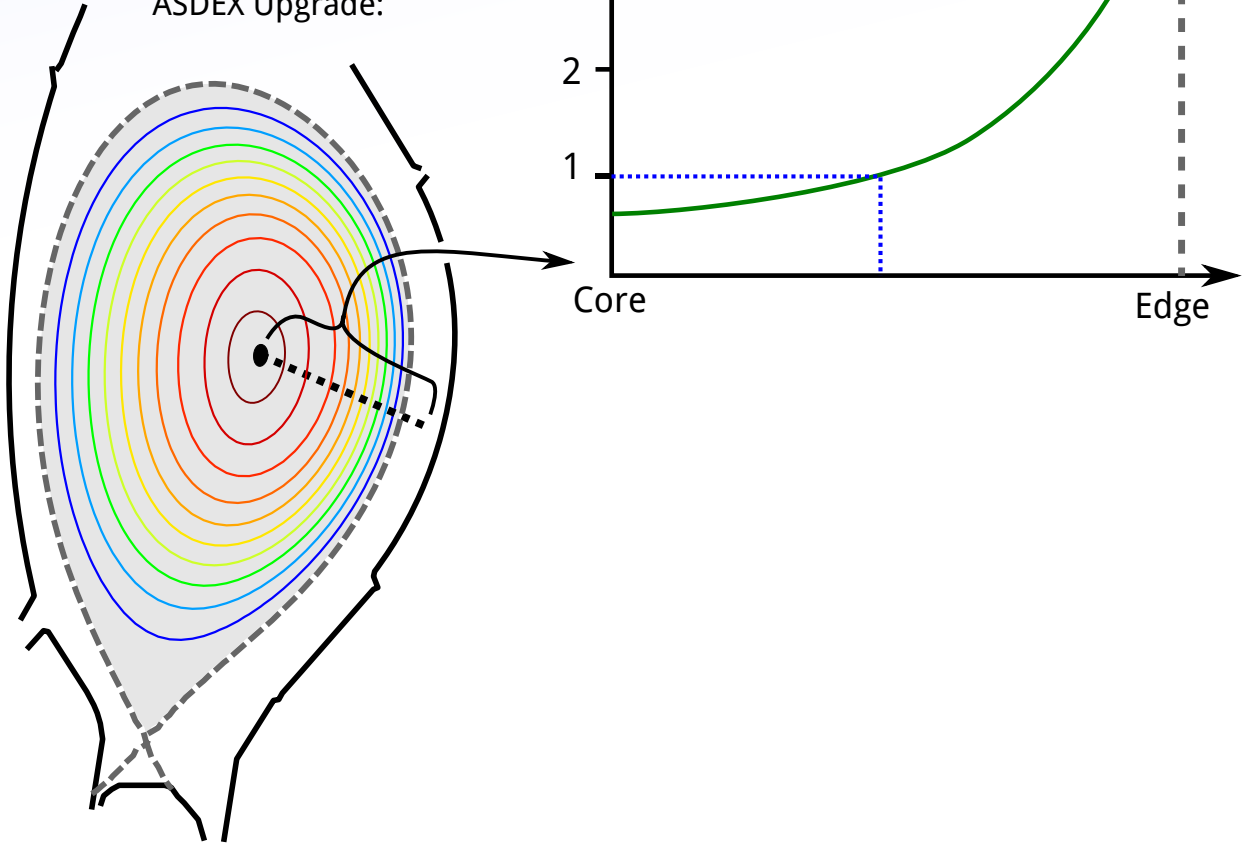

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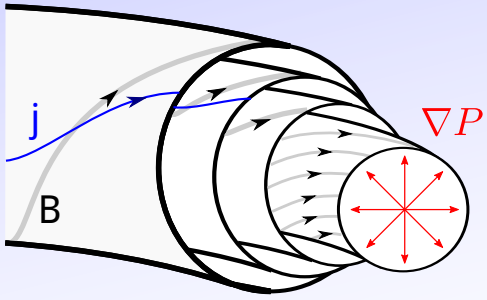

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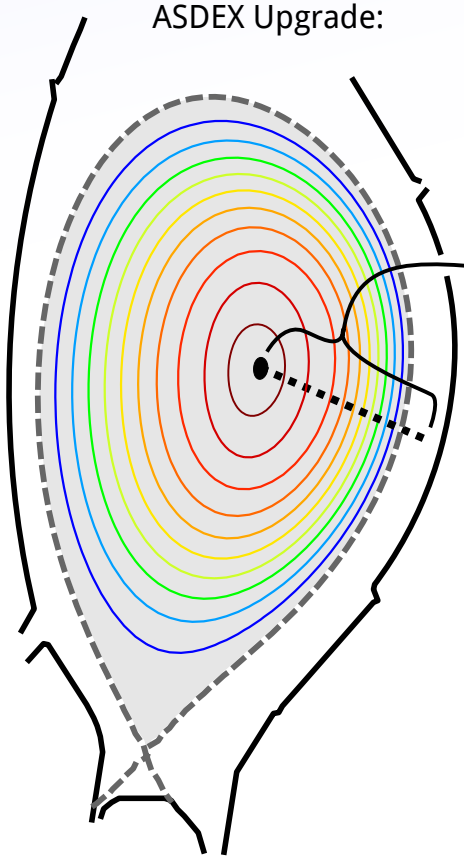

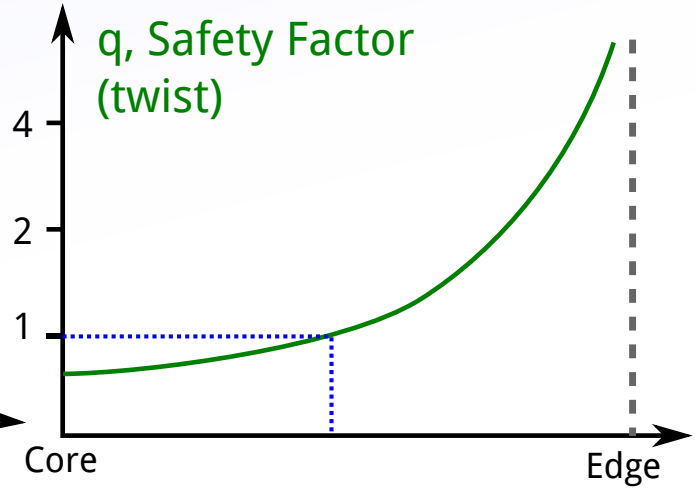

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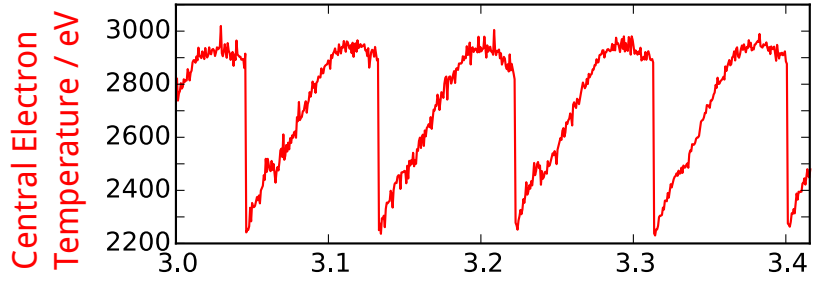

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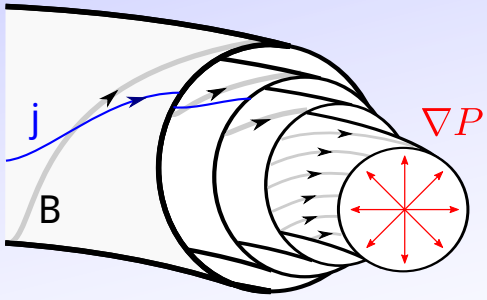

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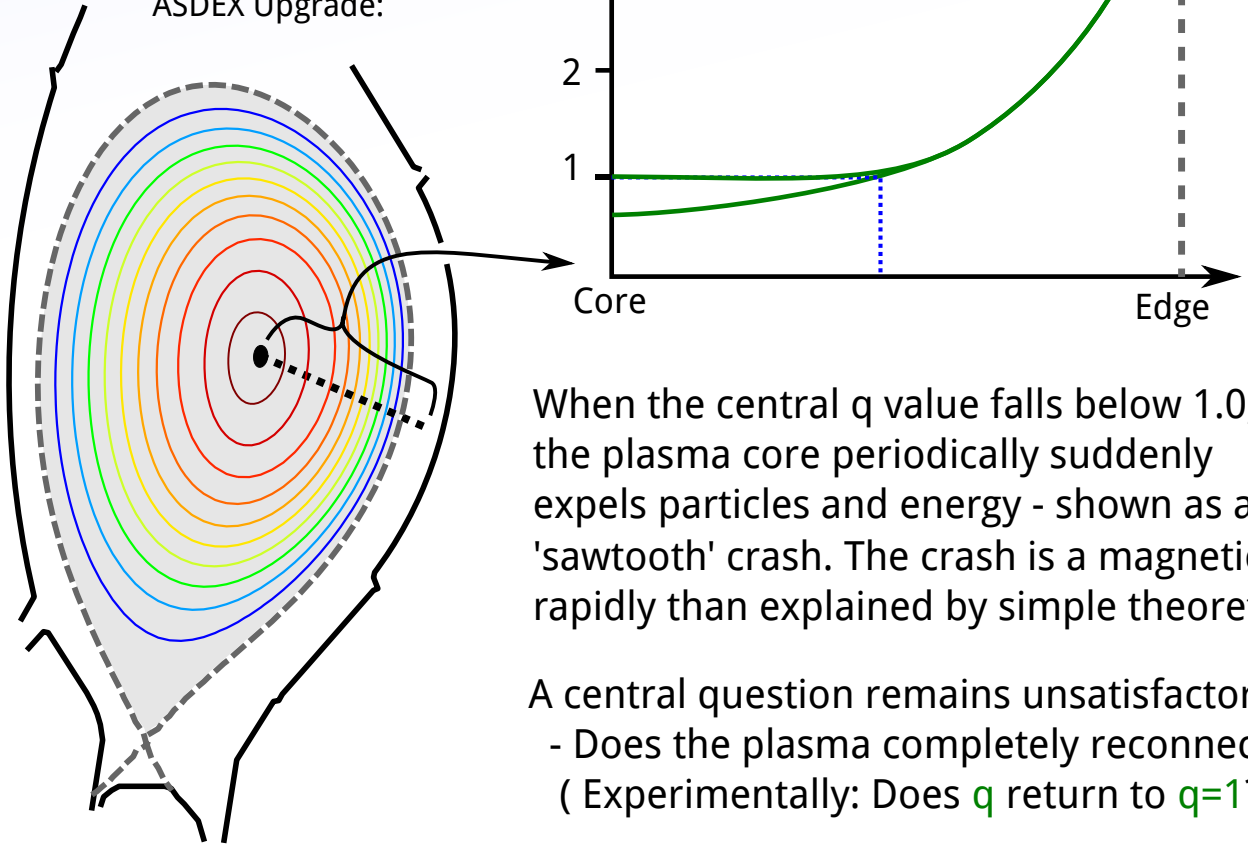

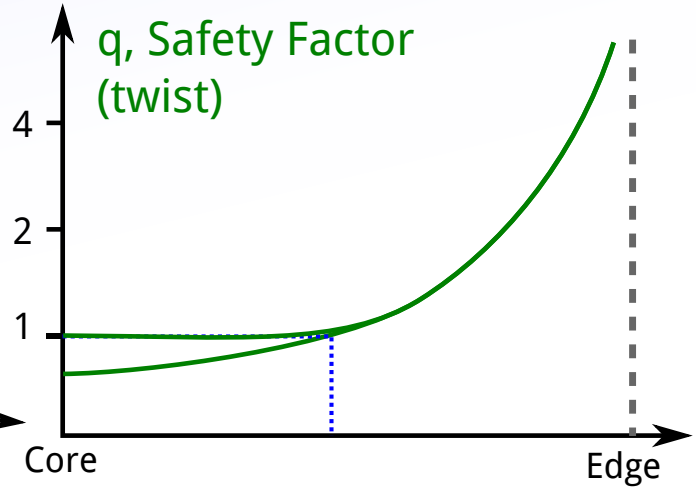

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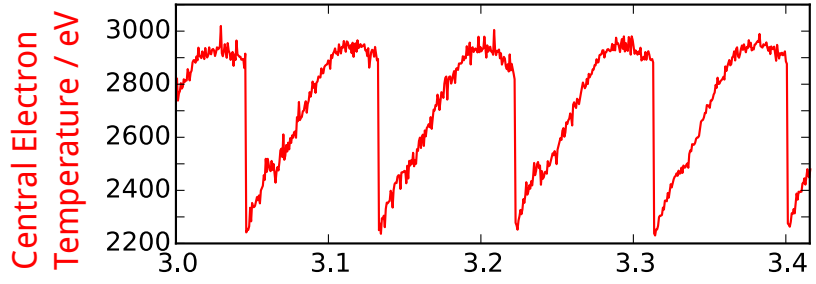

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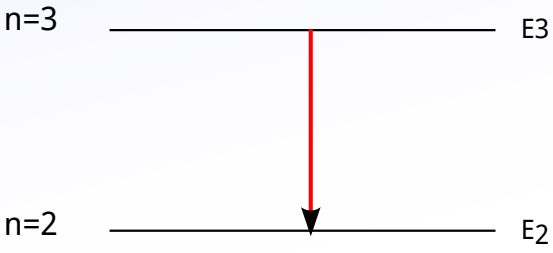
A central question remains unsatisfactorily answered:
- Does the plasma completely reconnect?
(Experimentally: Does q return to q=1?)

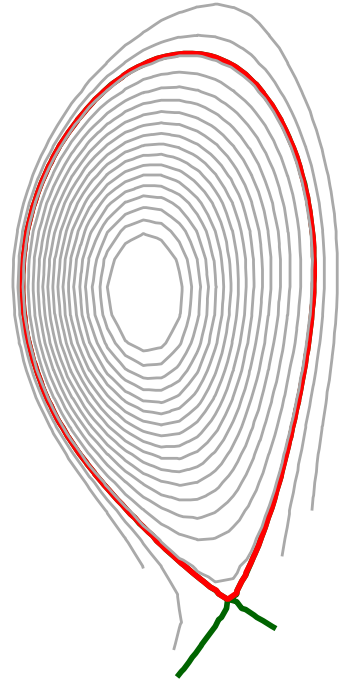
Stark/Zeeman Polarimetry

Spectral lines are split and polarised by E/M fields:
Zeeman Effect: Magnetic field.
Stark Effect: Electric field.

Magnetic Surfaces
Plasma Edge

e.g: Deuterium Balmer-α (Dα):





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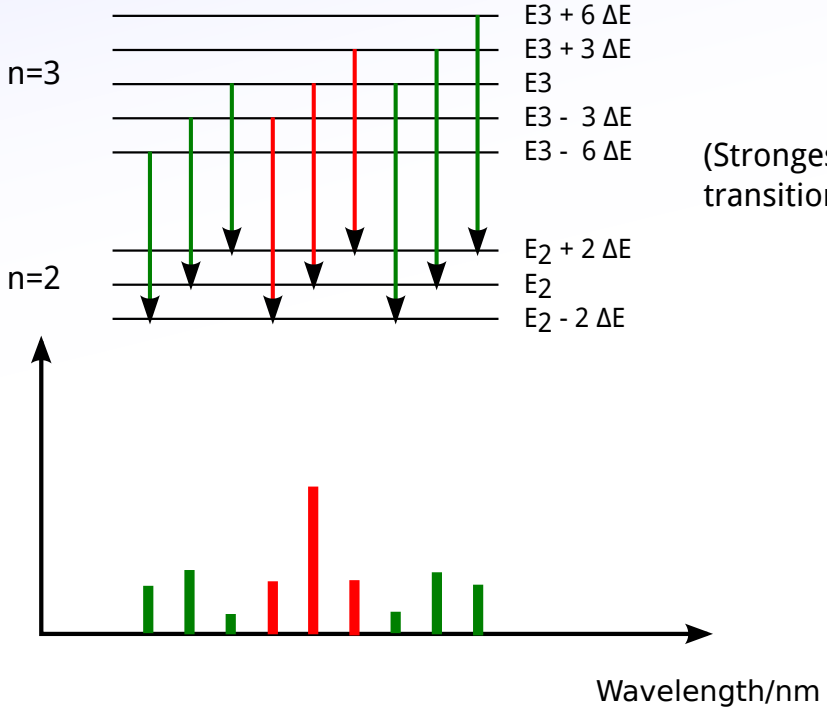

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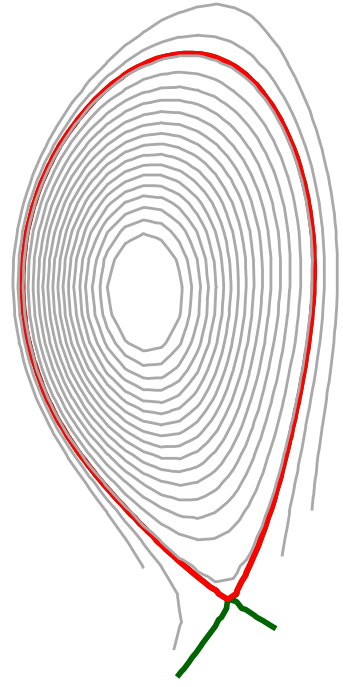

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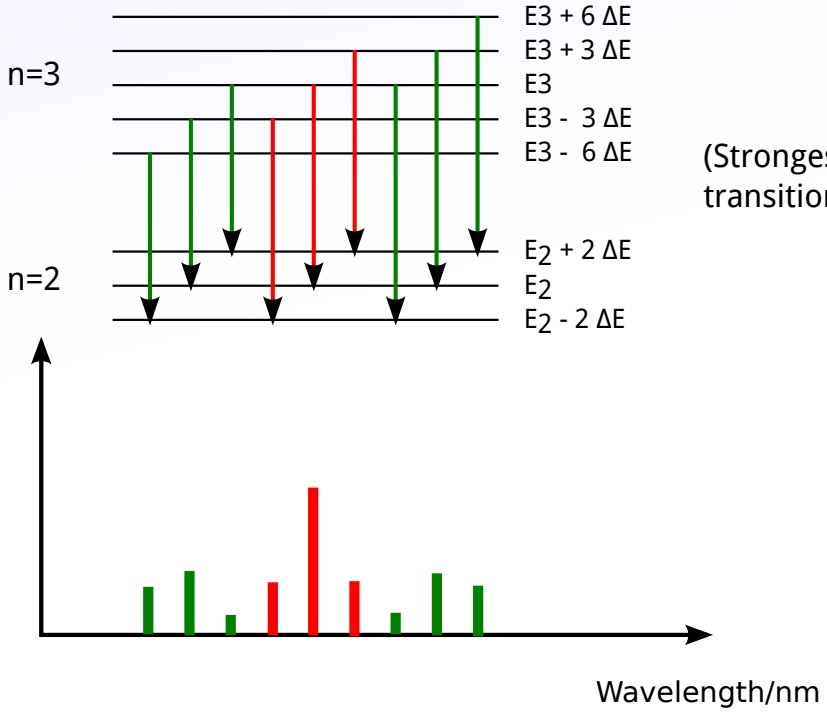

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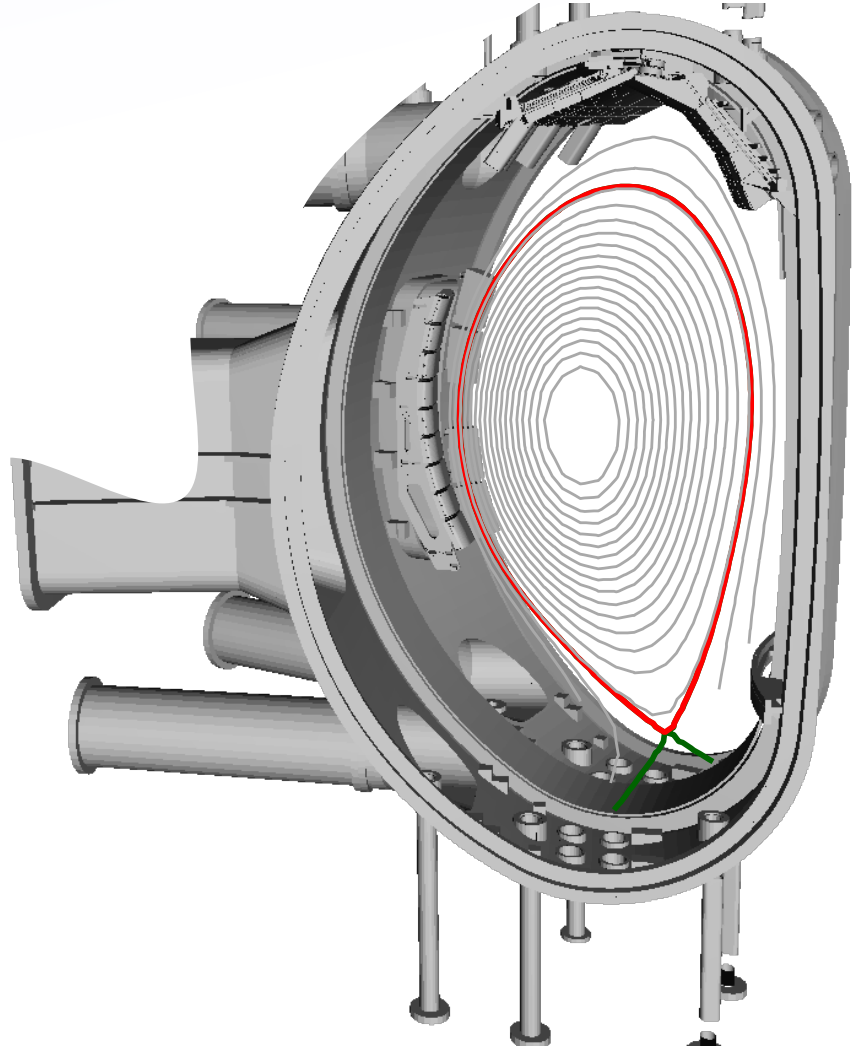
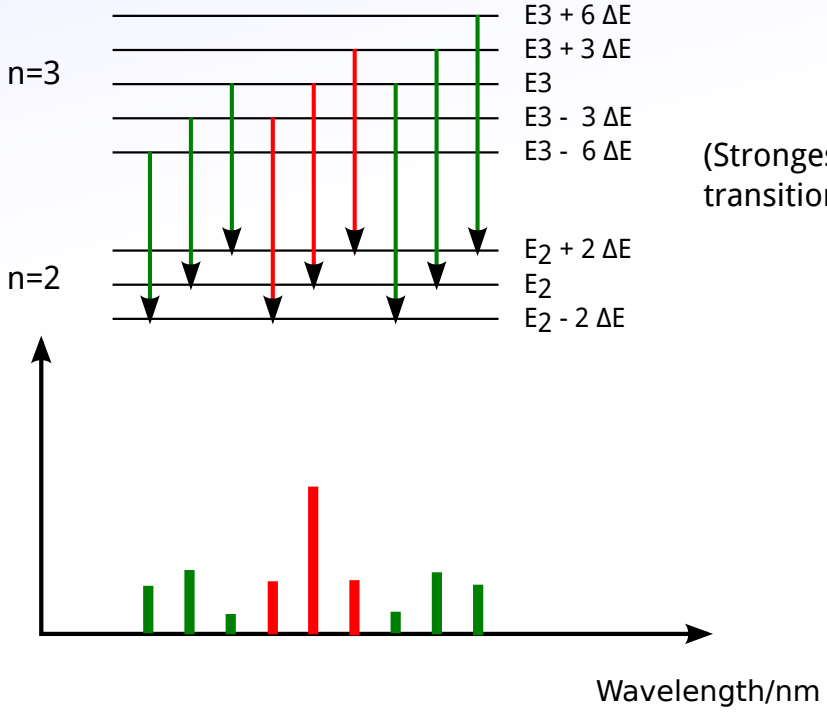


ASDEX Upgrade Vacuum Vessel

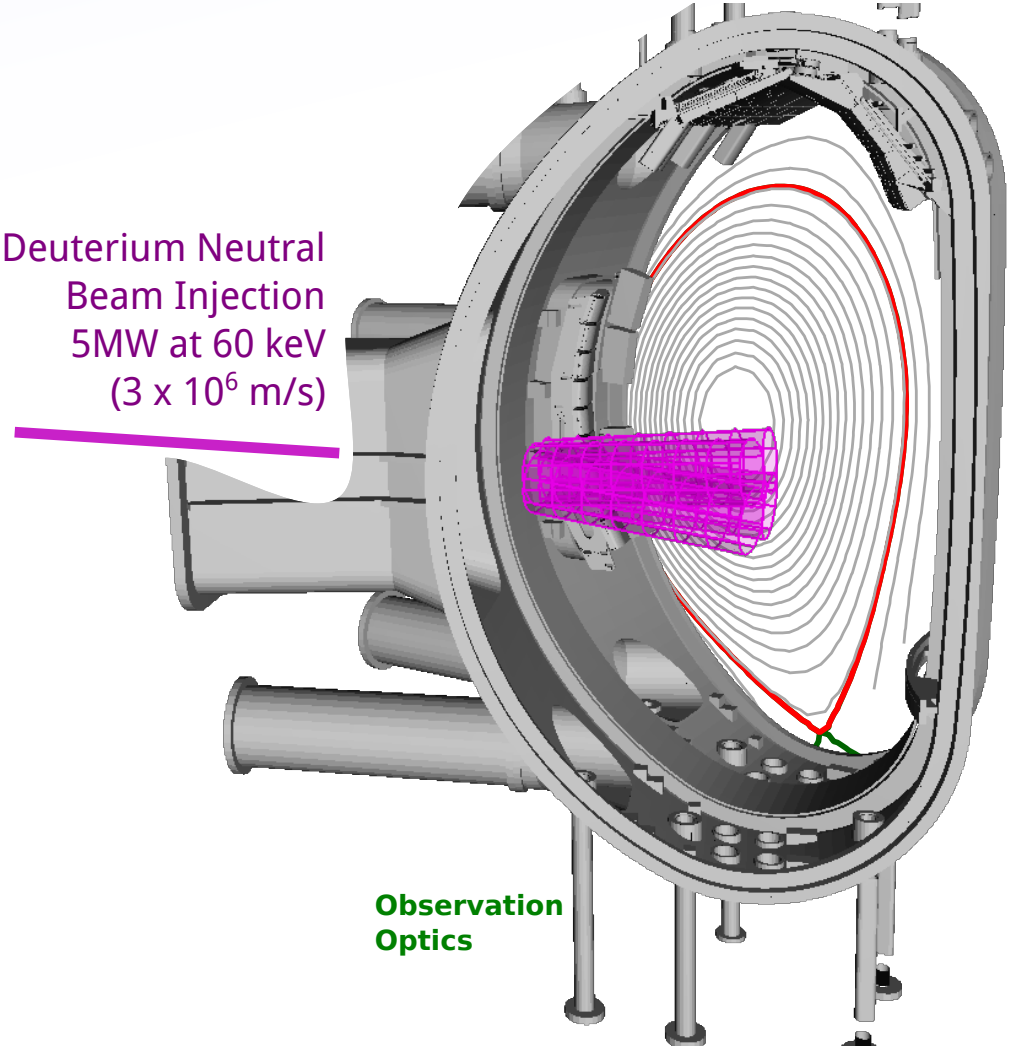
Stark/Zeeman Polarimetry

Spectral lines are split and polarised by E/M fields:
Zeeman Effect: Magnetic field.
Stark Effect: Electric field.

e.g: Deuterium Balmer-α (Dα):



(Strongest transitions)



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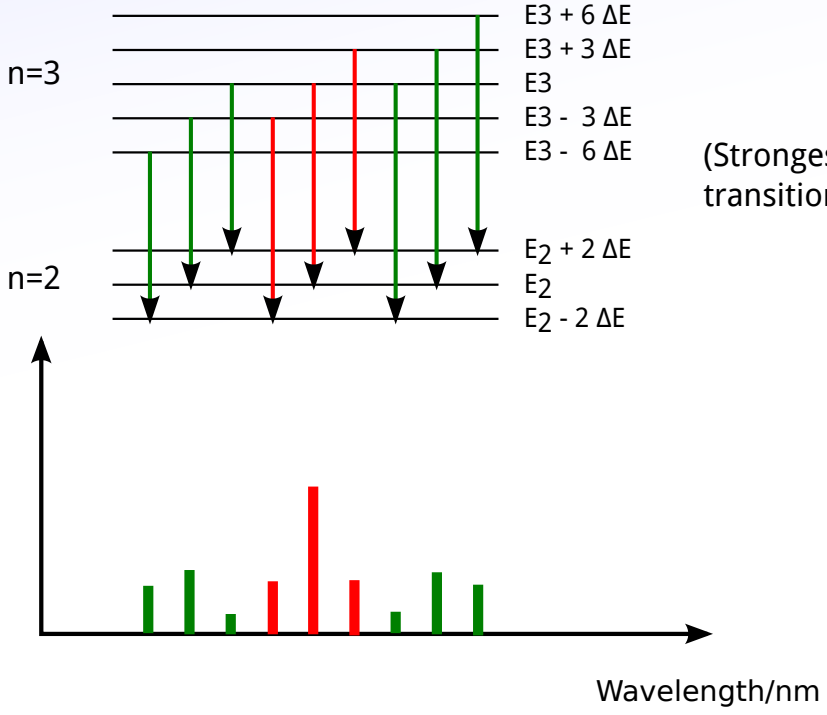

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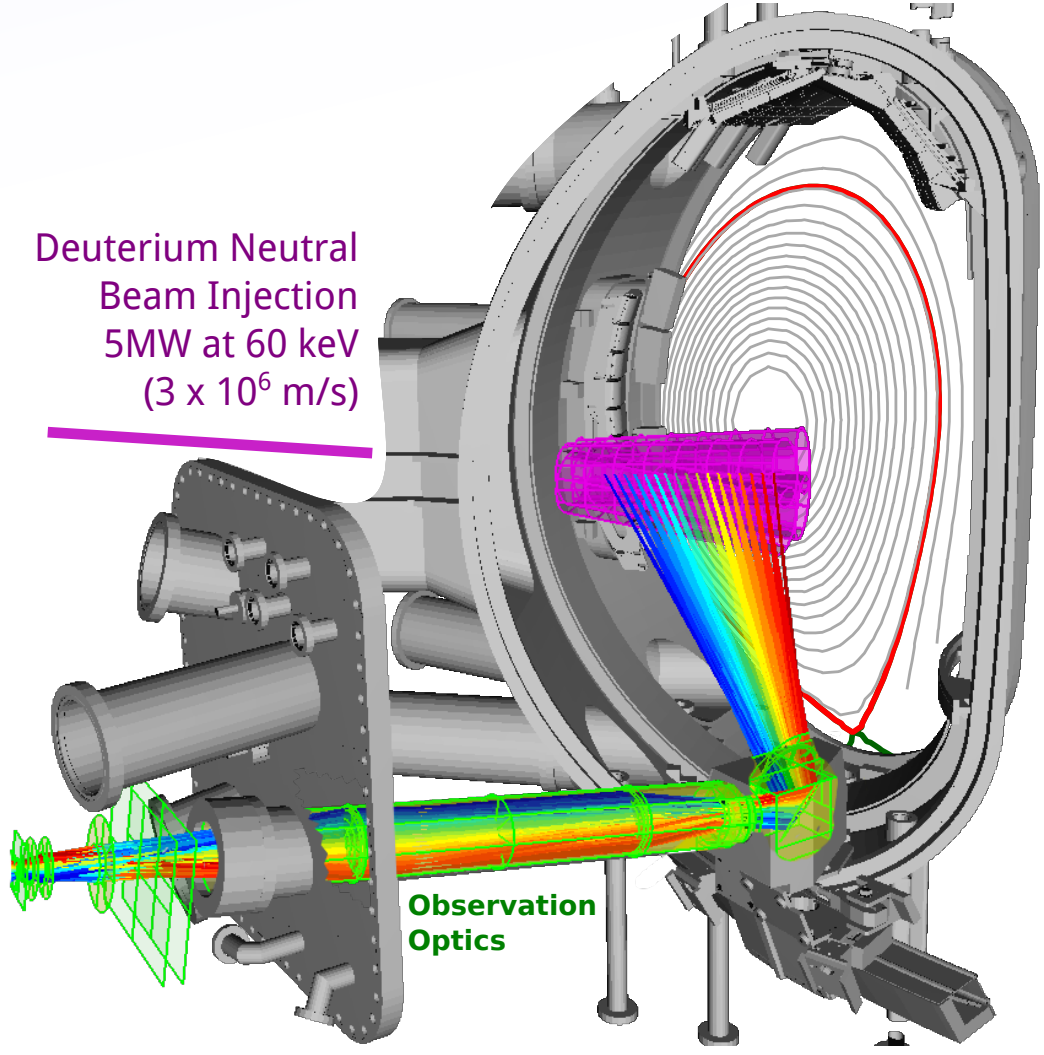
Magnetic Surfaces
Plasma Edge



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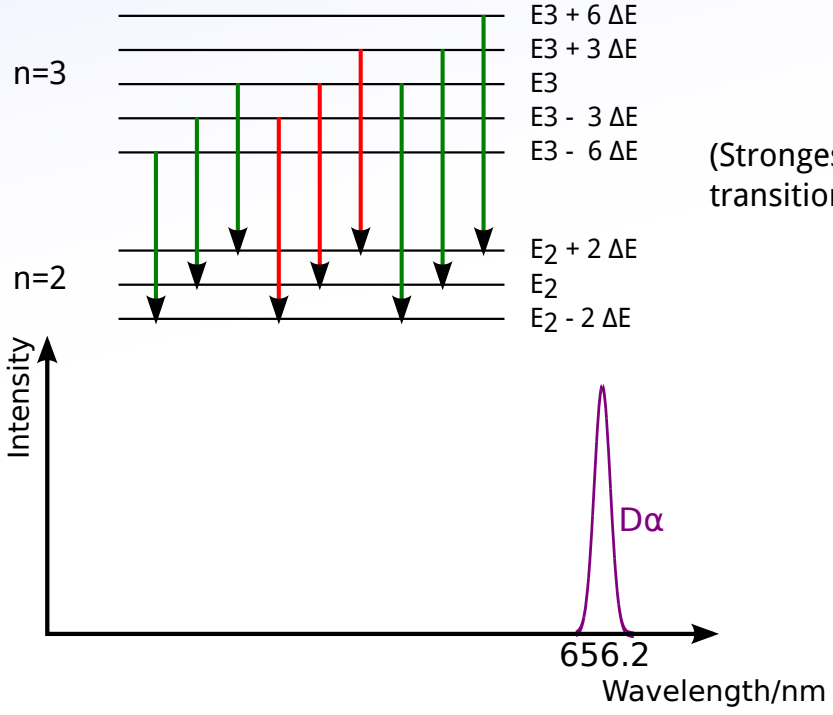

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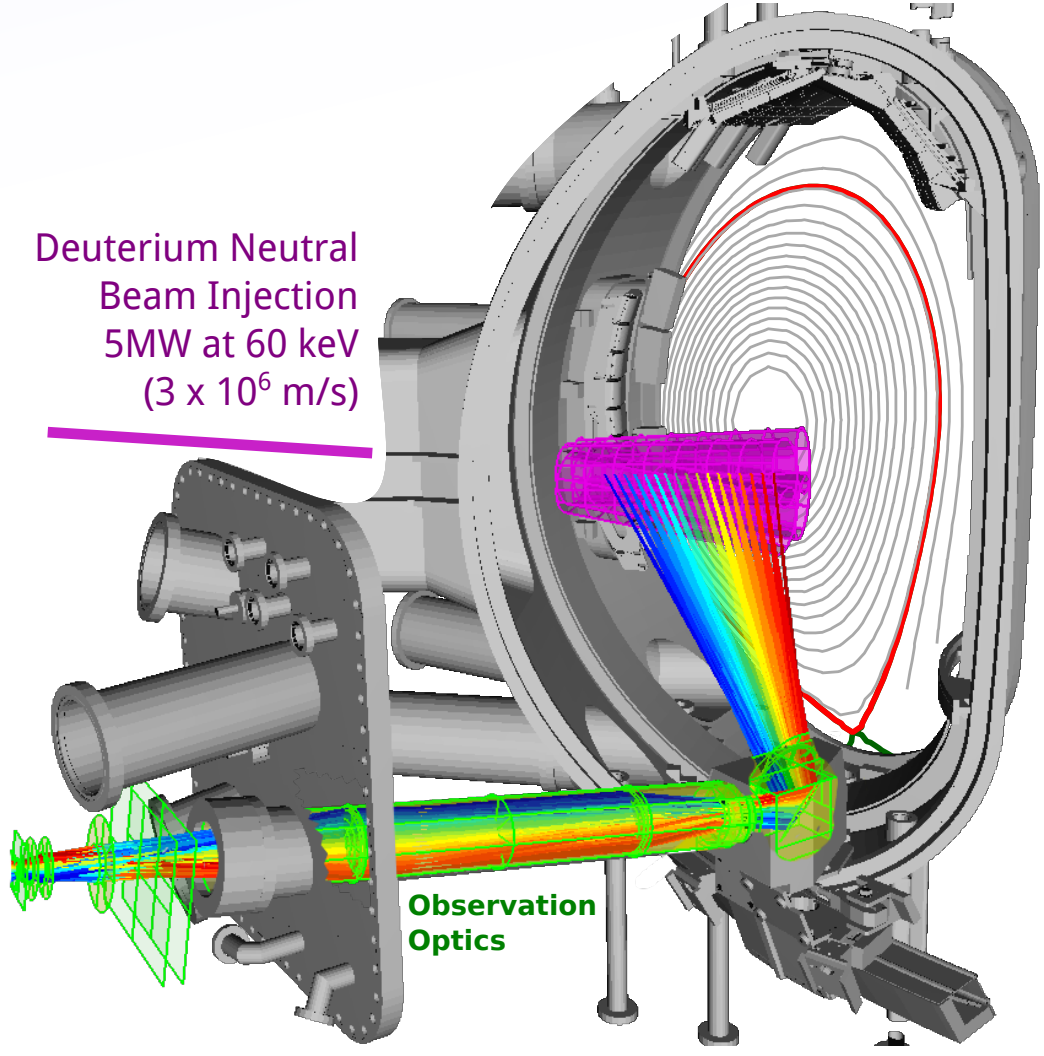

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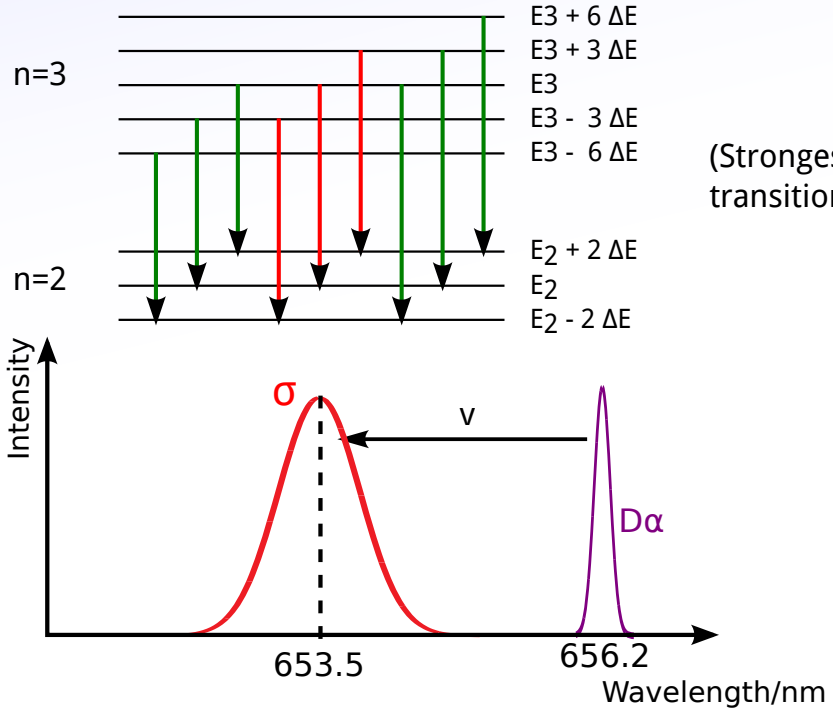
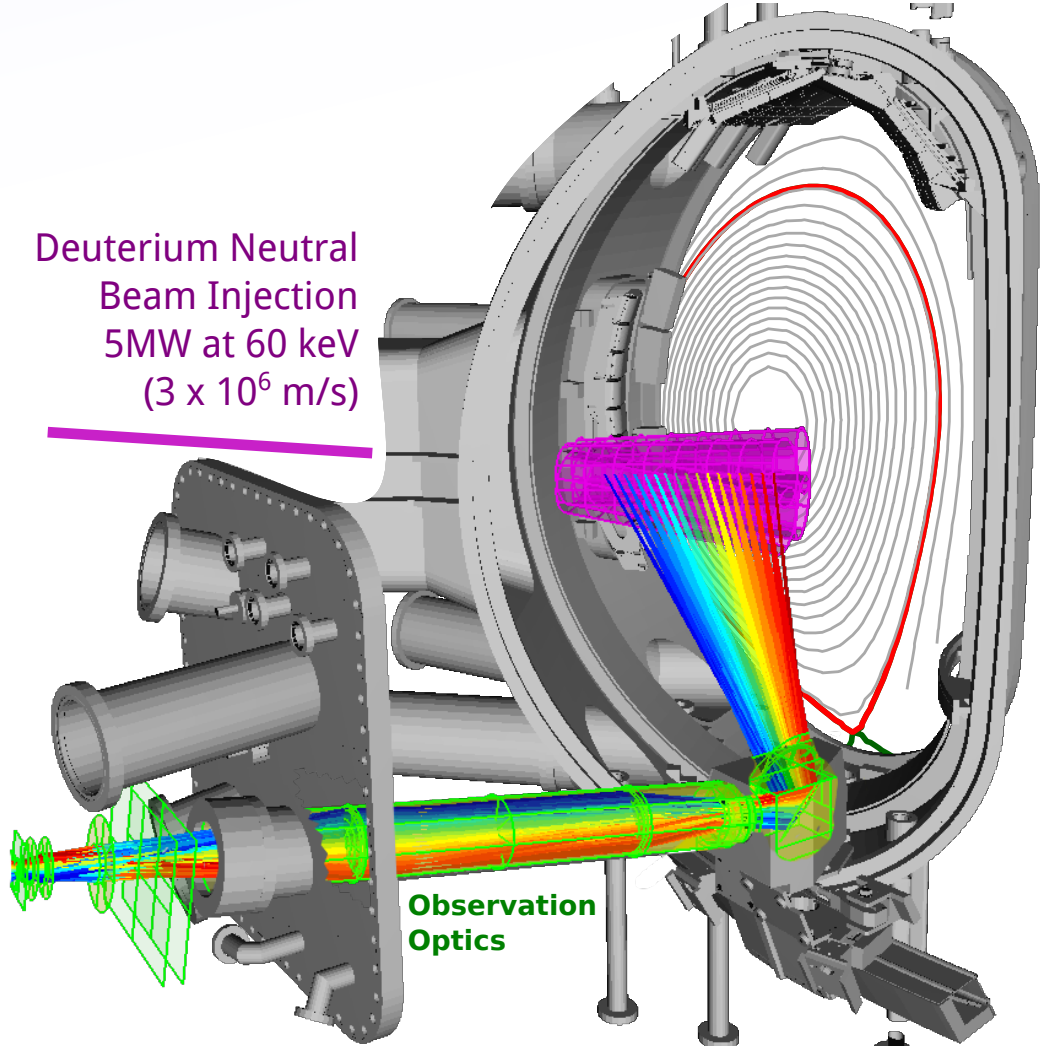


(Strongest transitions)

Magnetic Surfaces
Plasma Edge

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



ASDEX Upgrade Vacuum Vessel

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Spectral lines are split and polarised by E/M fields:

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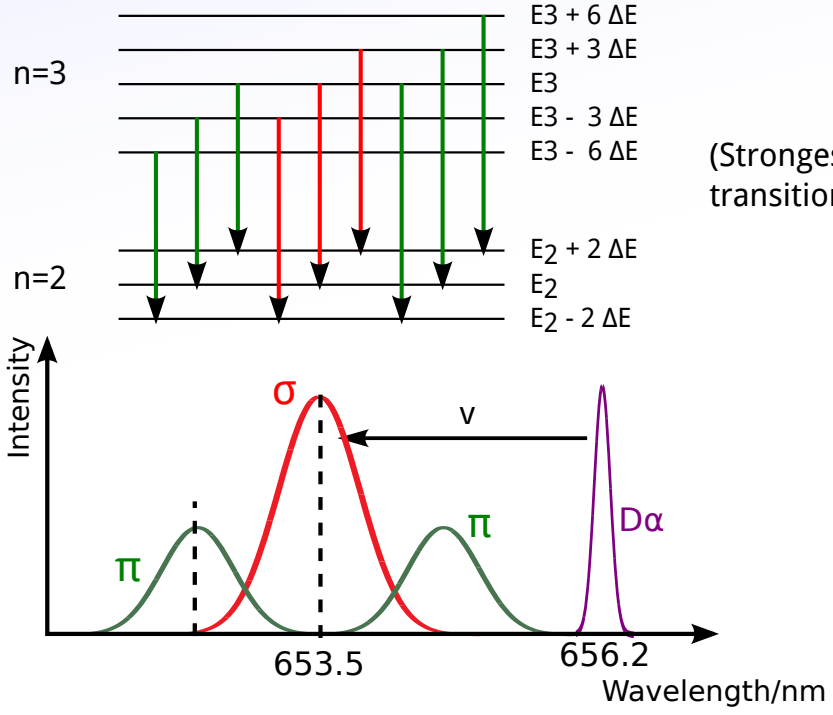

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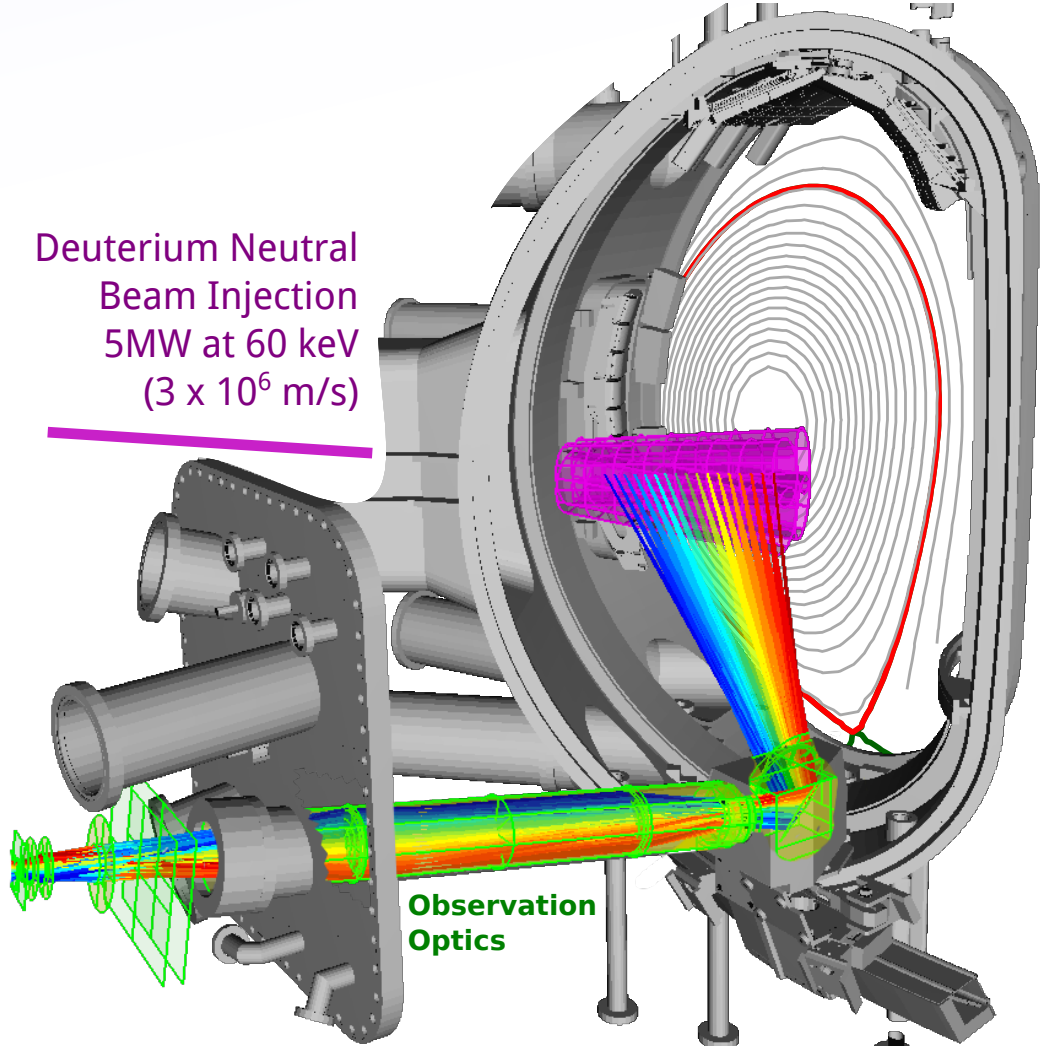

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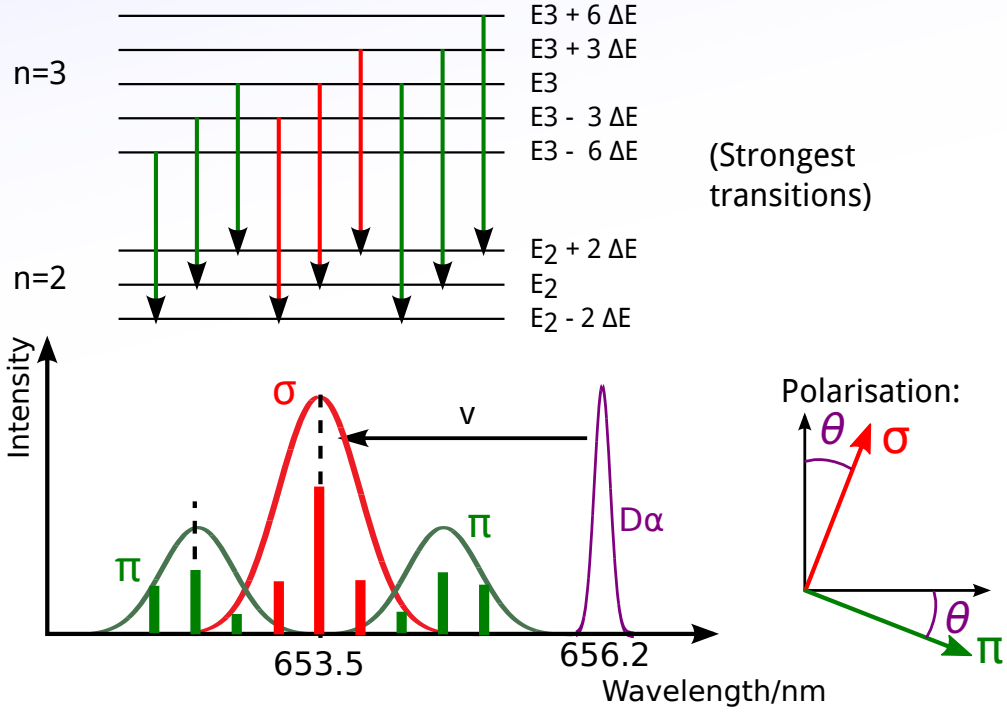

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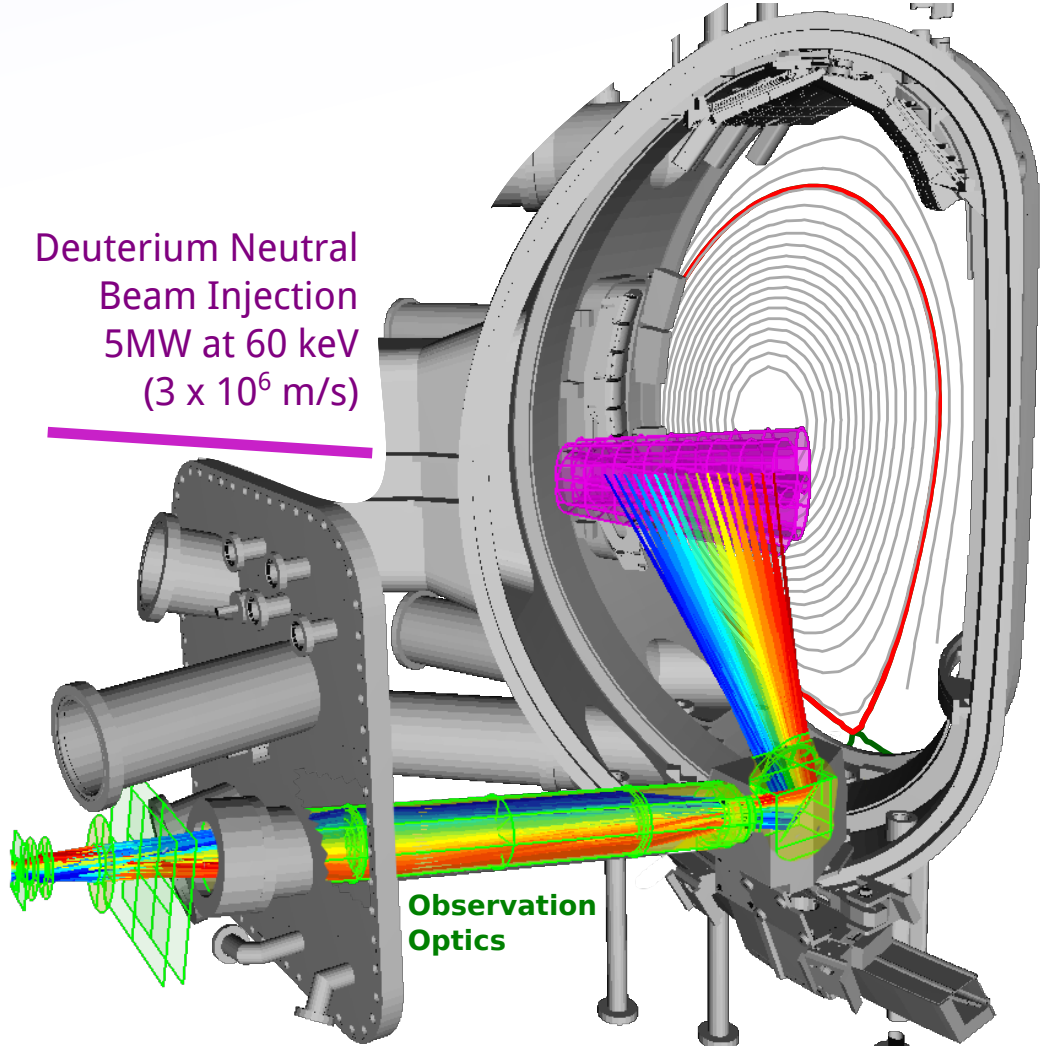

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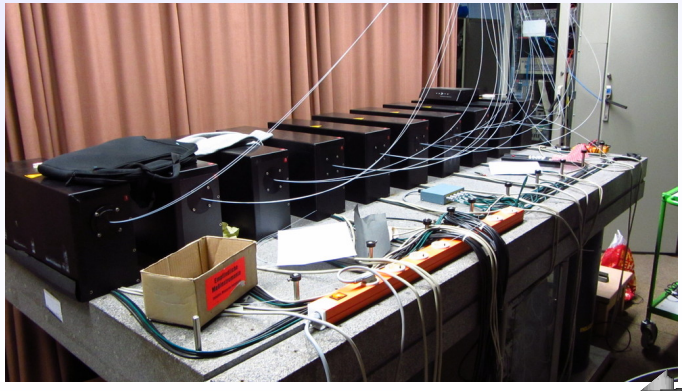

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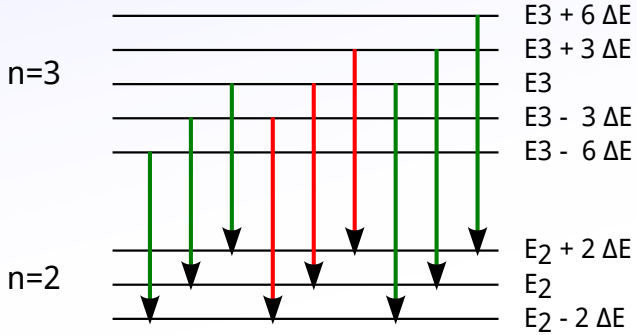
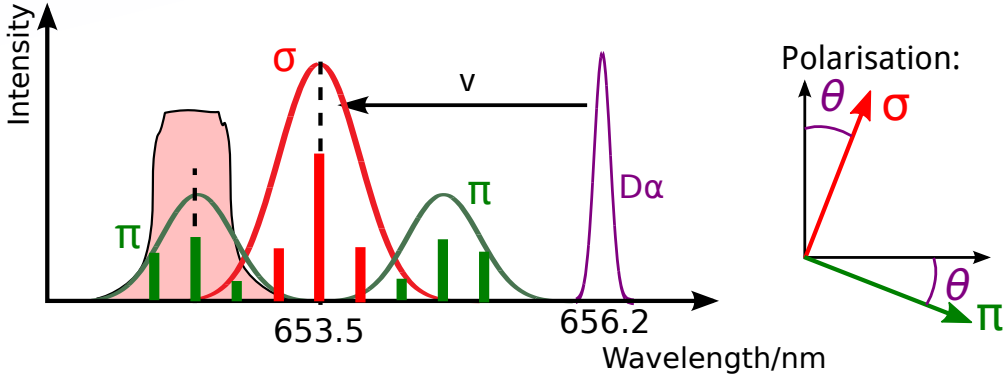
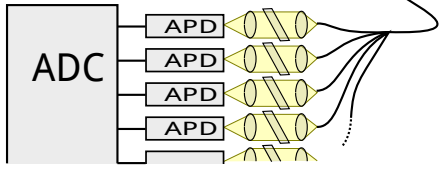


(Strongest transitions)



MSE is usually measured with Photo-elastic modulators (PEMs) or polarisers and individually tuned interference filters for each measurement (10 channels at AUG).



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Plasma Edge

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5MW at 60 keV
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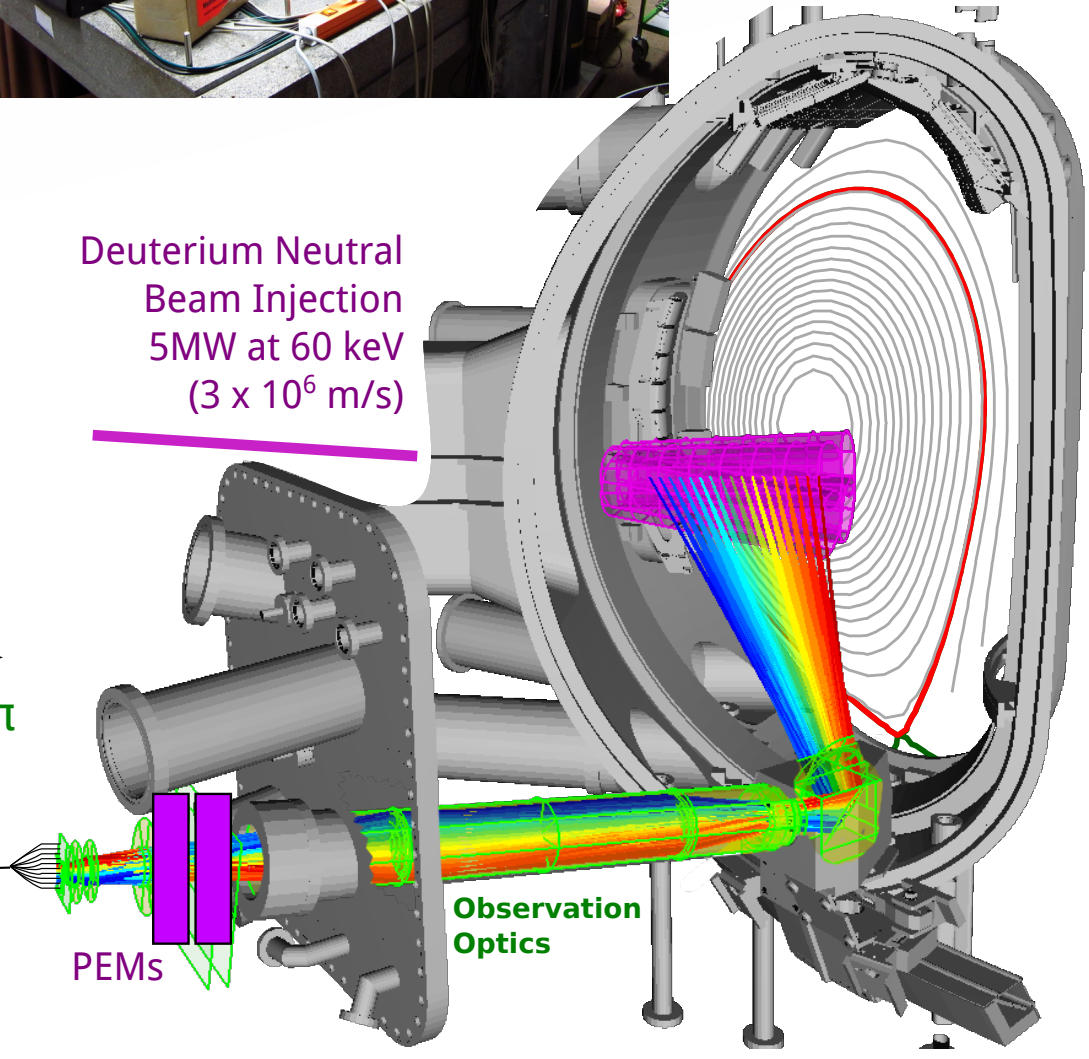
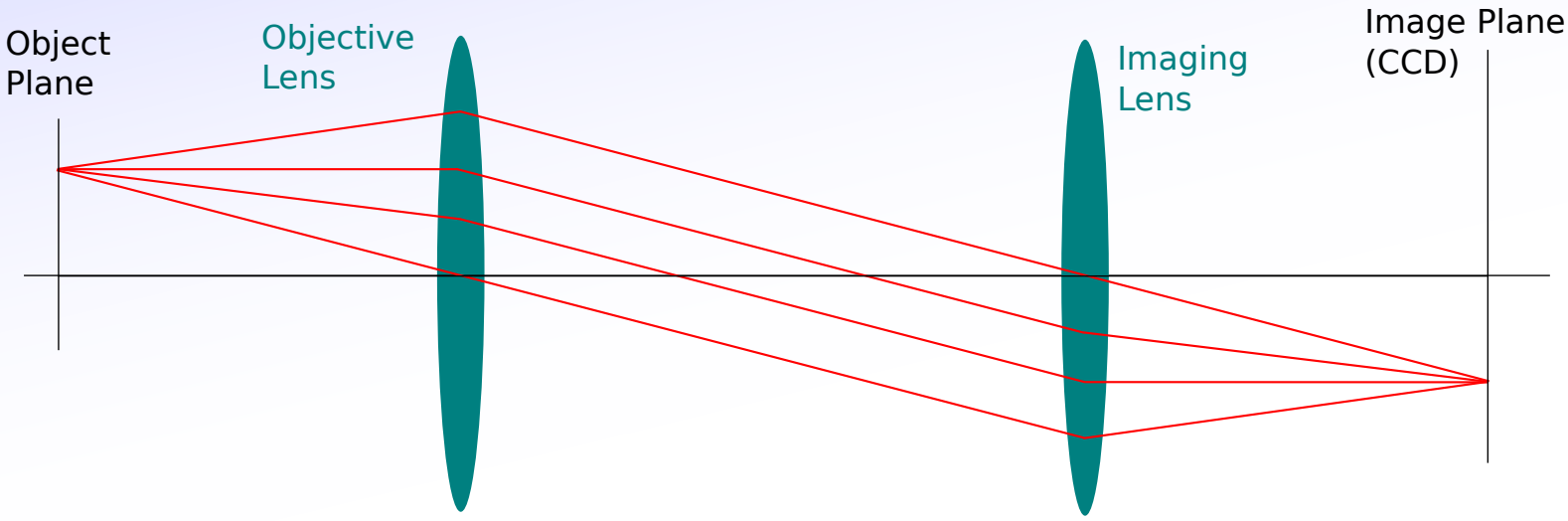
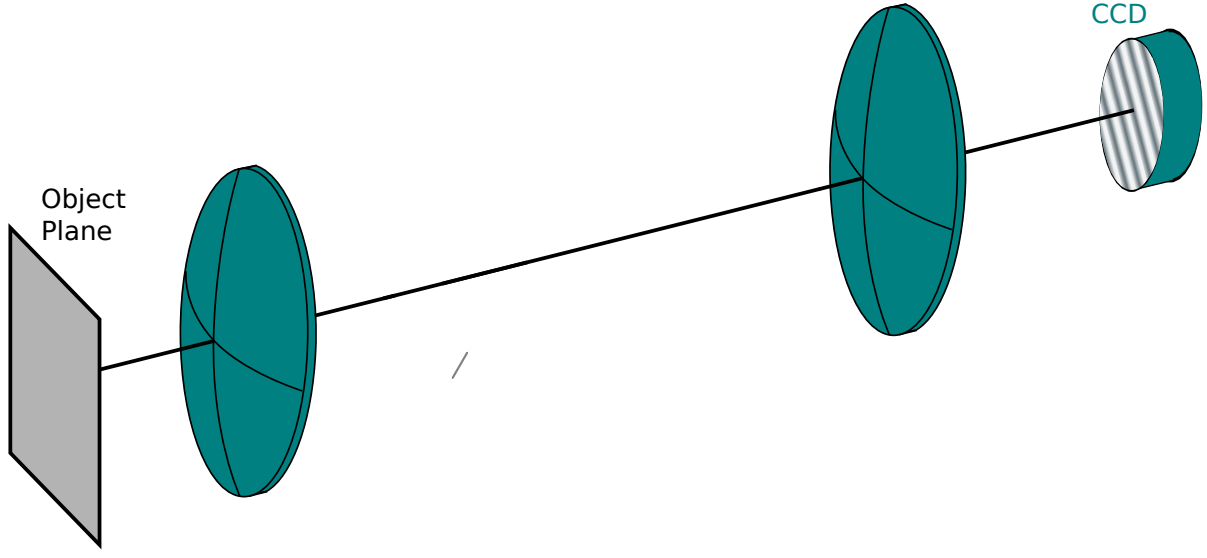


ASDEX Upgrade Vacuum Vessel

Coherence Imaging

Coherence Imaging: Capture image with a CCD camera, modulated with interference pattern





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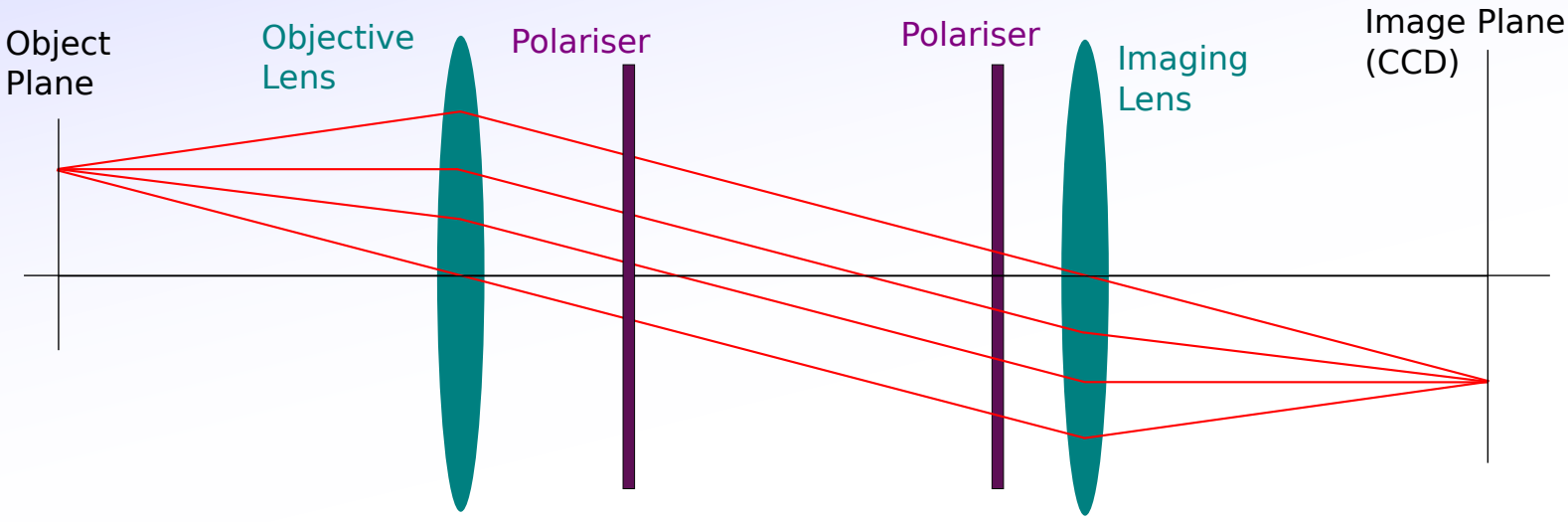

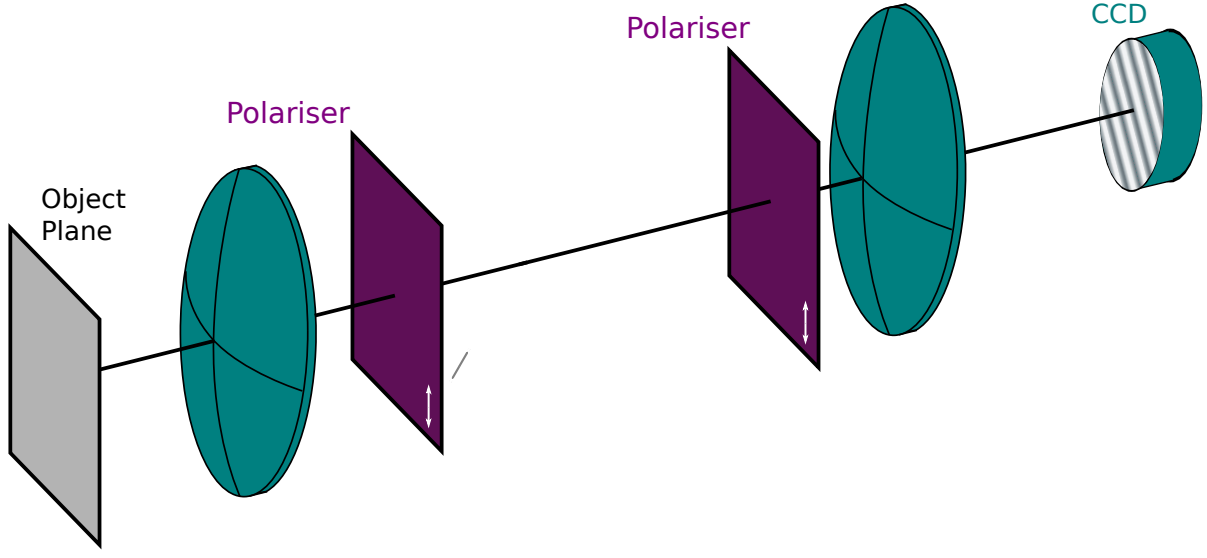

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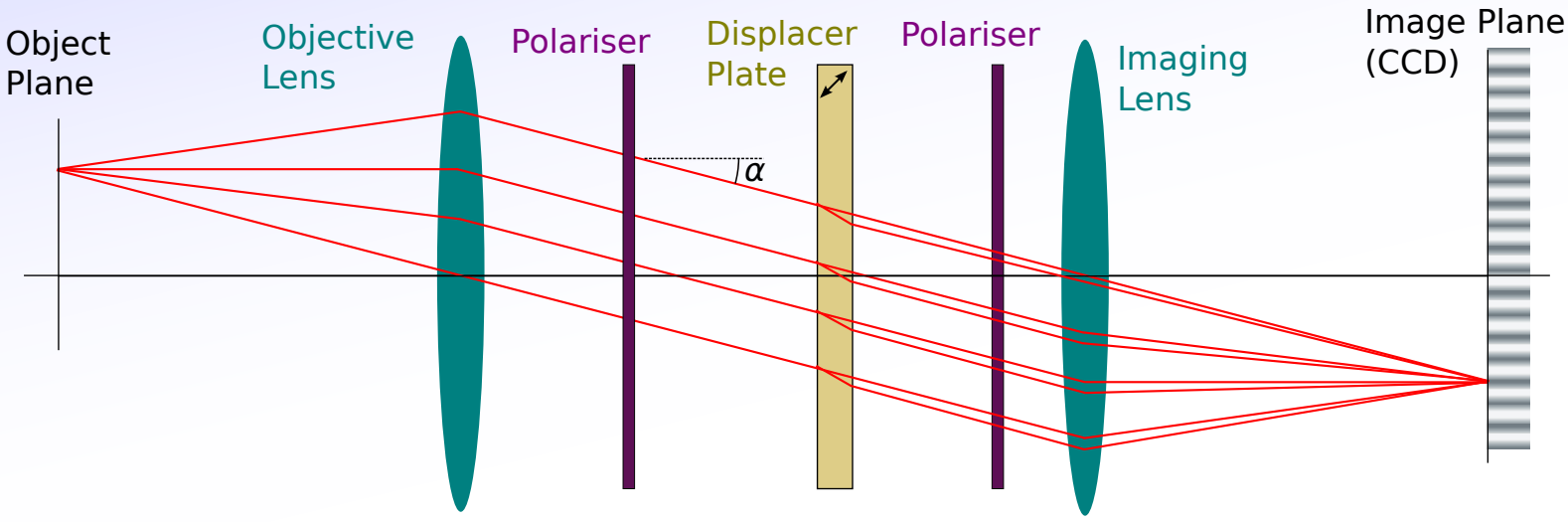
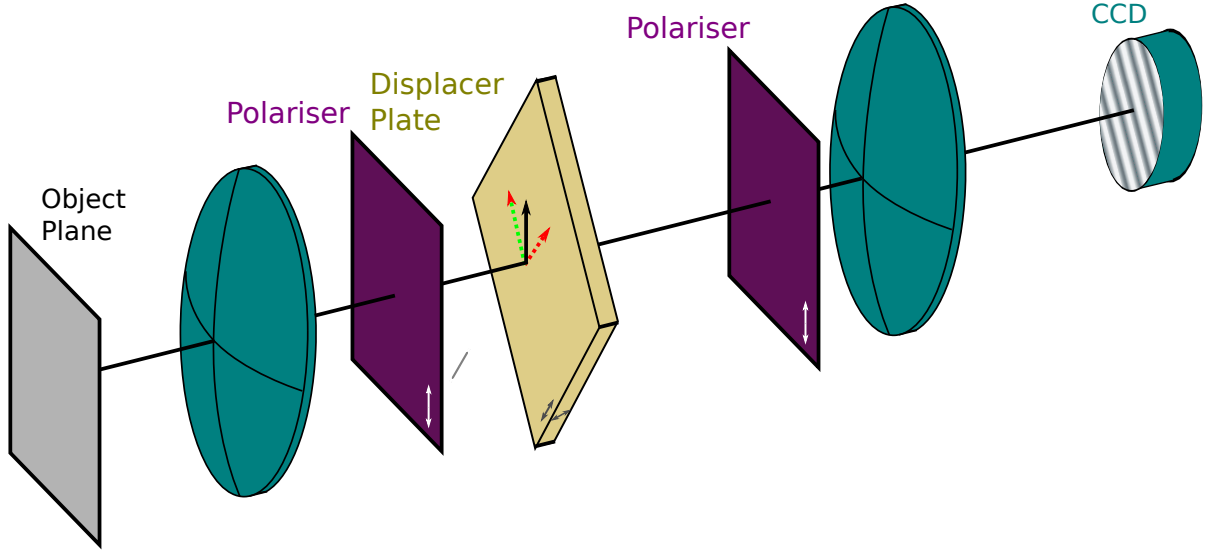
Coherence Imaging: Capture image with a CCD camera, modulated with interference pattern created by a 'Displacer plate' - Birefringent crystal with axis tilted with respect to surface.





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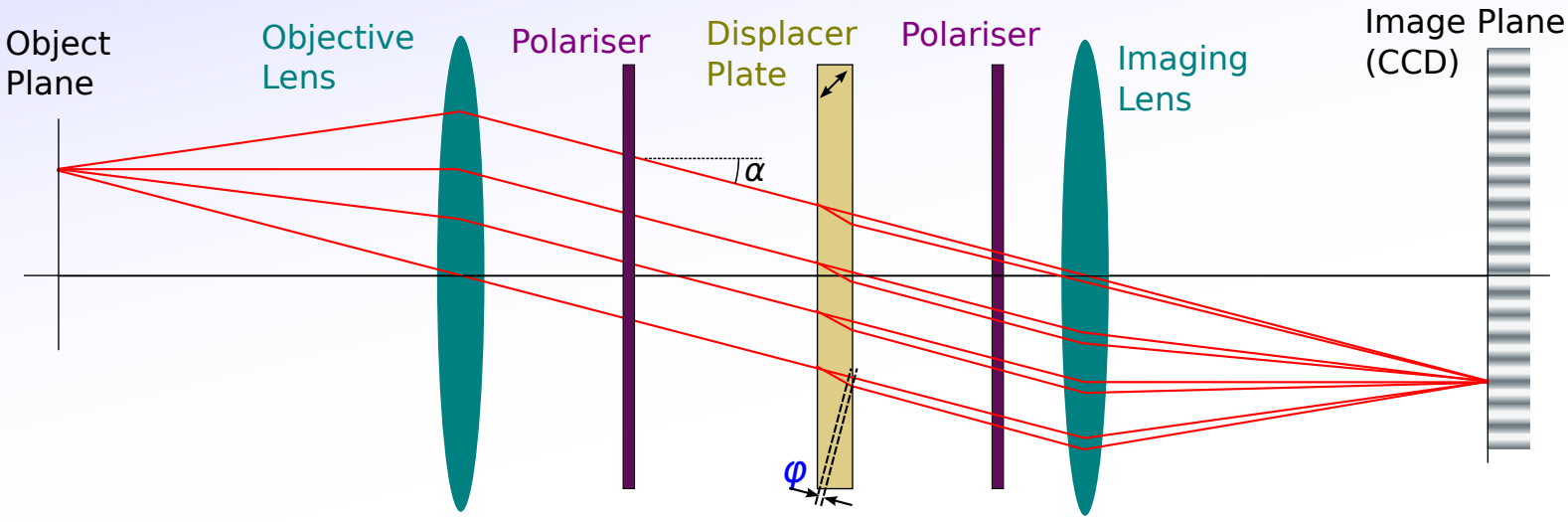

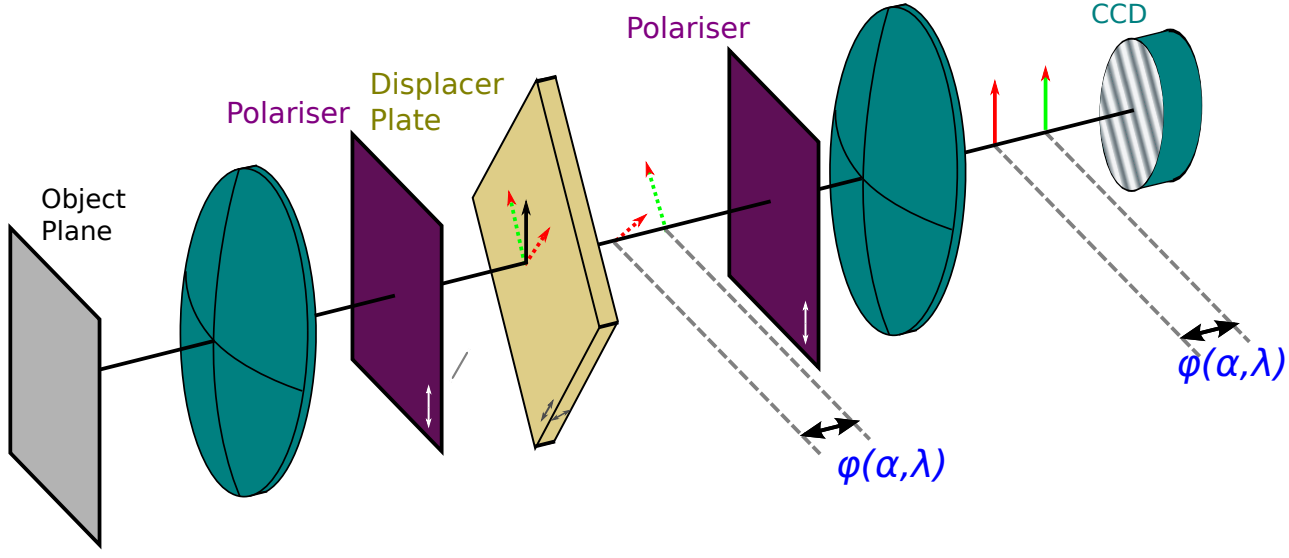

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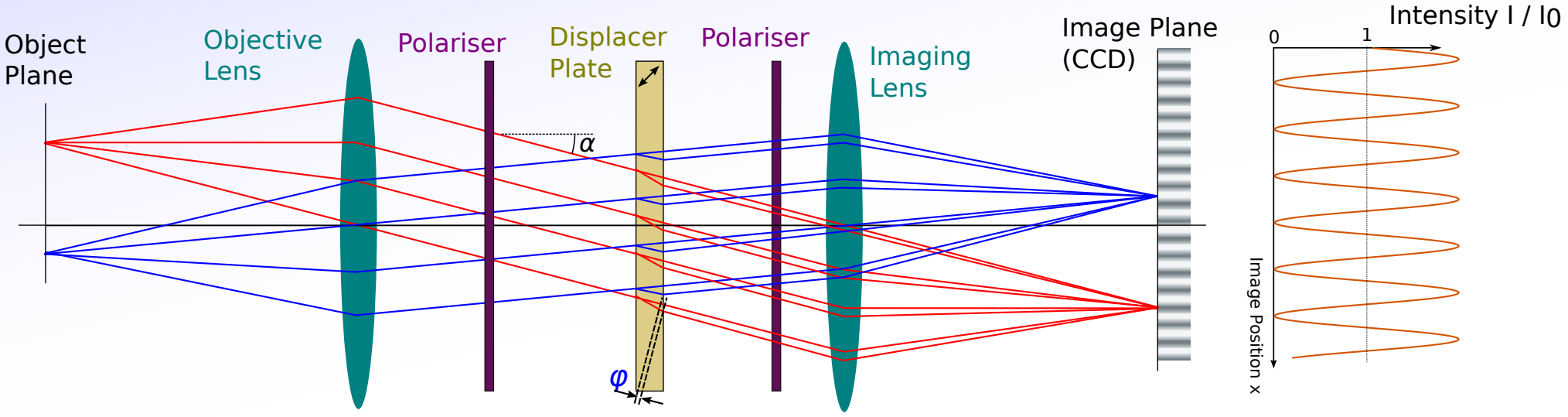

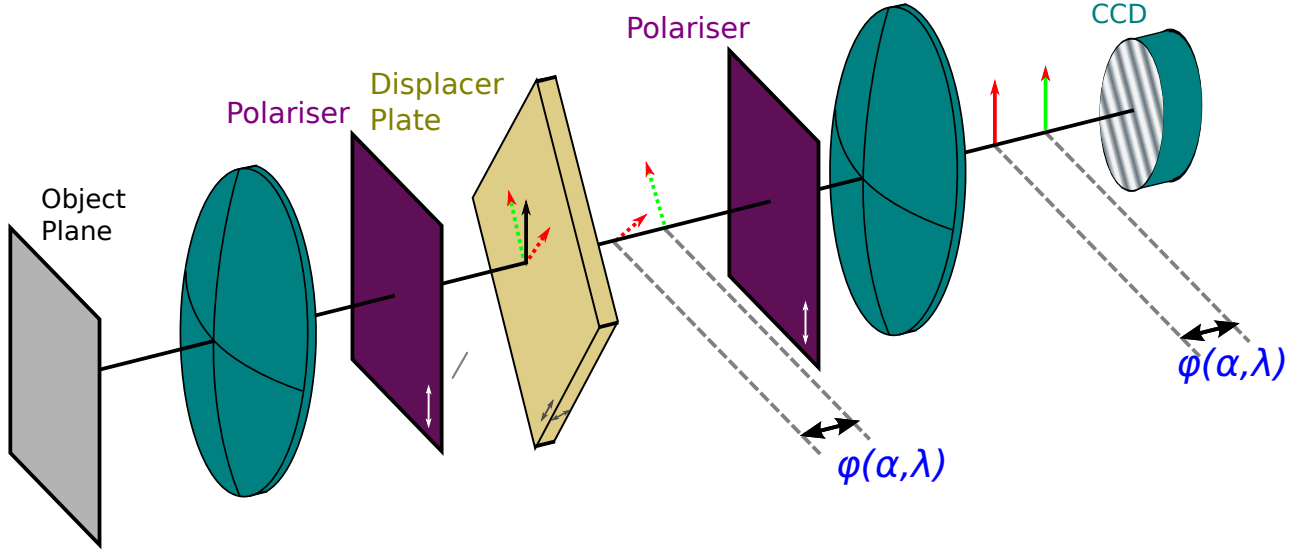

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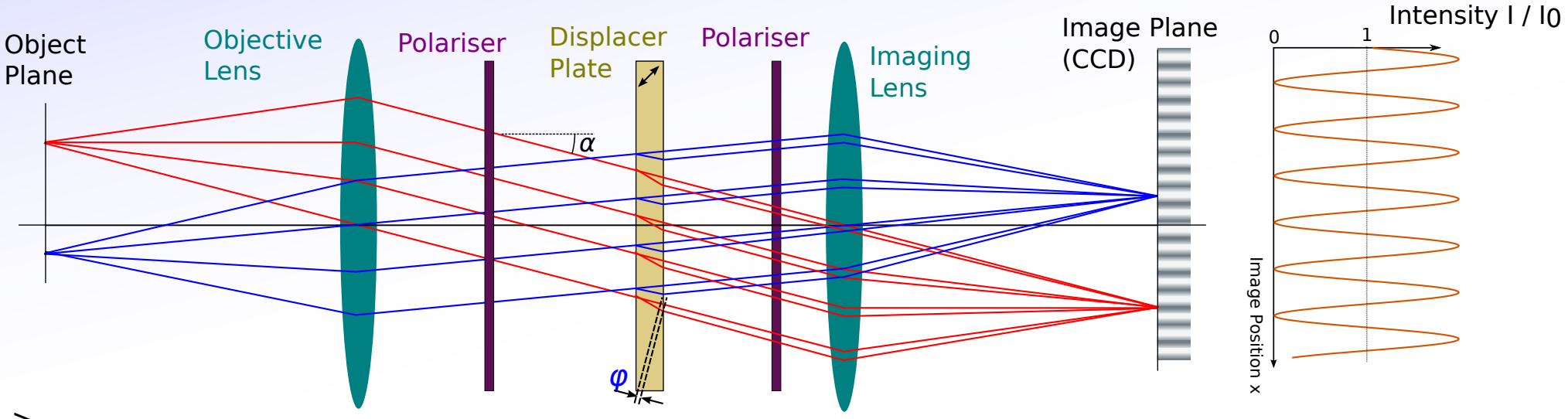
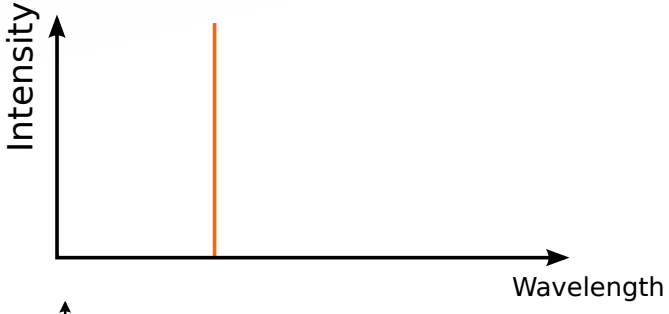
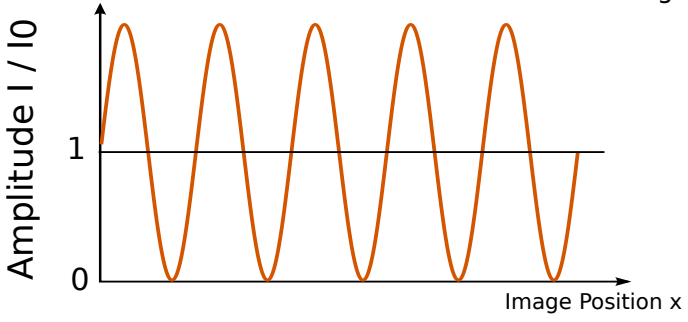
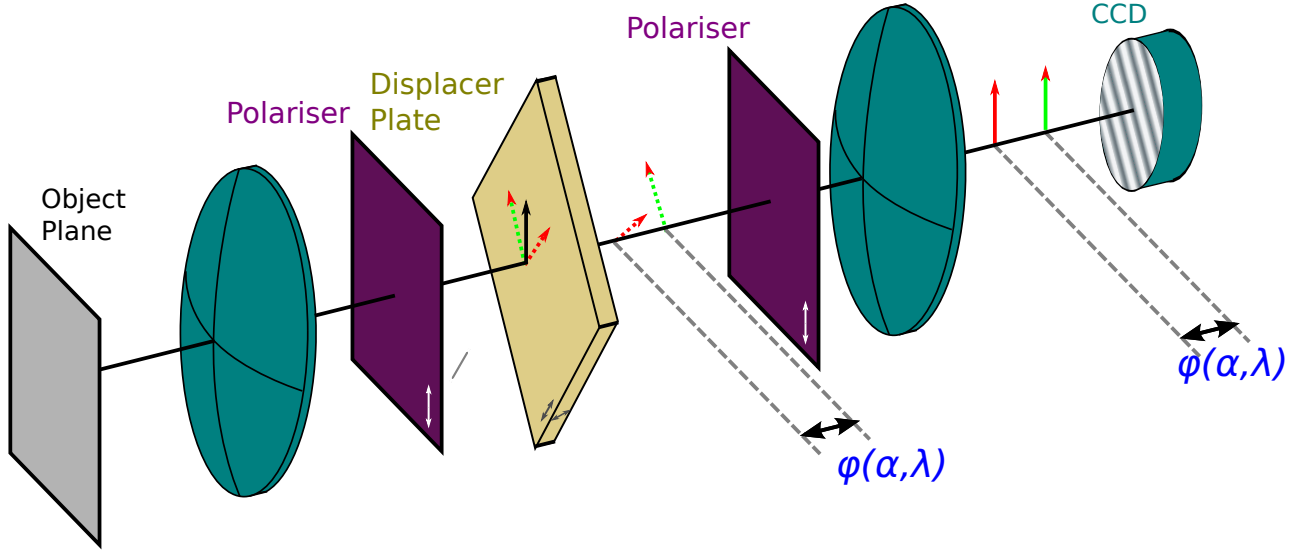






$$I \propto 1 + \zeta \cos((\omega + \Delta\omega)x)$$



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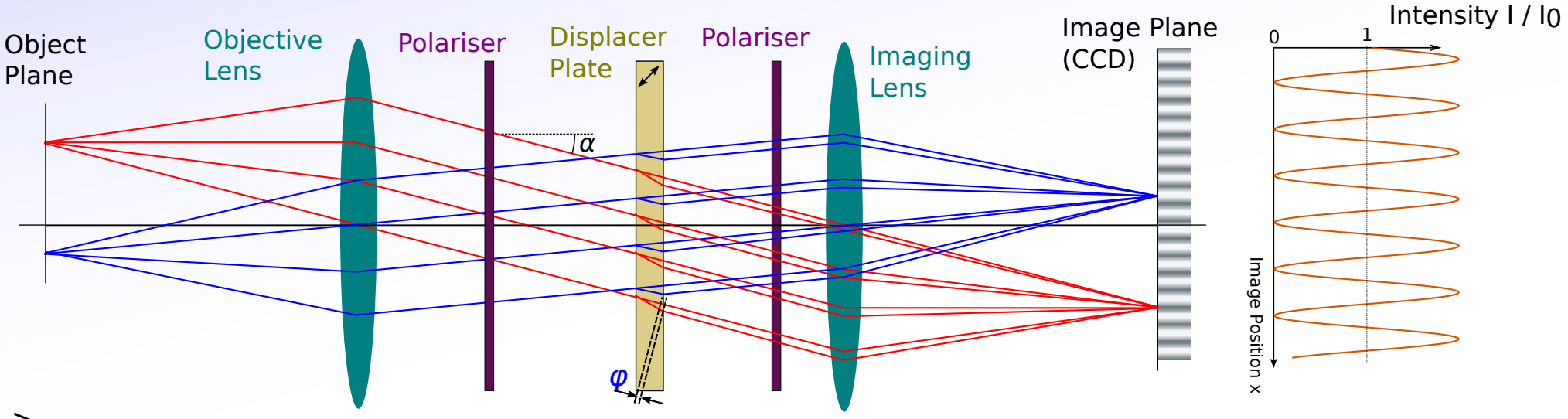
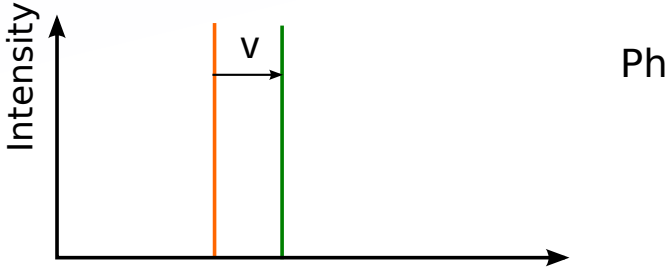
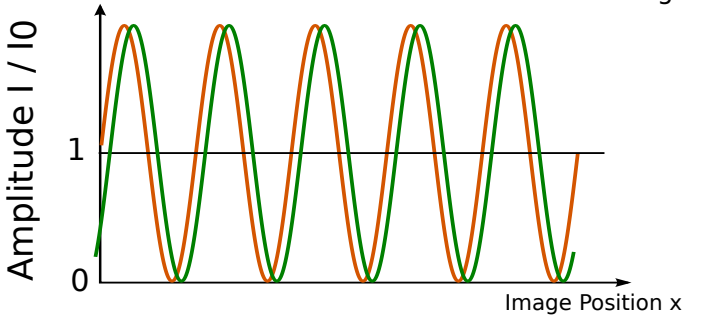




Phase ⟶ Wavelength → Velocity



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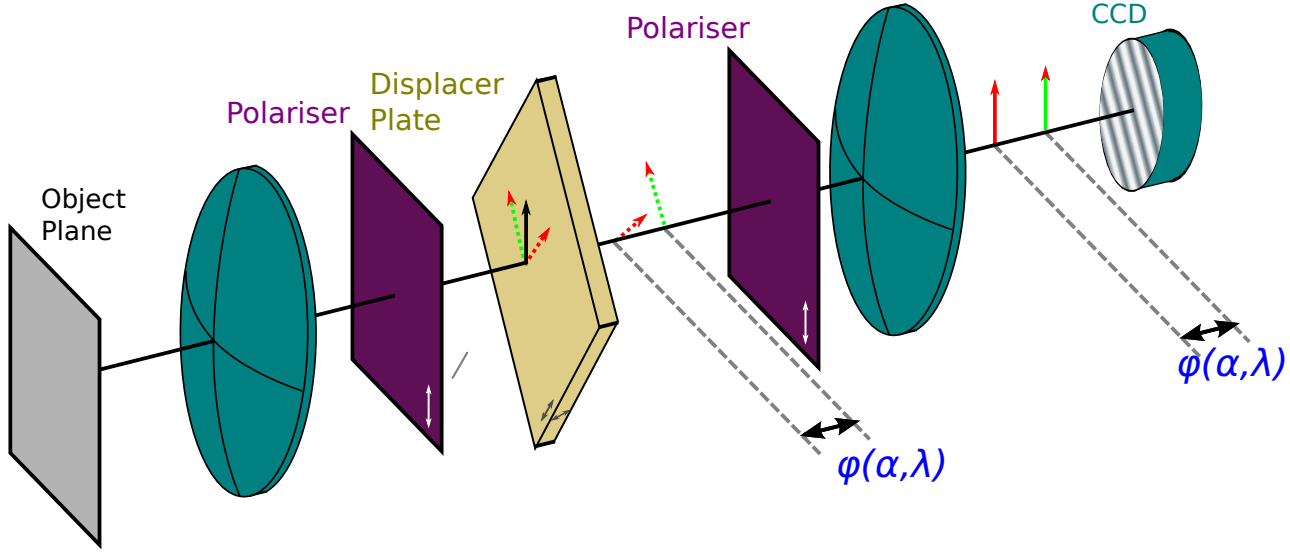

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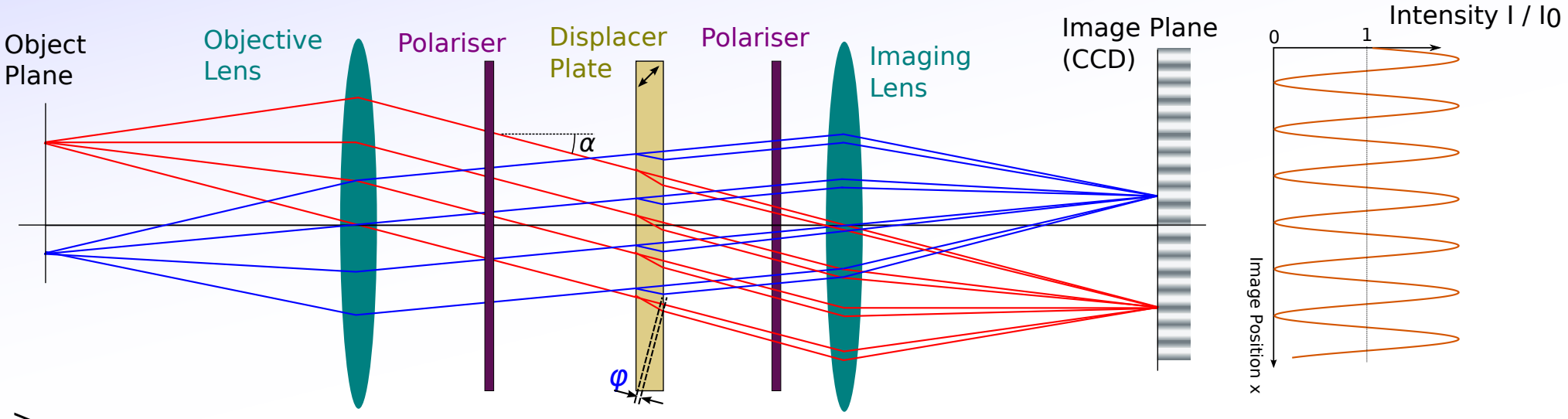
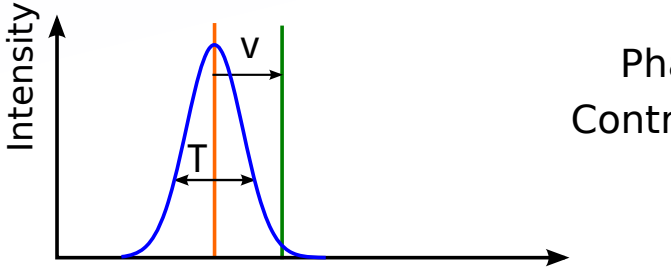
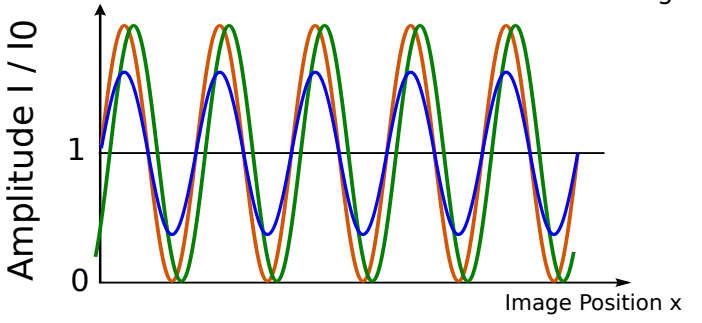




Phase ⟶ Wavelength → Velocity

Contrast ⟶ Width ⟶ Temperature



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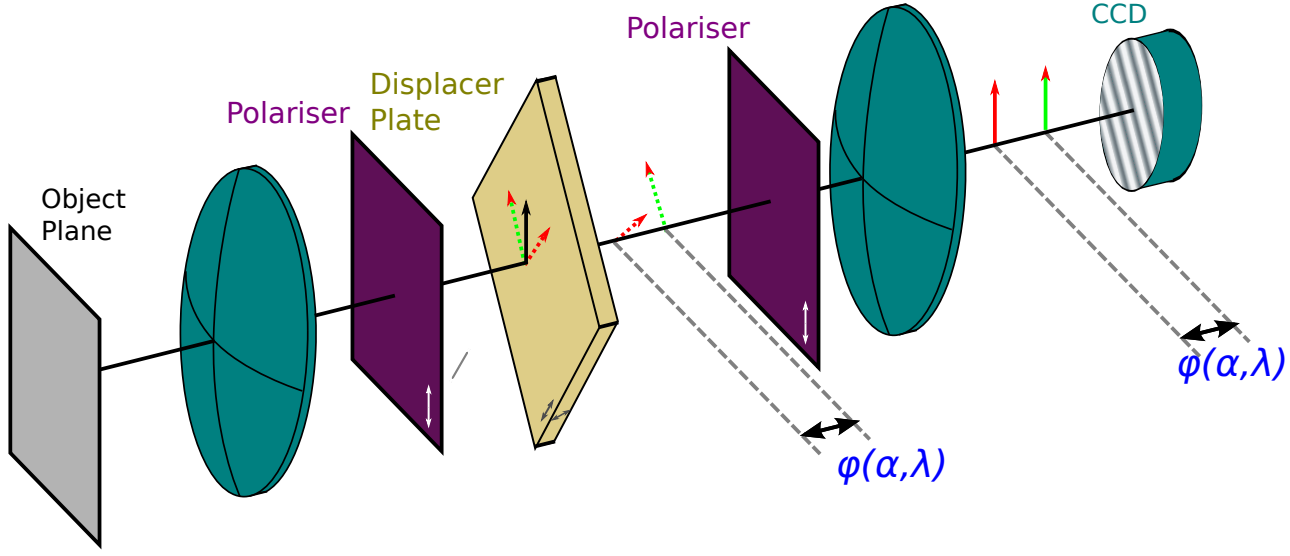

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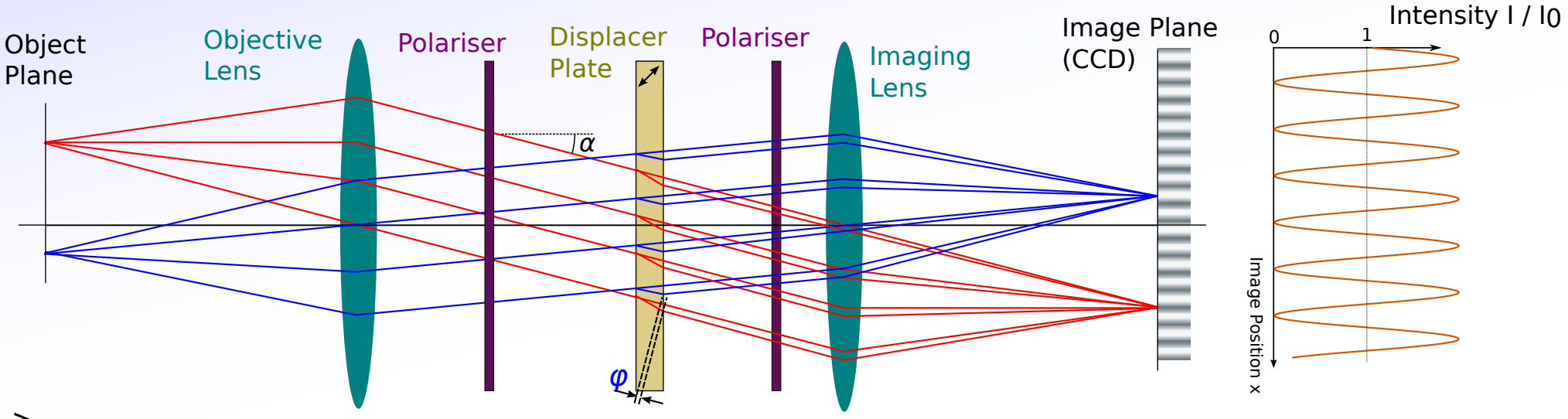
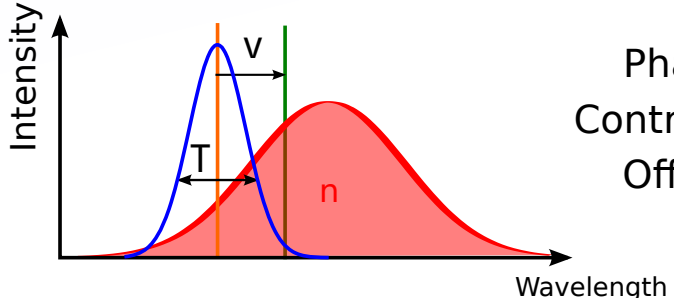
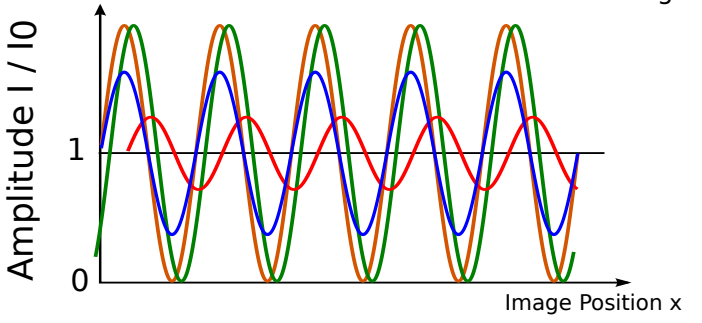




Phase ⟶ Wavelength → Velocity
Contrast ⟶ Width ⟶ Temperature
Offset ⟶ Integral ⟶ Density



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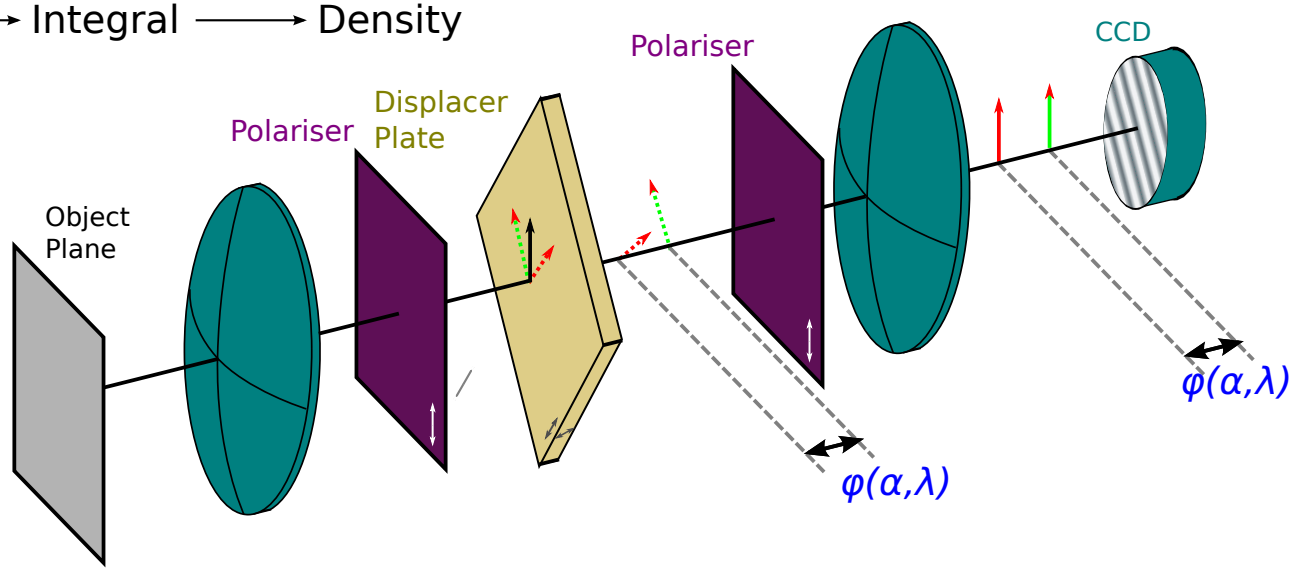
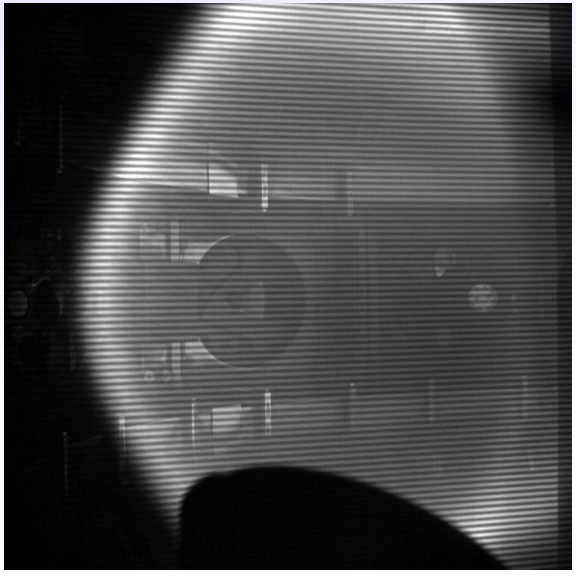


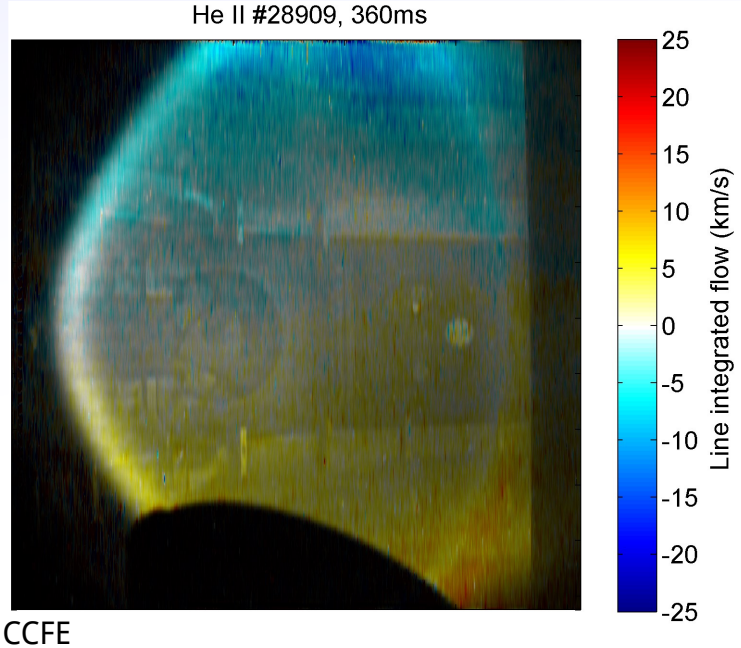
Doppler Coherence Flow Imaging

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

Raw Image:

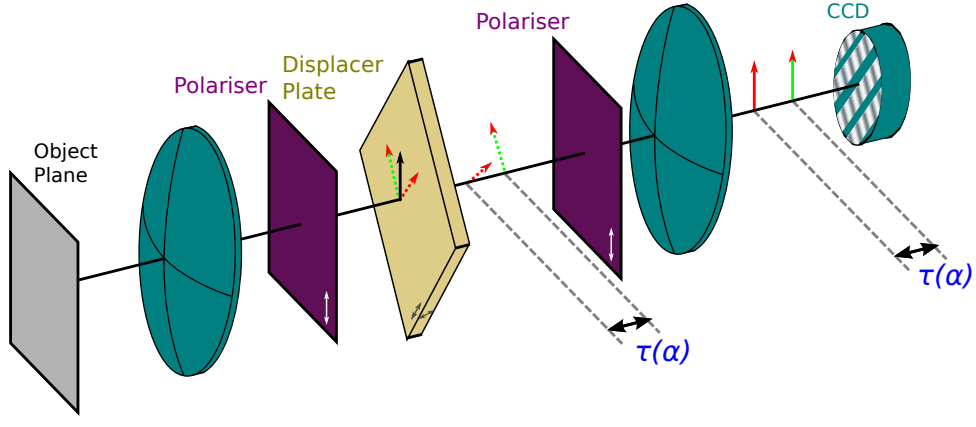


Helium Flow Velocity:



MAST
Mega Amp Spherical Tokamak, CCFE, Culham, UK

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



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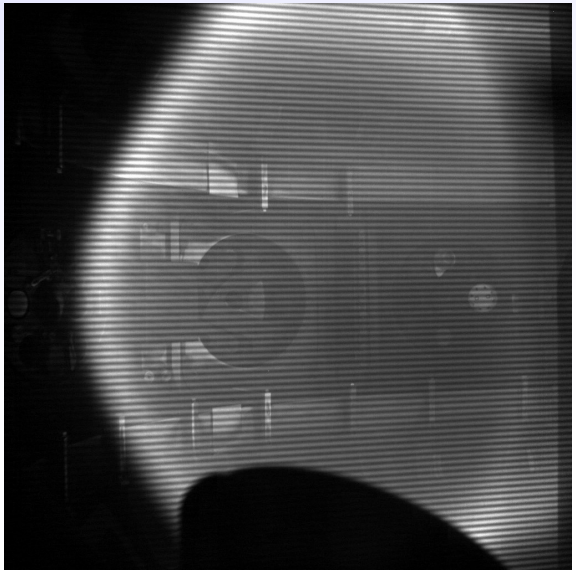
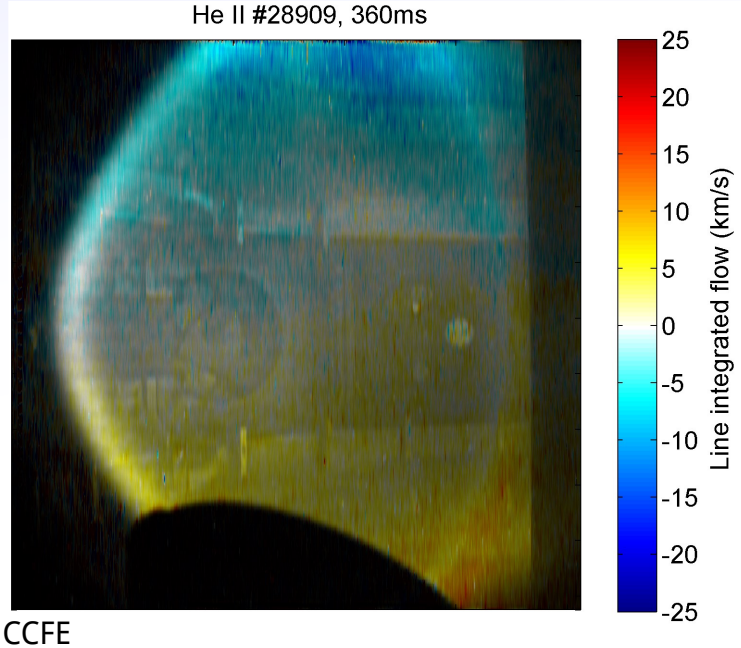
Some results of neutral Helium flow in the (relatively) cold edge of MAST:

Raw Image:



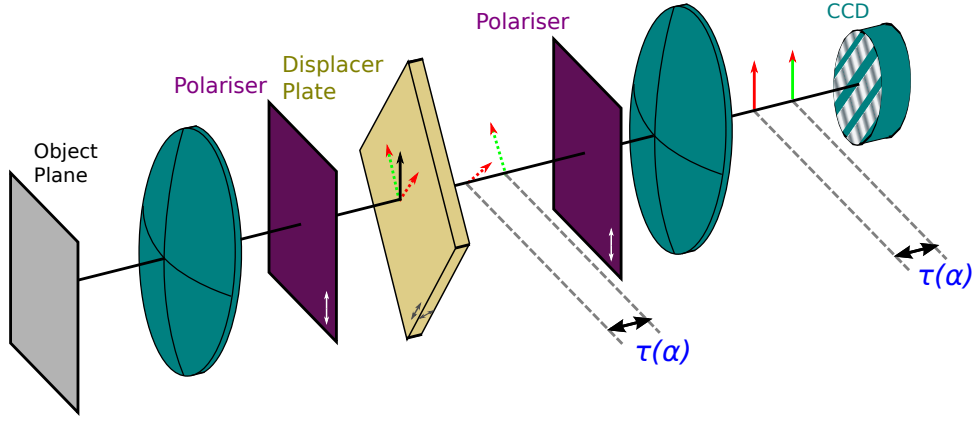
Helium Flow Velocity:



MAST
Mega Amp Spherical Tokamak, CCFE, Culham, UK

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

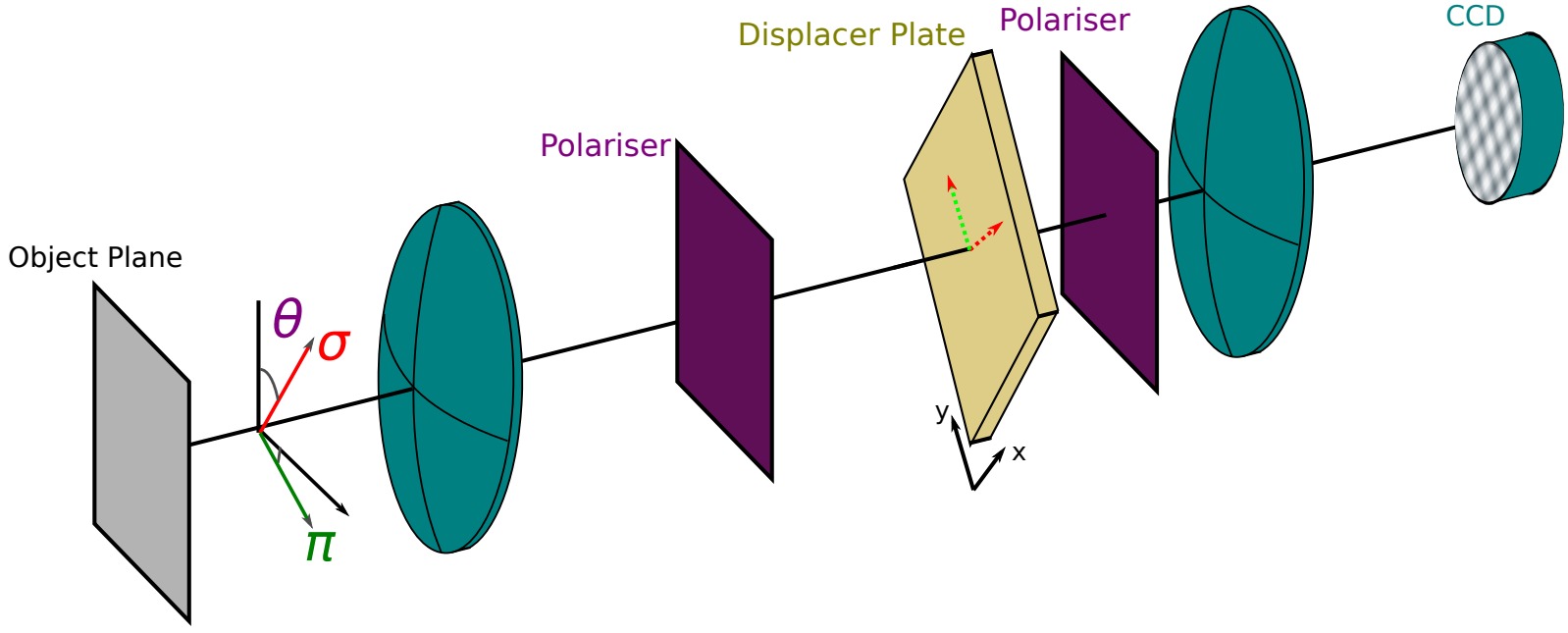
IPP: D.Gradic - PhD student project implementing coherence imaging for VINETA II, a linear plasma device for investigation of magnetic reconnection:



Multiplet Polarisation Coherence Imaging

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

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



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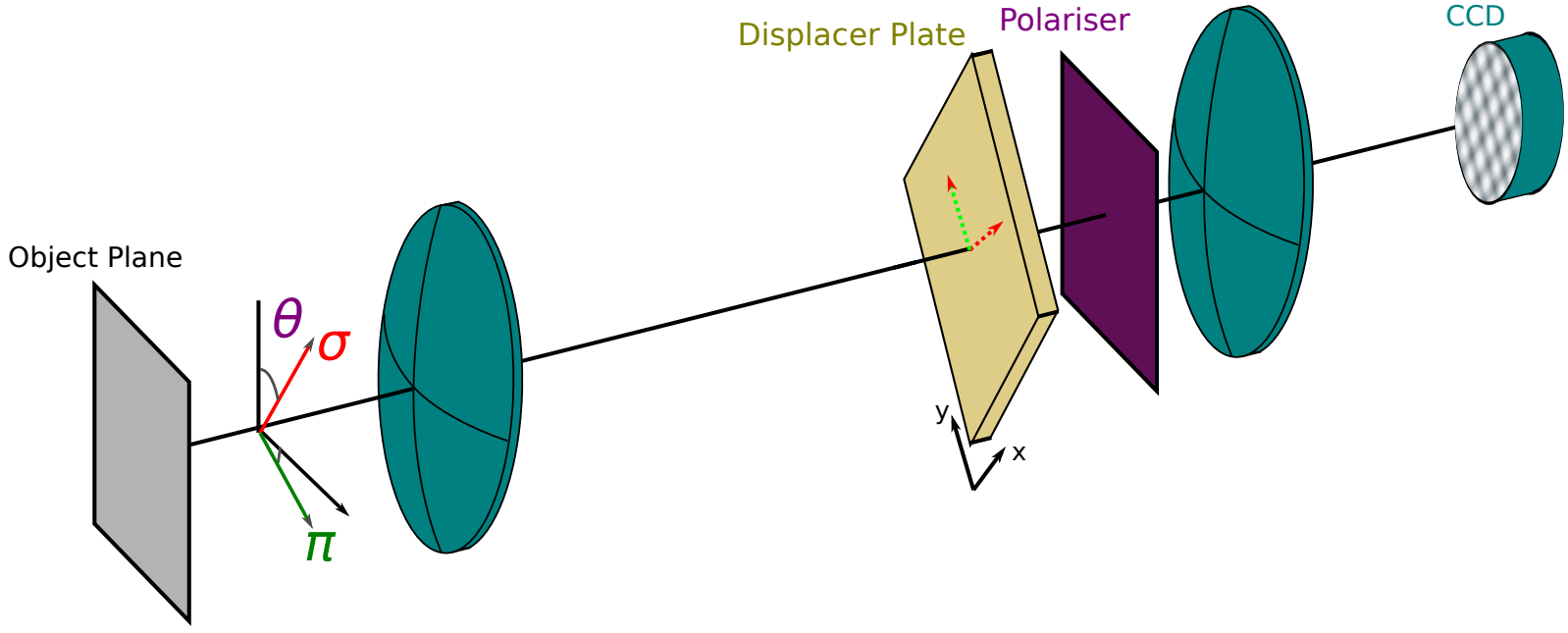

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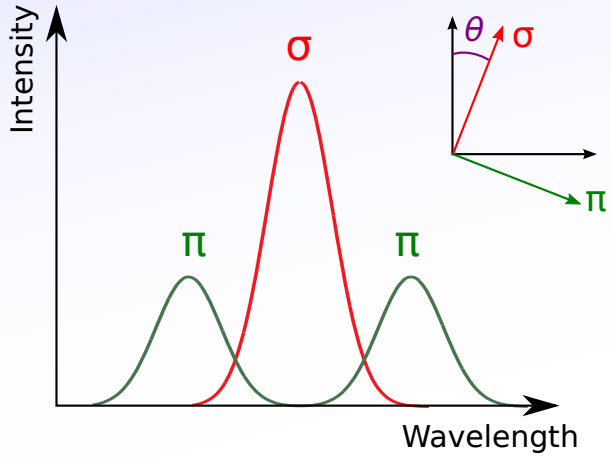

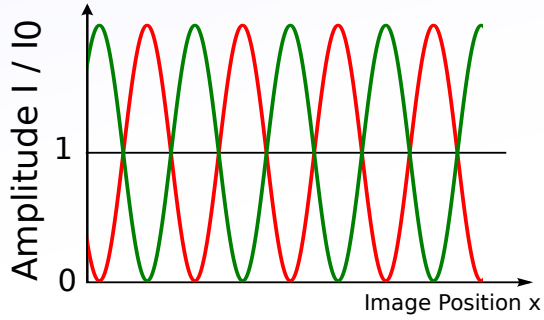

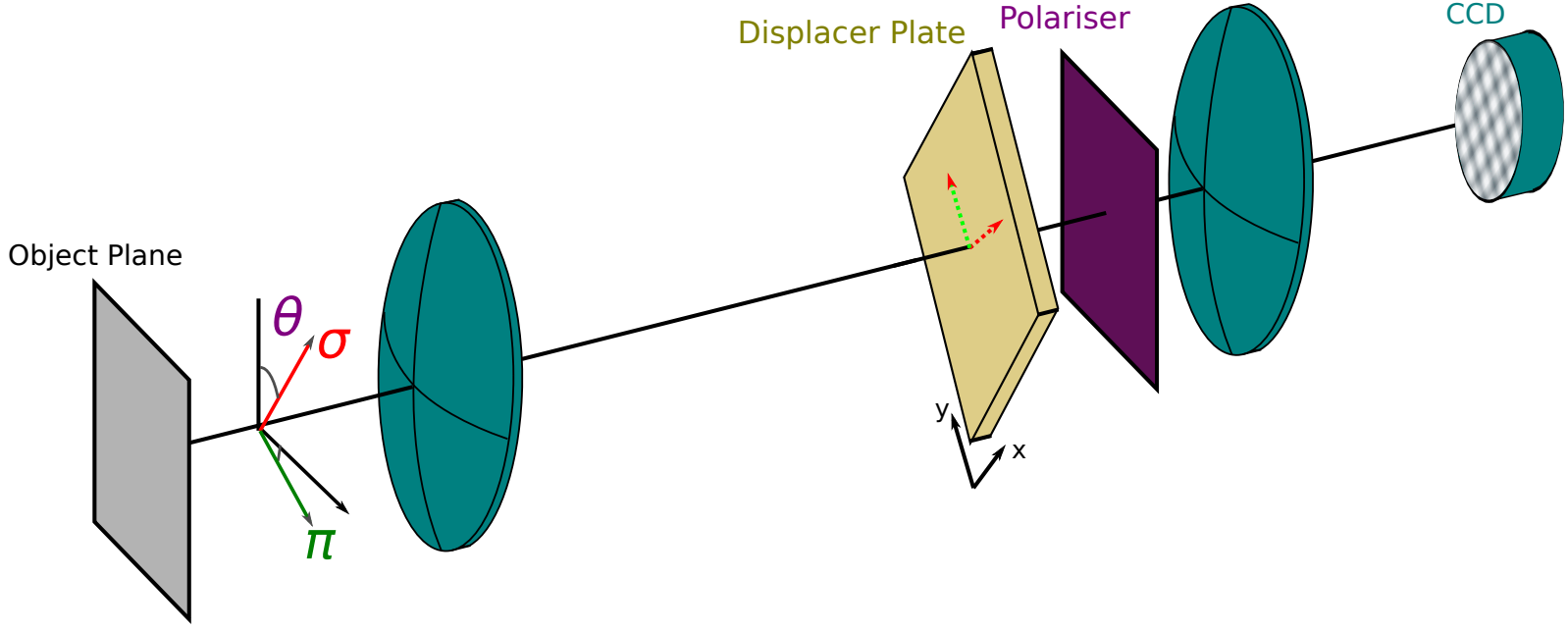

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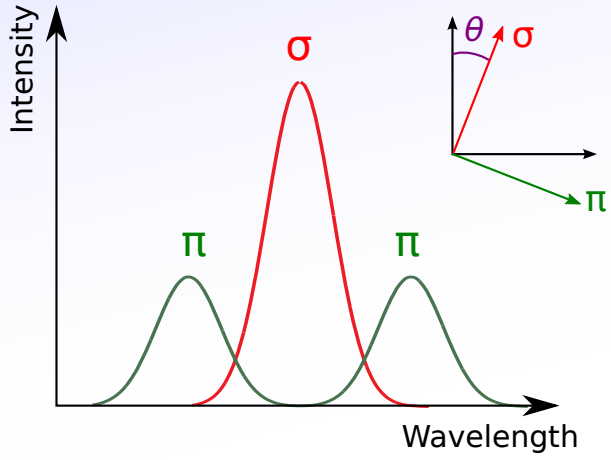
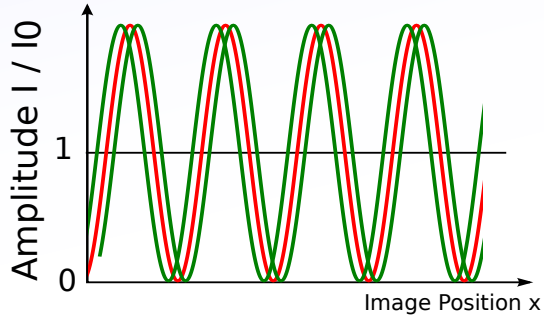
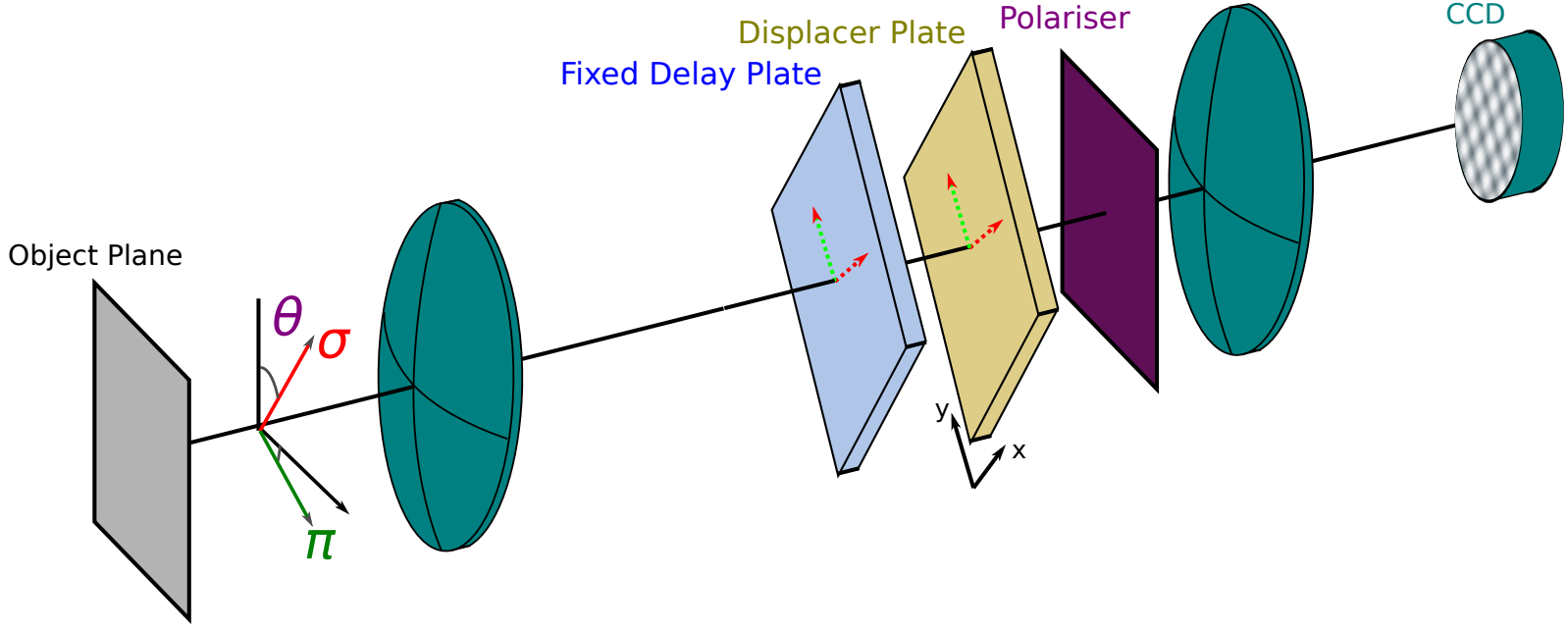
At some specific plate thickness τ, the phase of the π wings is 180° from σ. This cancels the 180° from the opposite polarisation, and the patterns add. We add a delay plate with the optimal τ_0.







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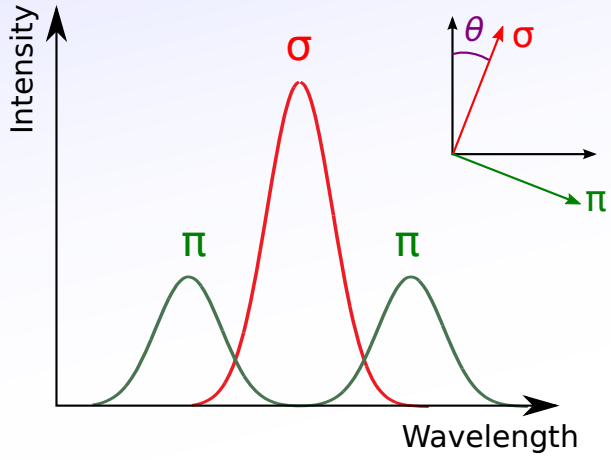

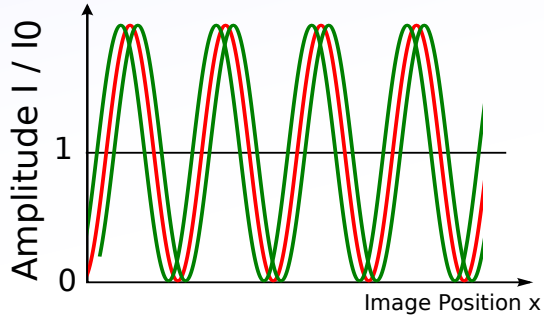

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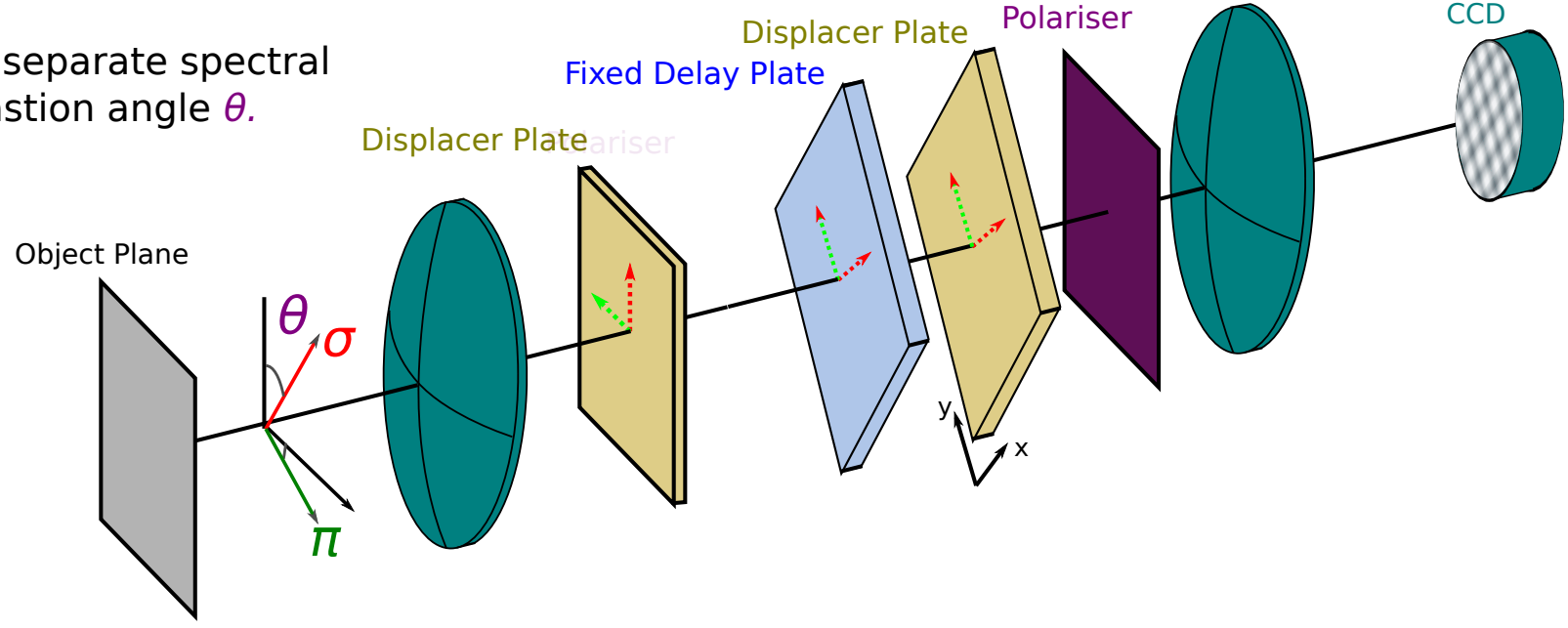
However, we now need to separate spectral contrast ζ from the polariastion angle θ.



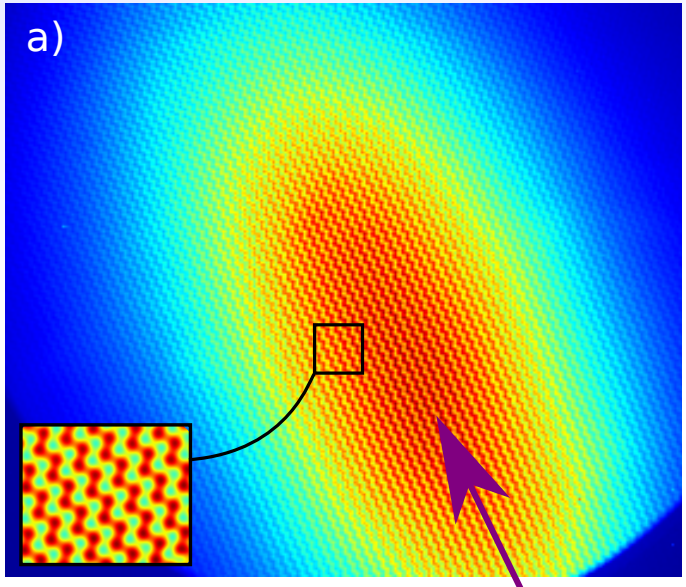
add another displacer at 45°. Combined effect adds 2 extra terms:

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

Image Demodulation

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

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



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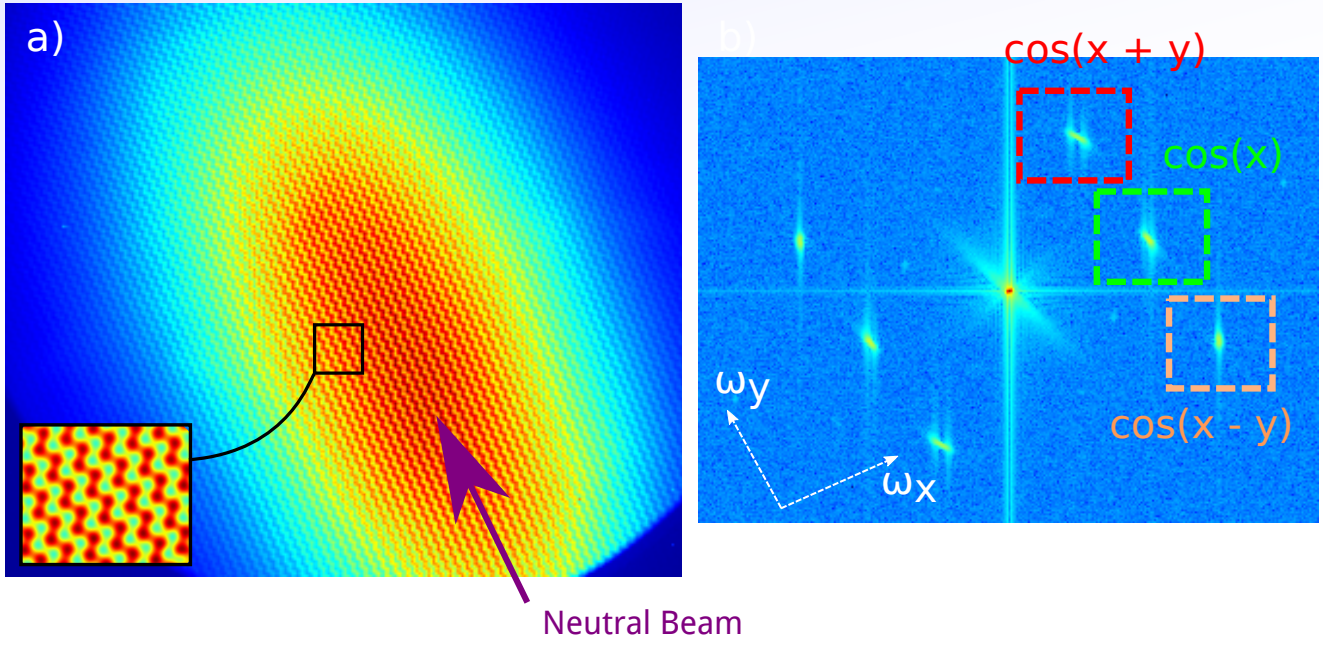

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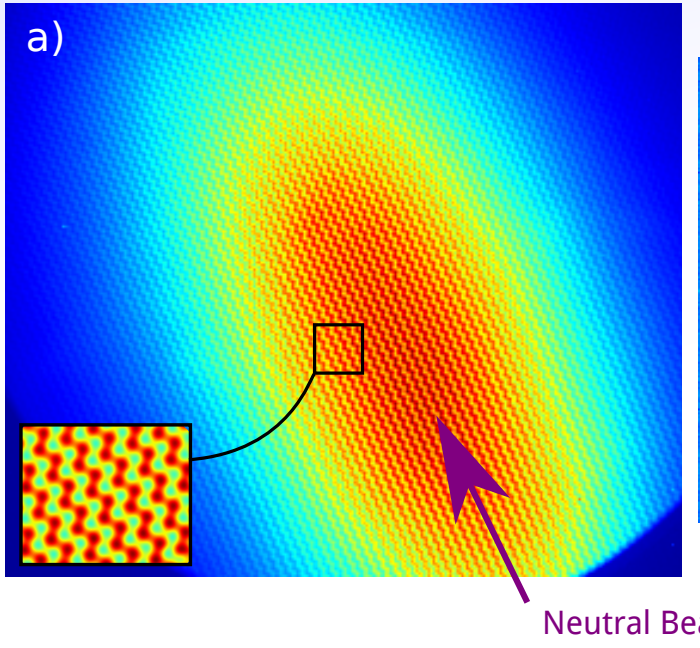

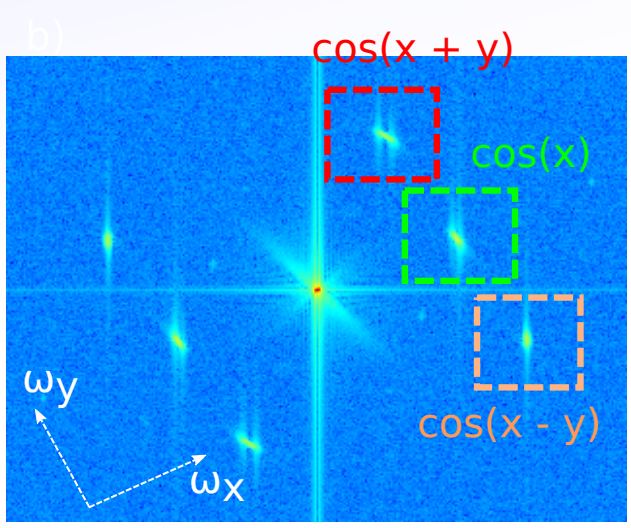

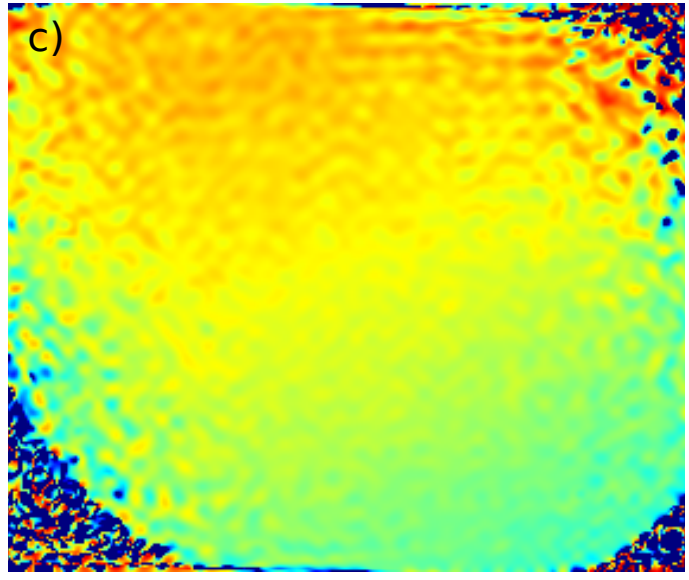

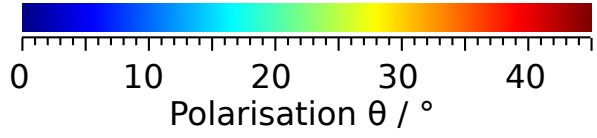

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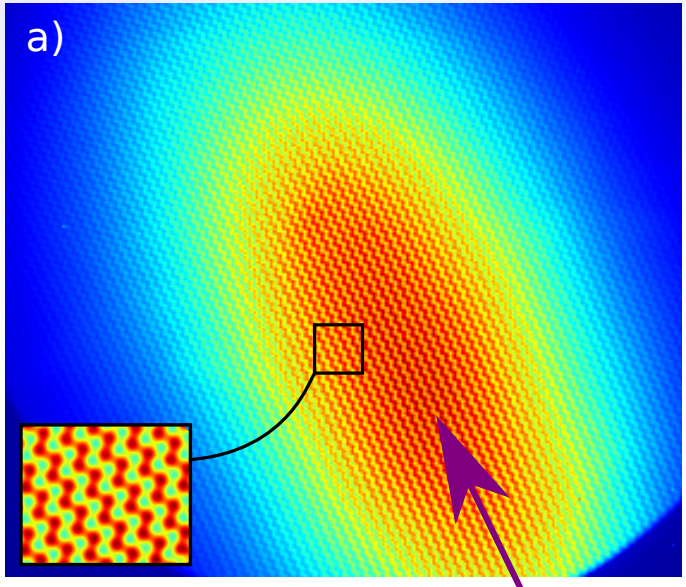
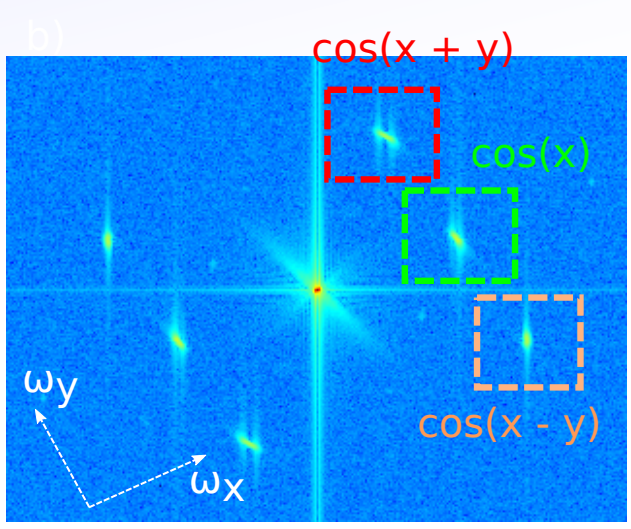
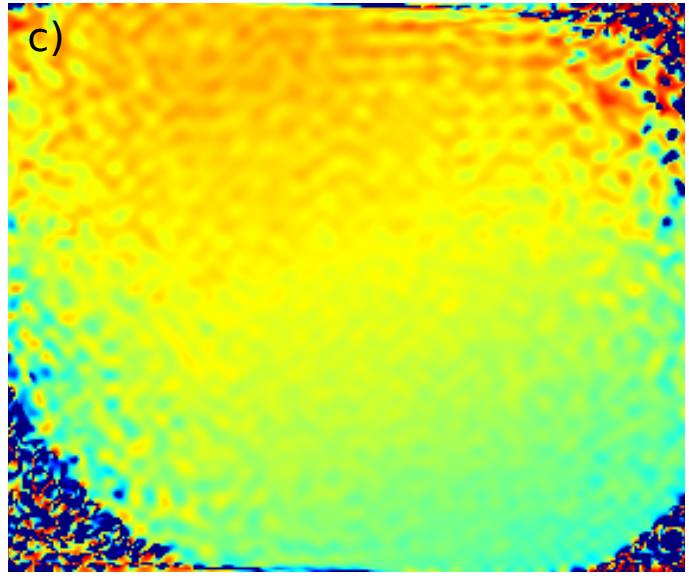
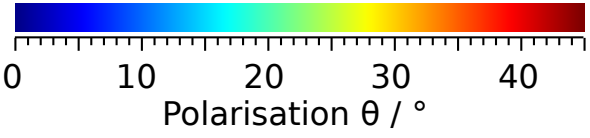
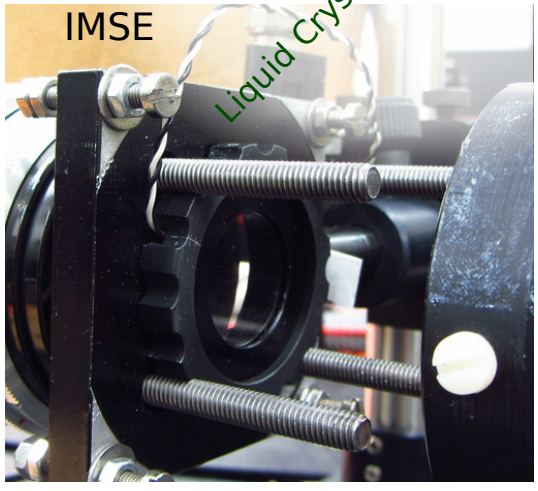








The hardware:



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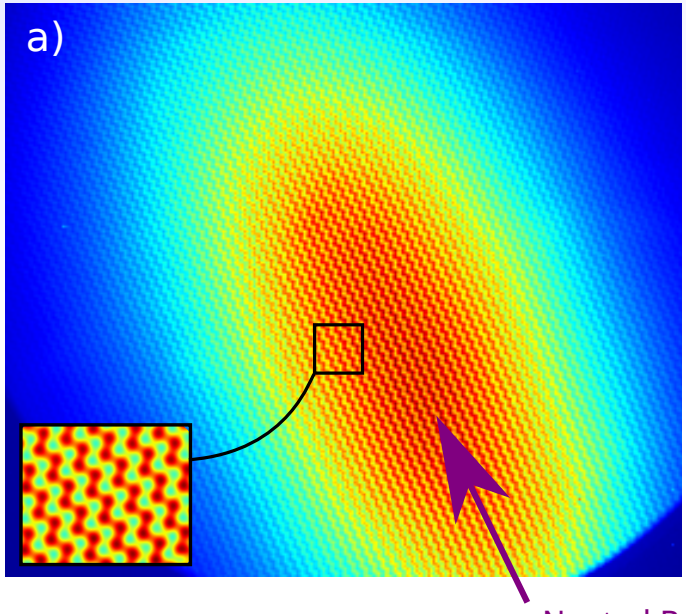

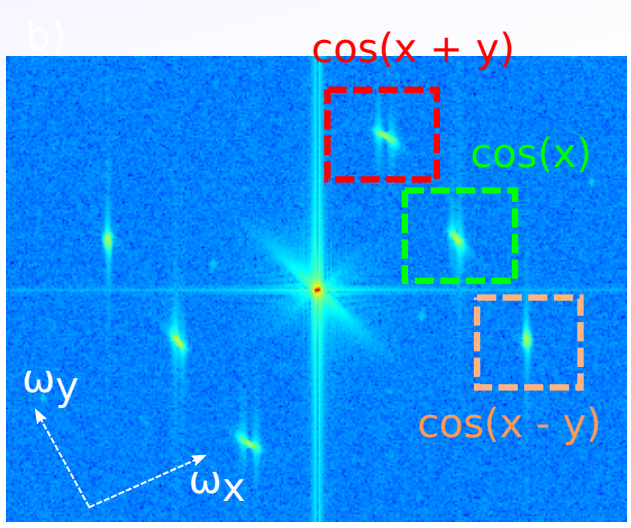

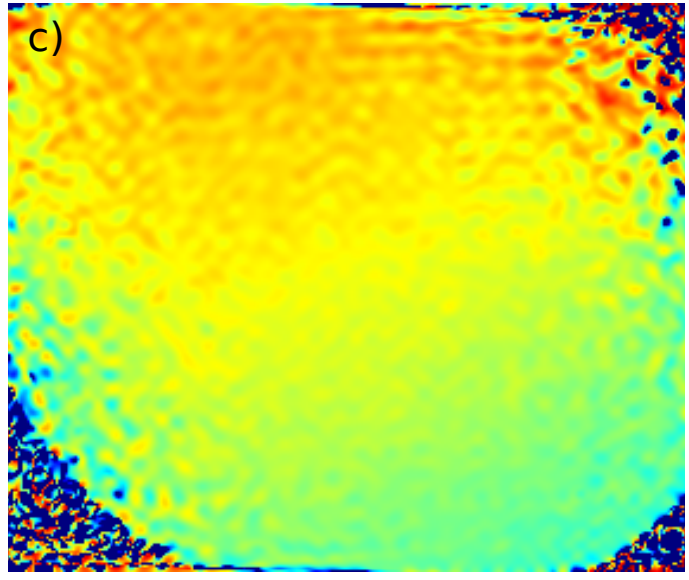

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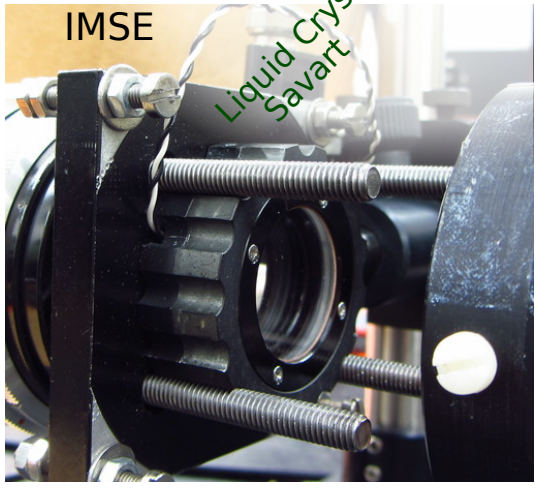

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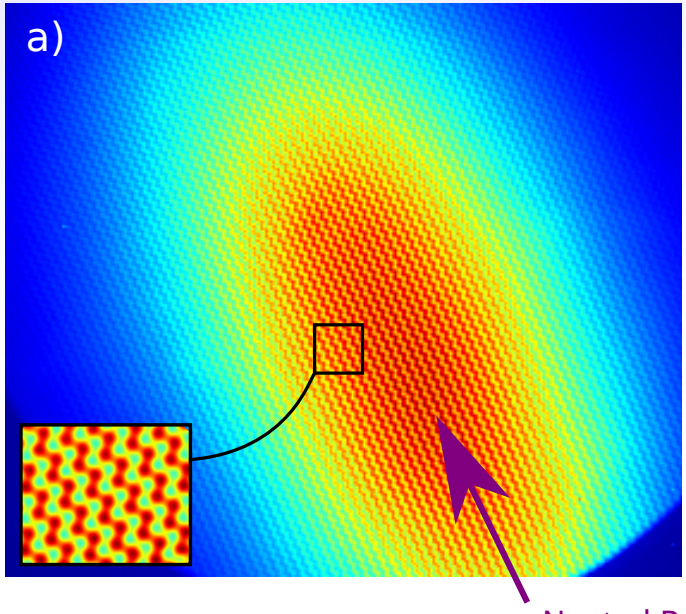

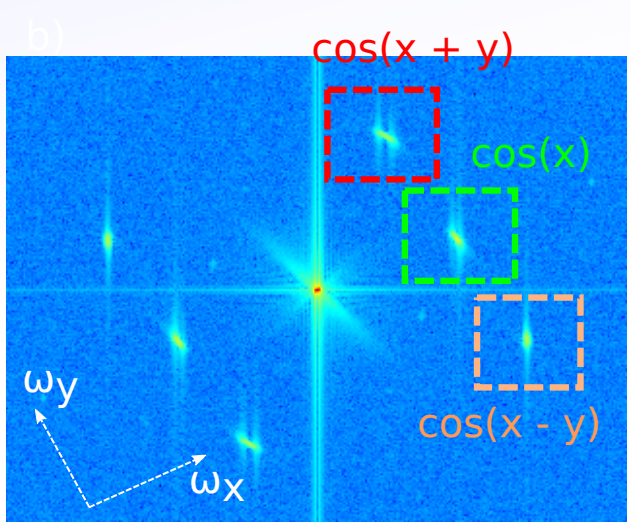

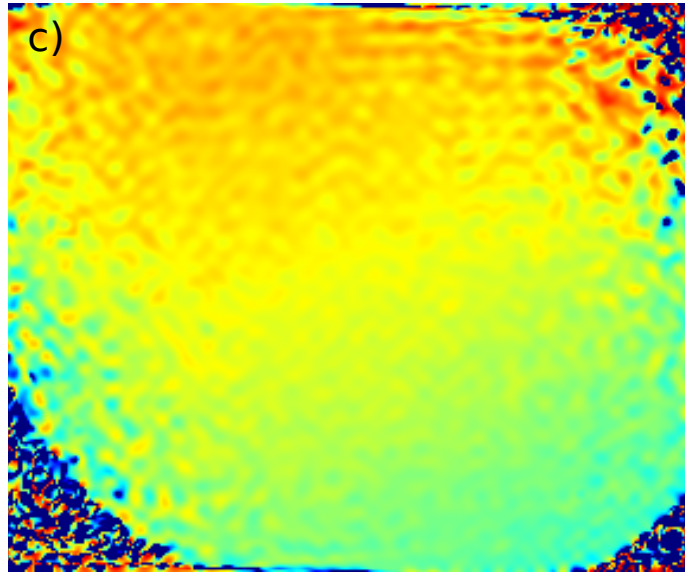

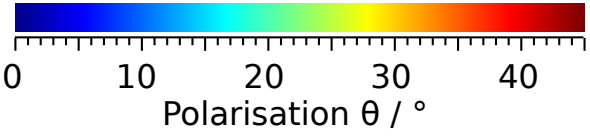

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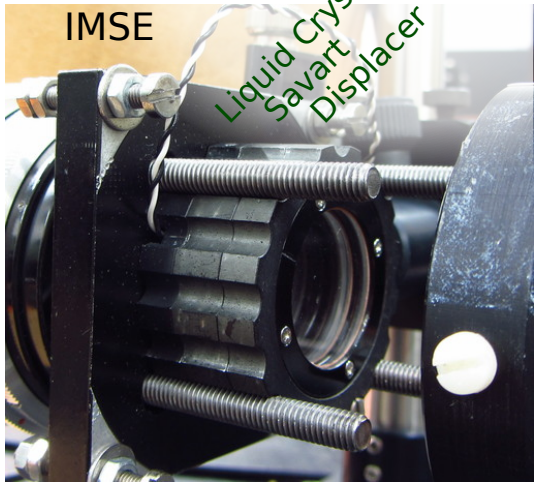

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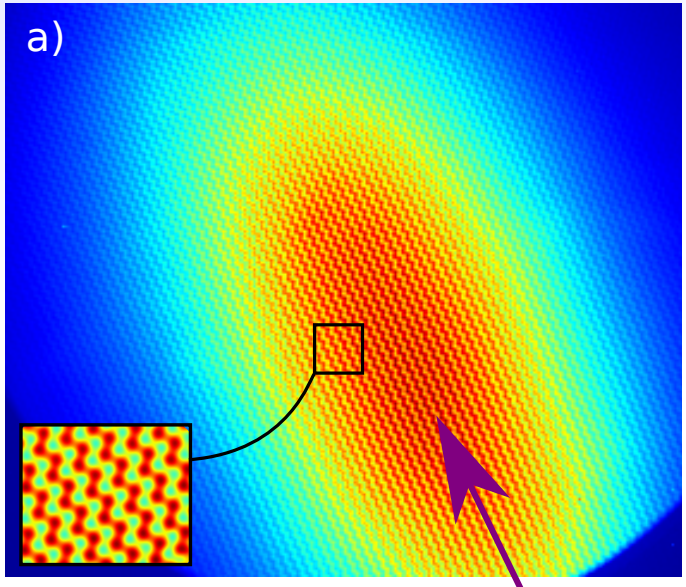

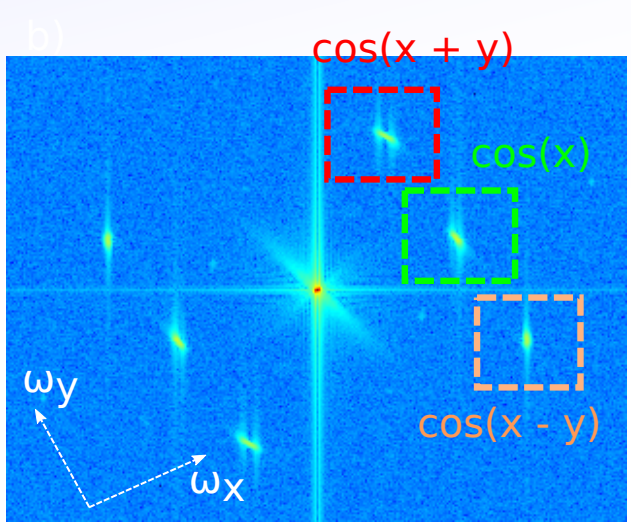

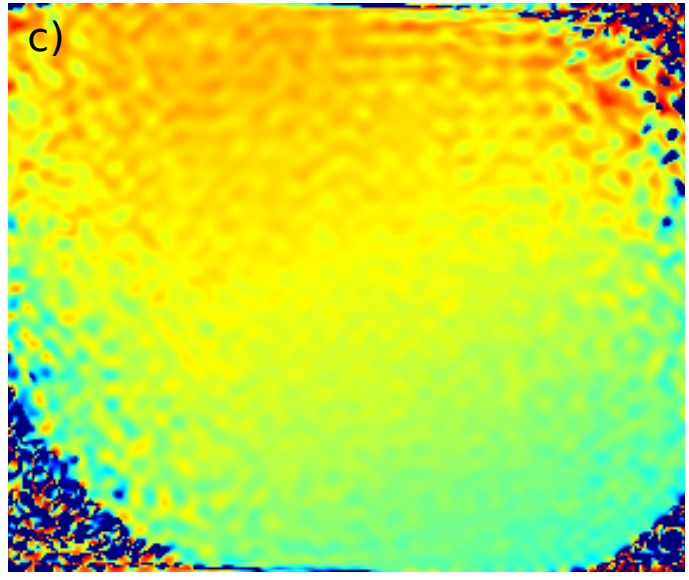

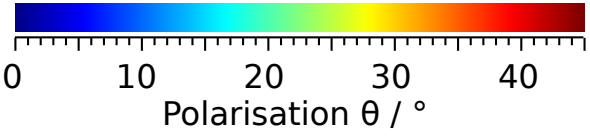

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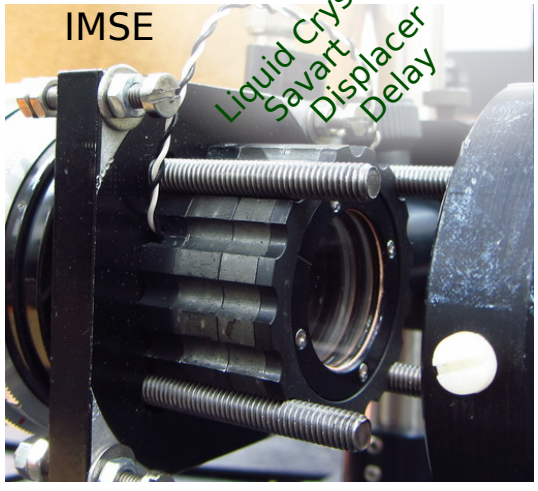

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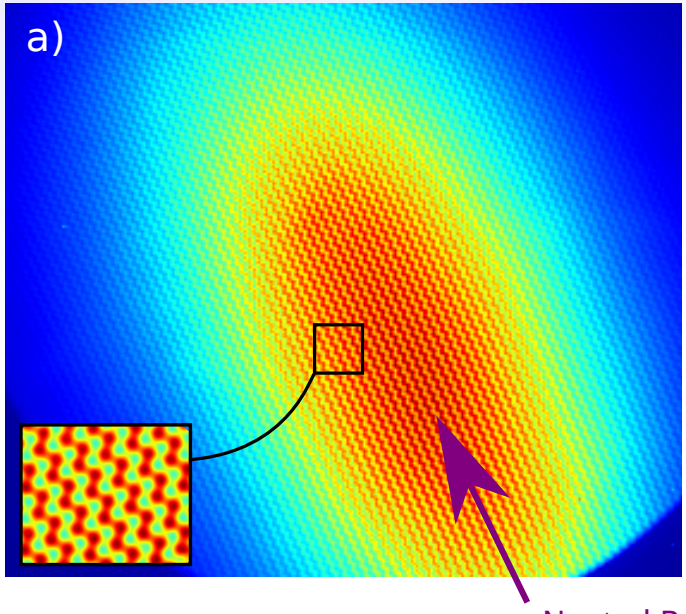

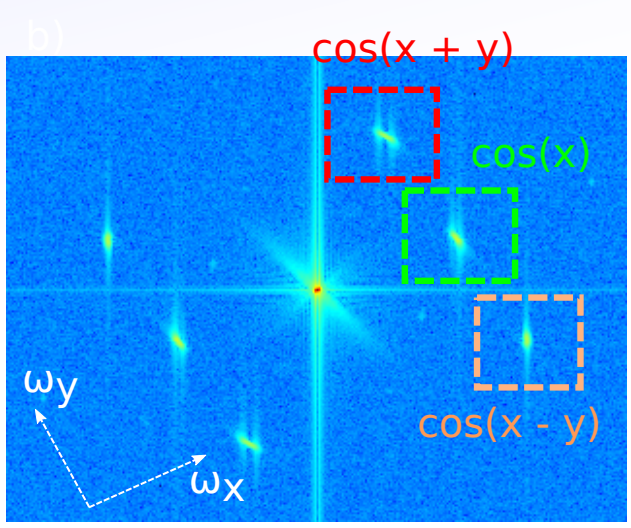

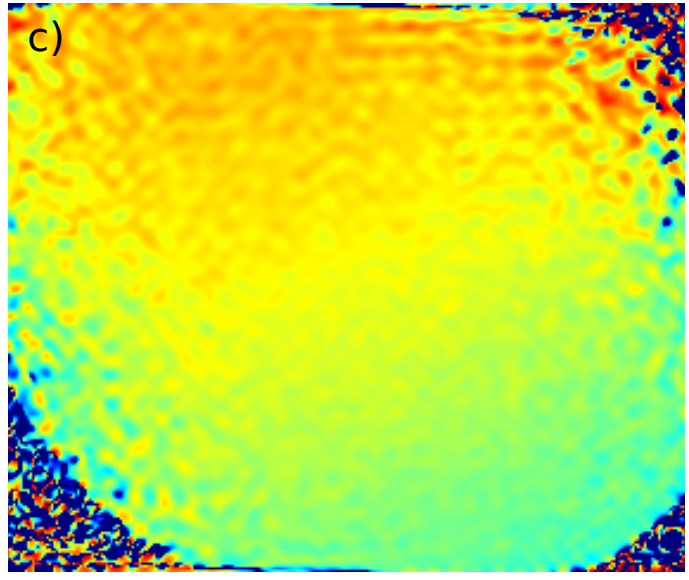

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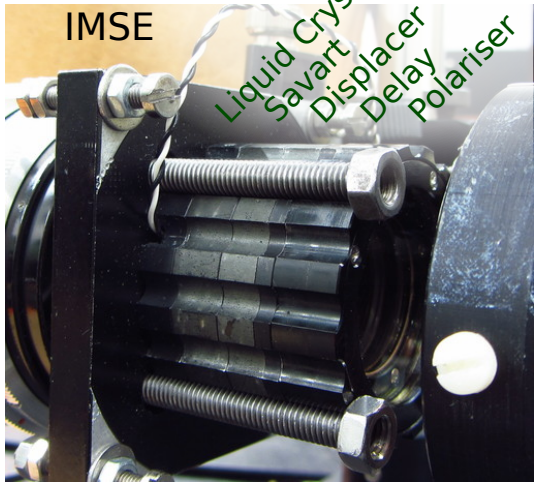

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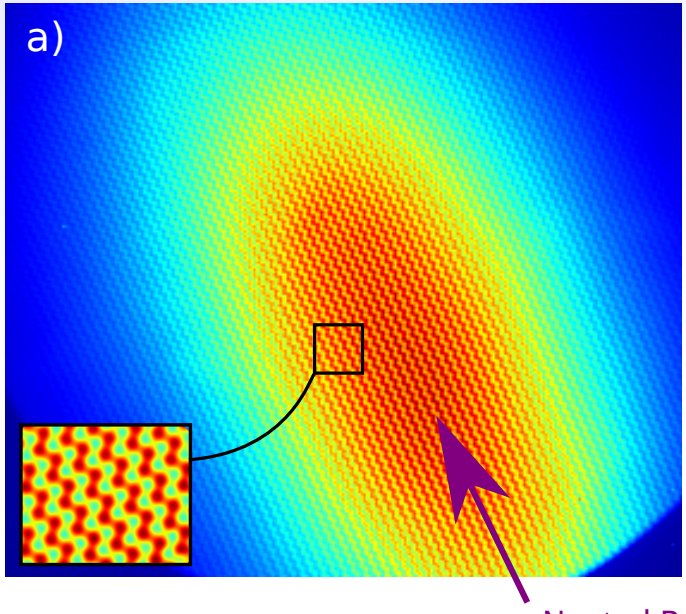

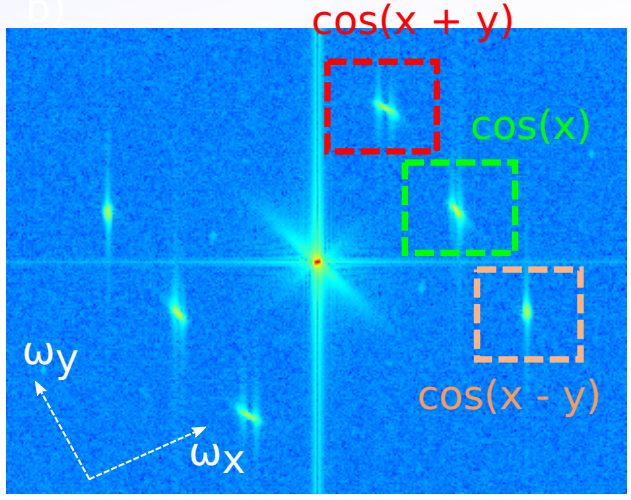

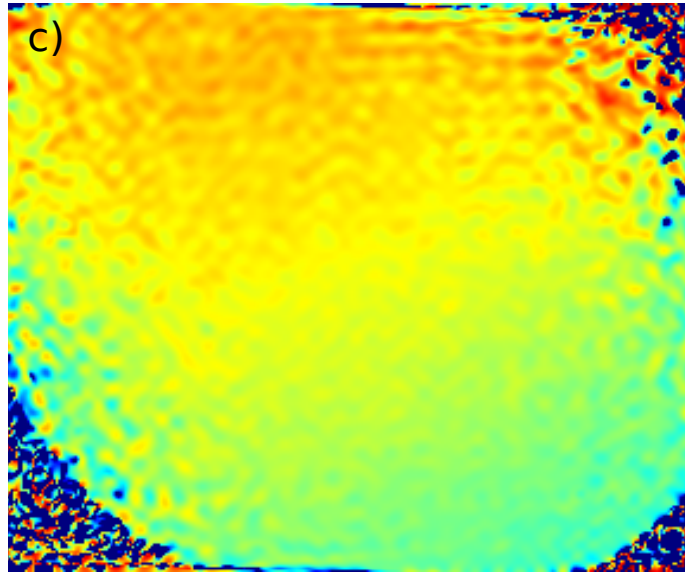

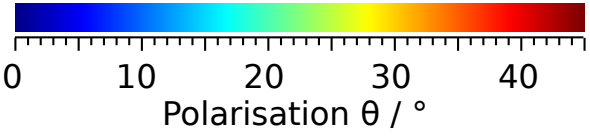

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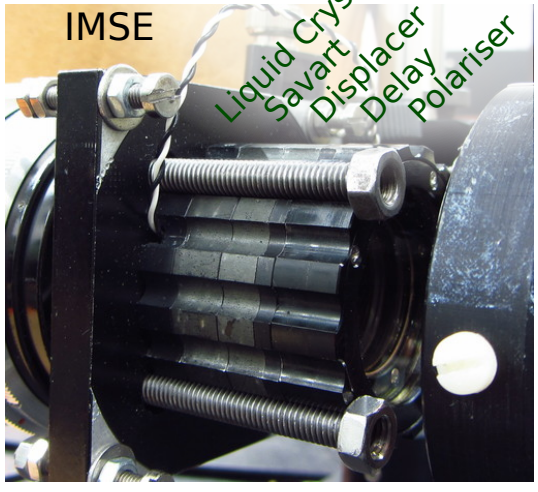

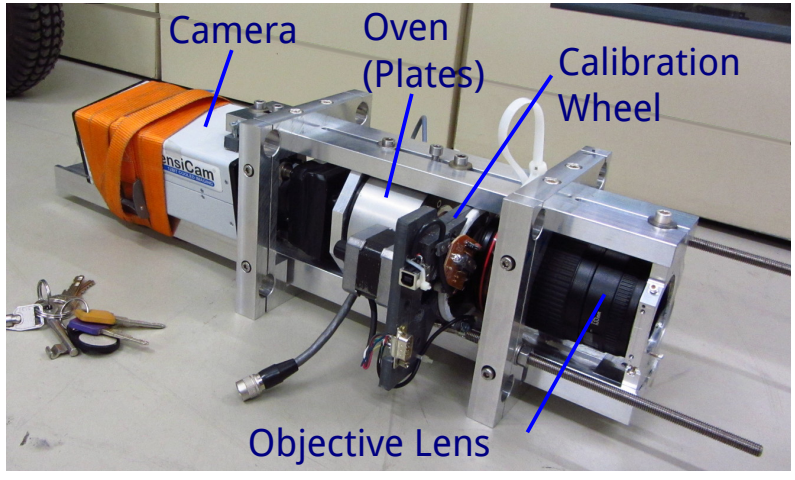

Oliver Ford
IPP Greifswald

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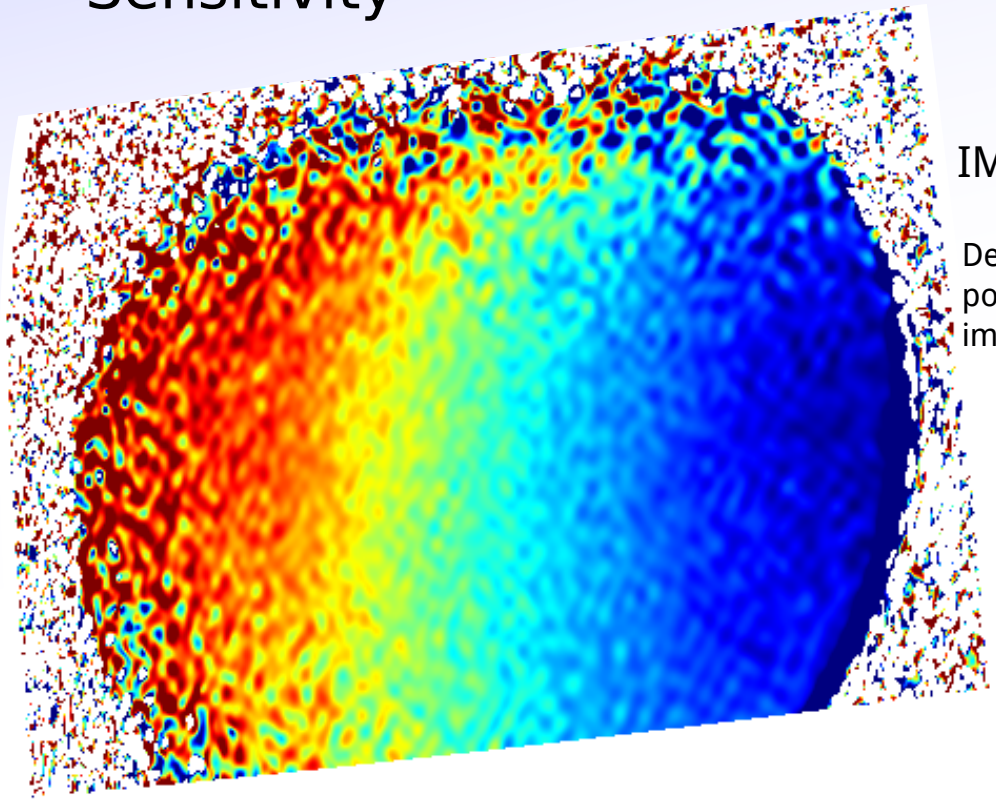
Comparing the new IMSE to the old MSE system on a similar plasma discharge, we get good agreement, higher time resolution and with a new a fast CMOS imaging camera (15k€), a much higher sensitivity.



IMSE 2014

Demodulated polarisation angle image

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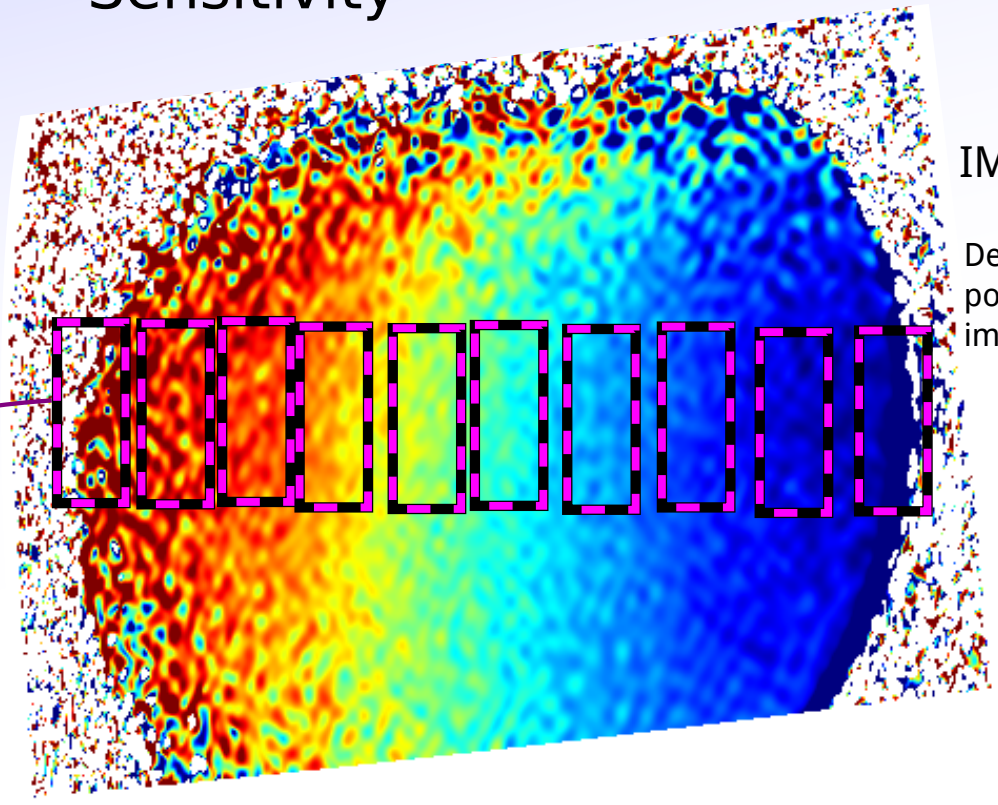

IMSE 2014

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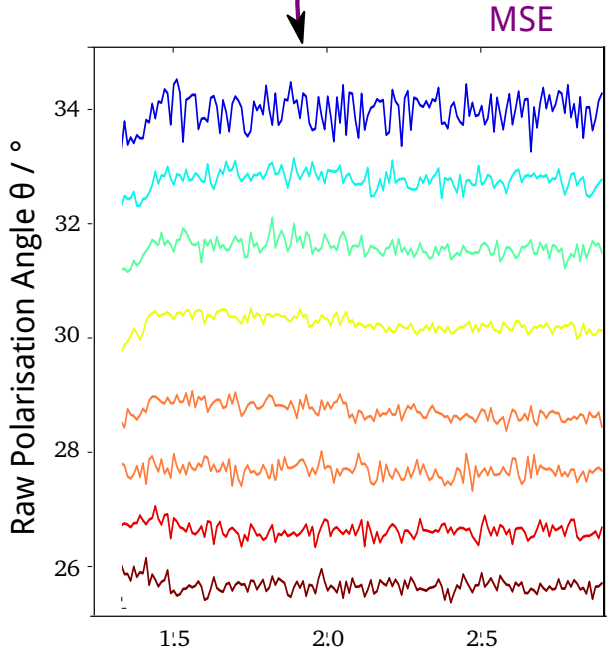
MSE equivalent areas



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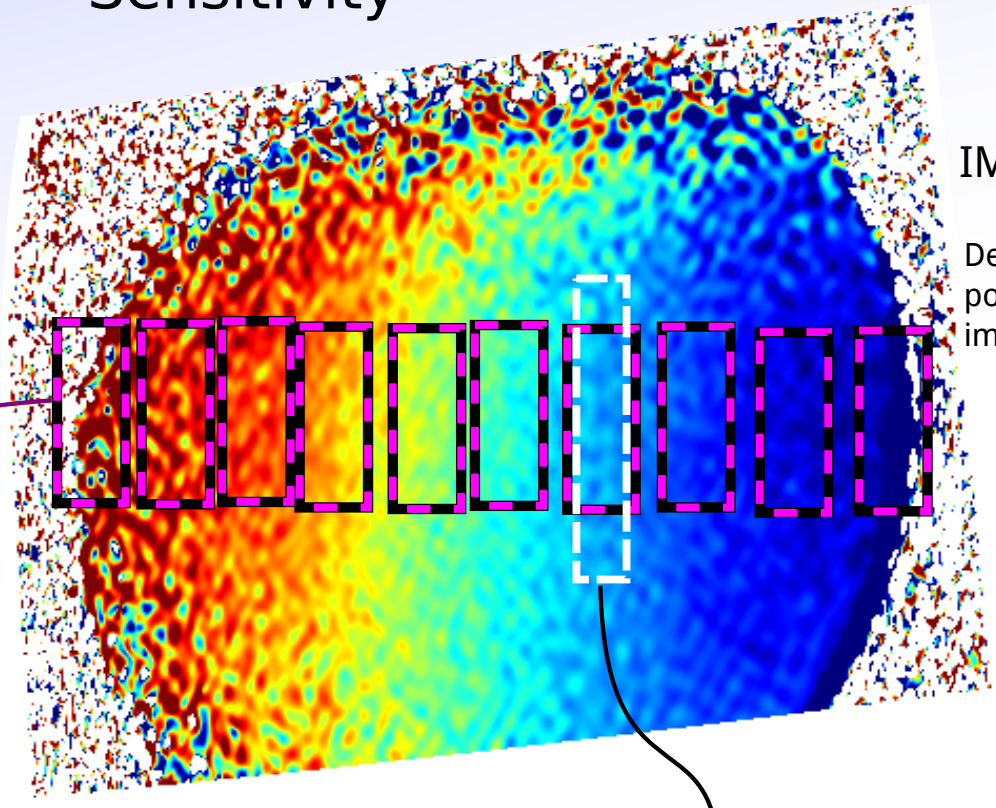

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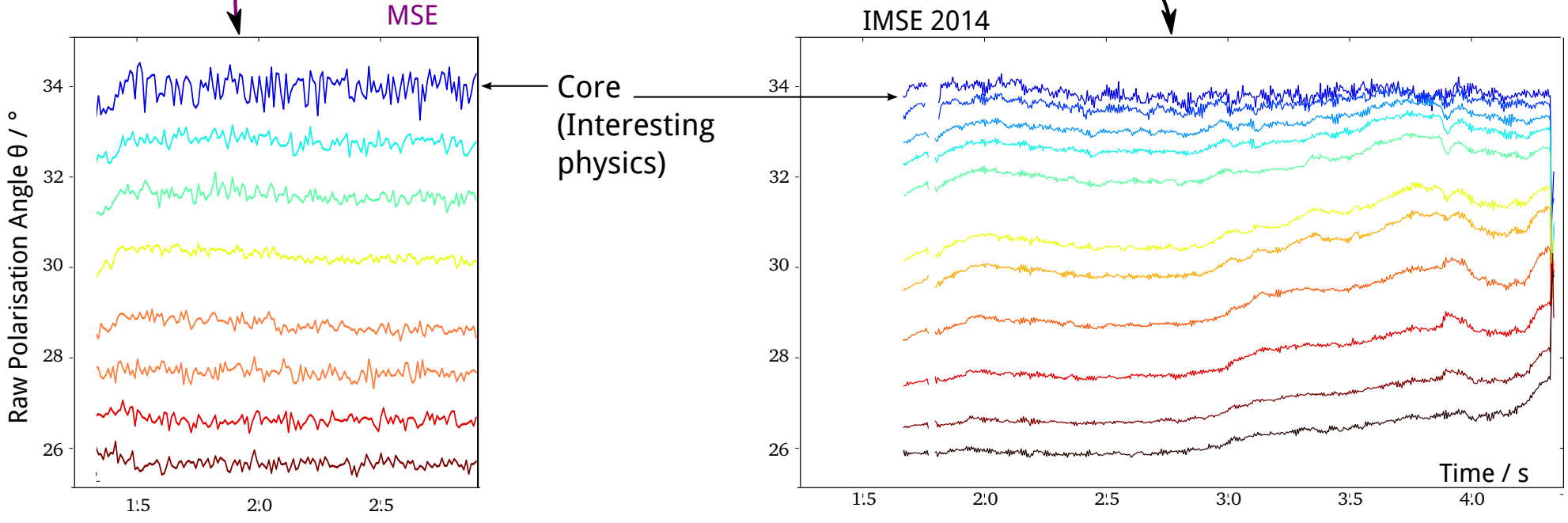

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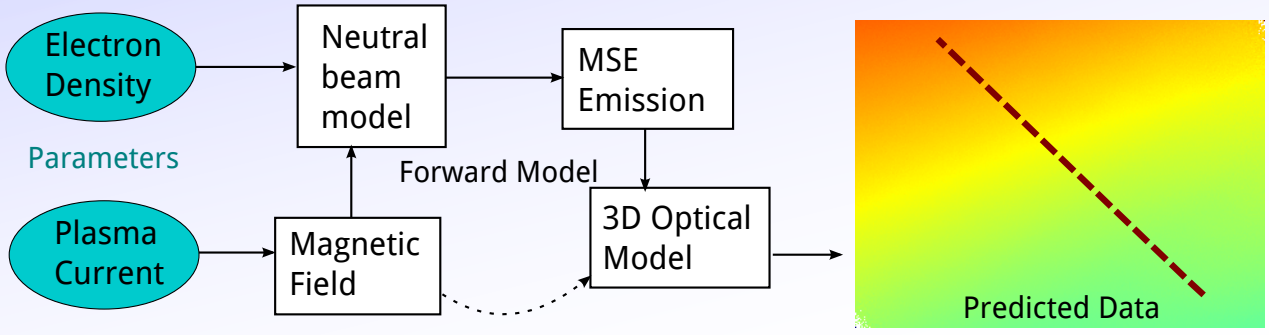

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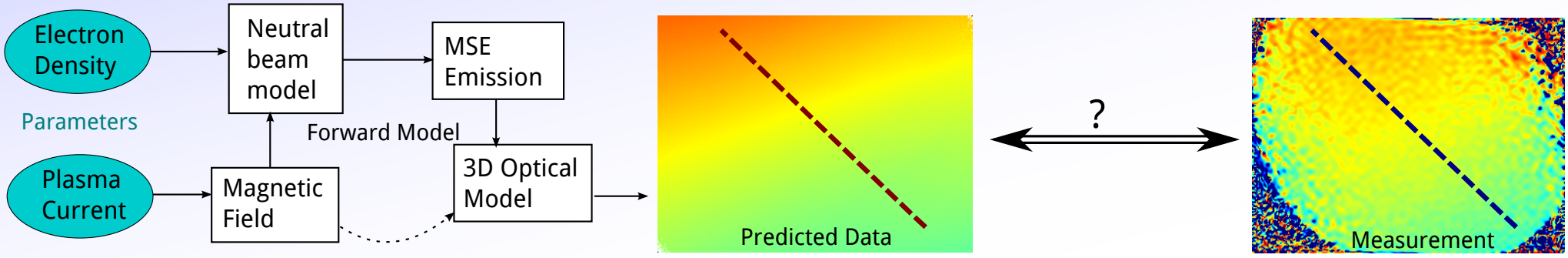

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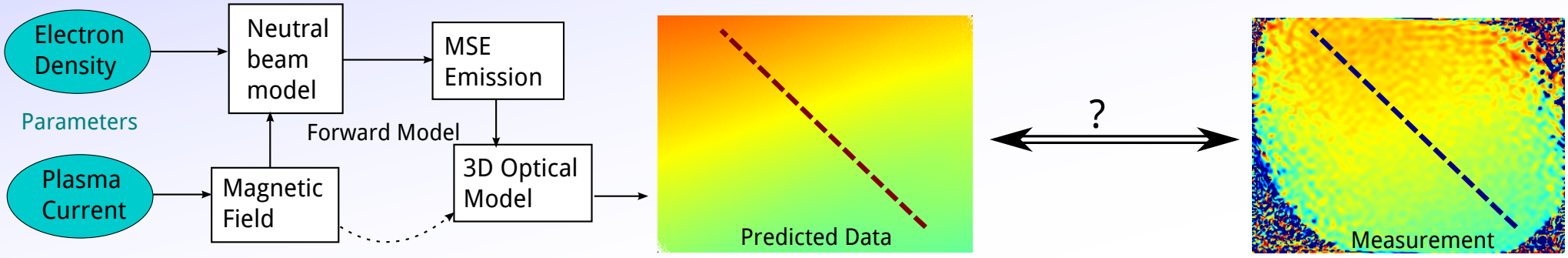

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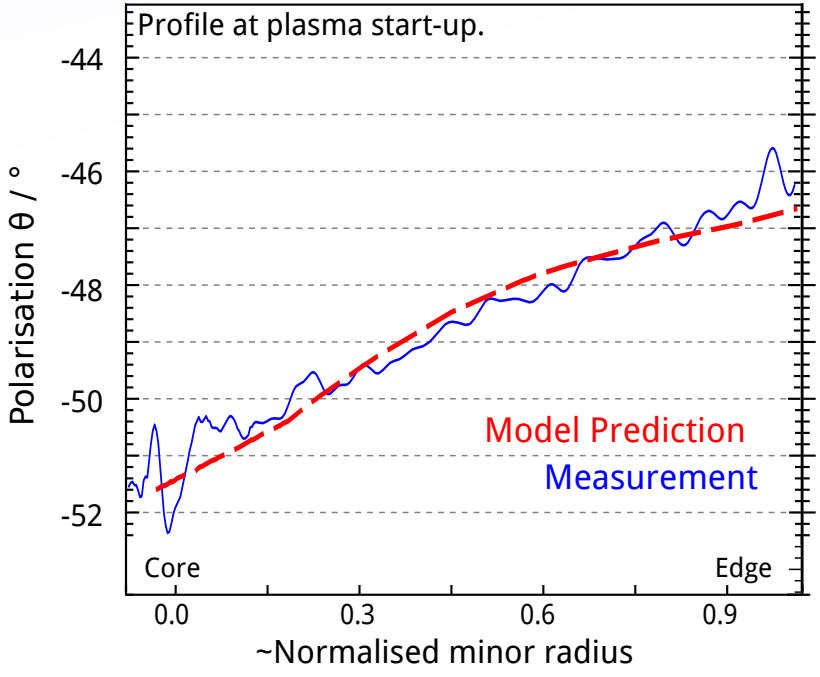

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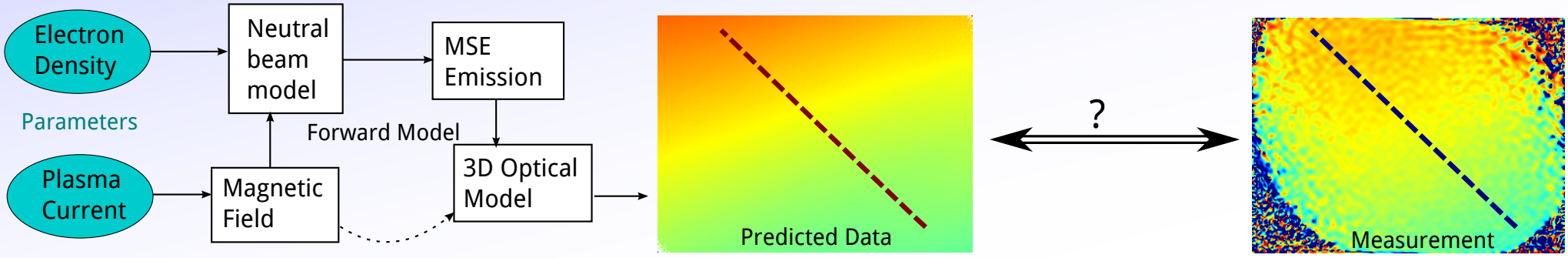

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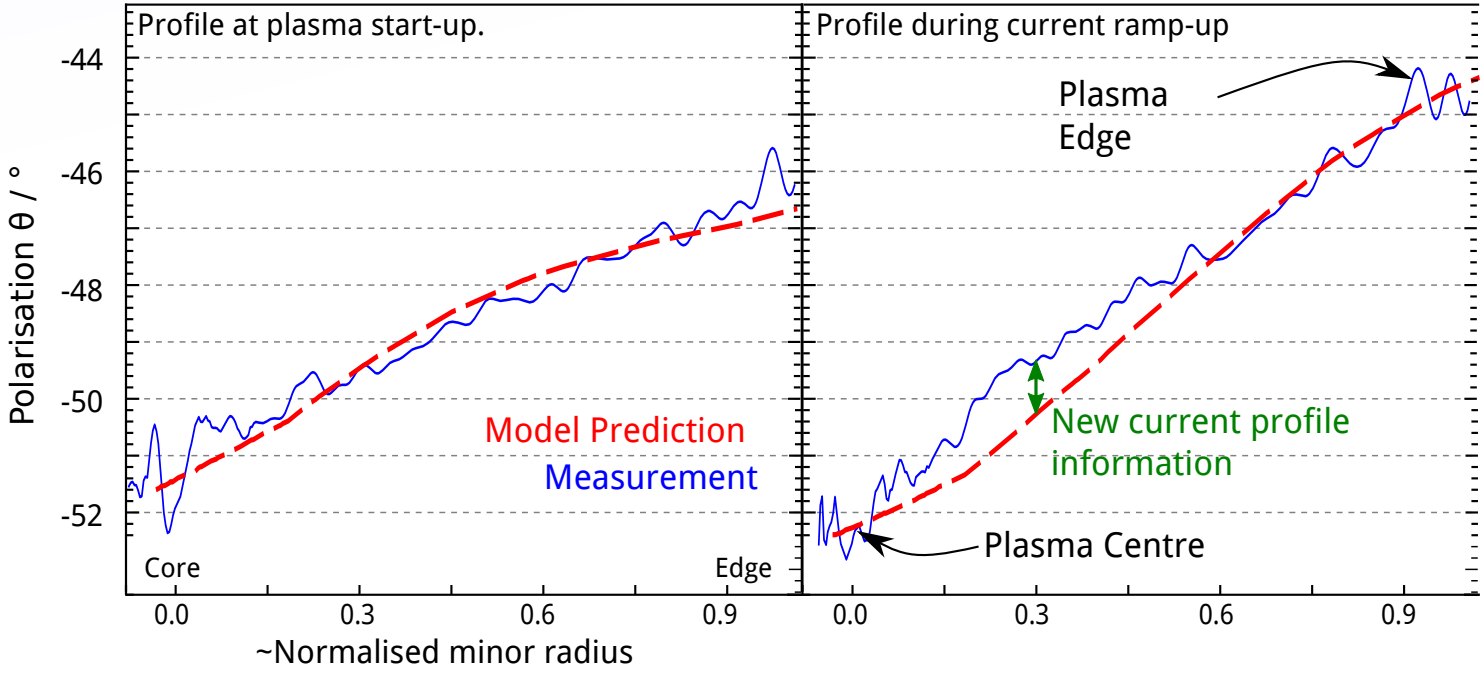

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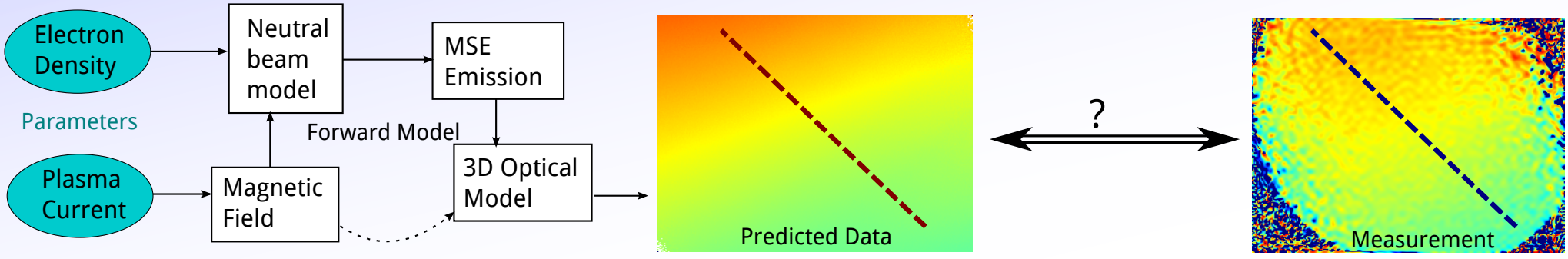

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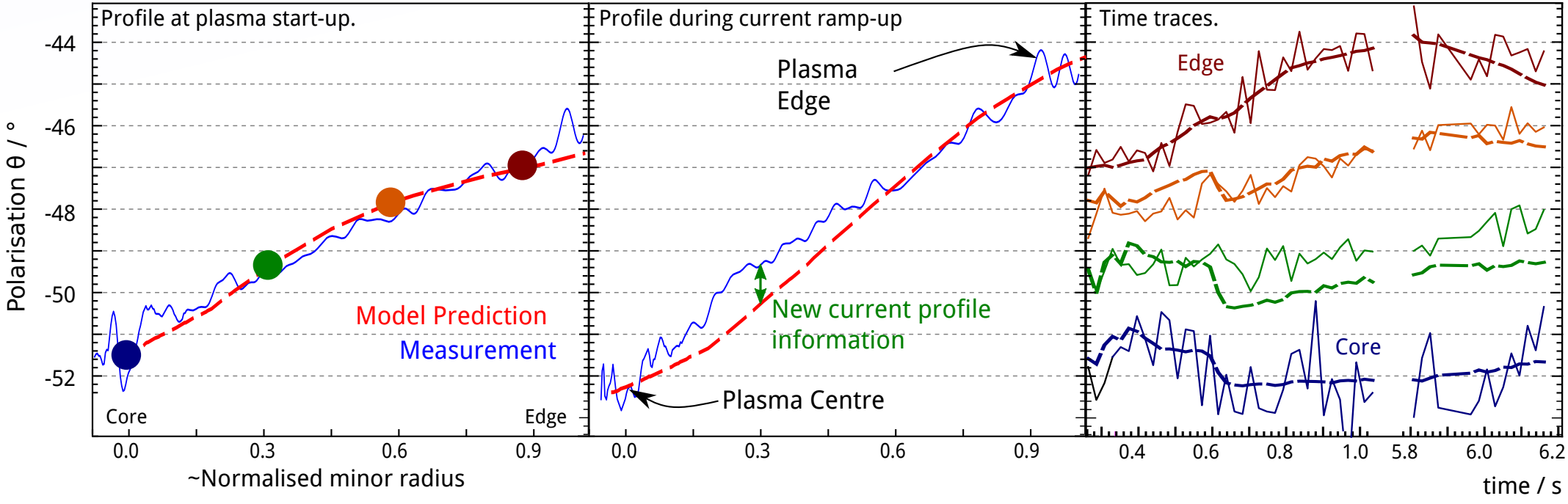

The forward model is part of a Bayesian Analysis framework, which will be used to infer the plasma quantities from the measured images.

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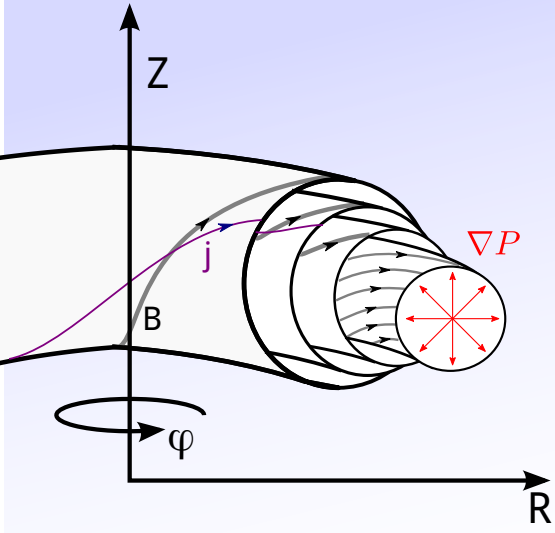
IPP Greifswald

Data Analysis - Equilibrium Solutions



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+ Pressure constant on magnetic surfaces
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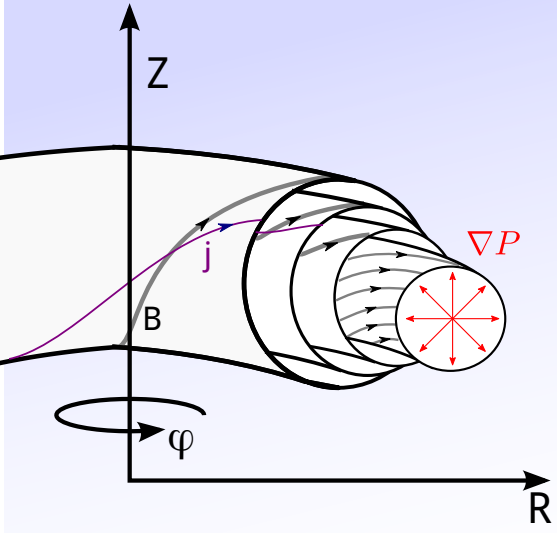

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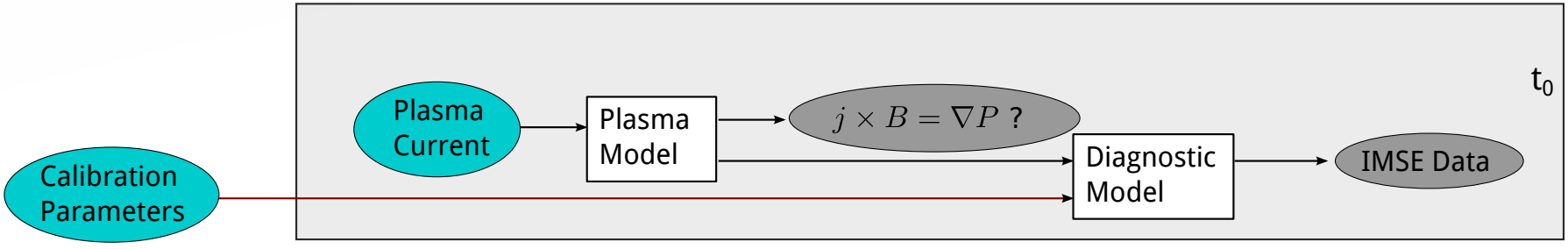

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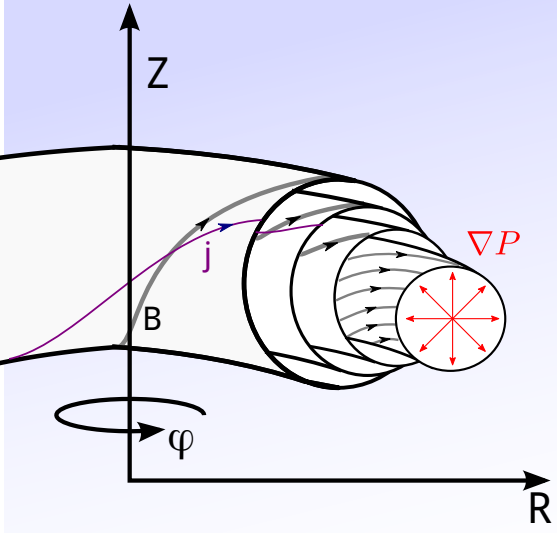

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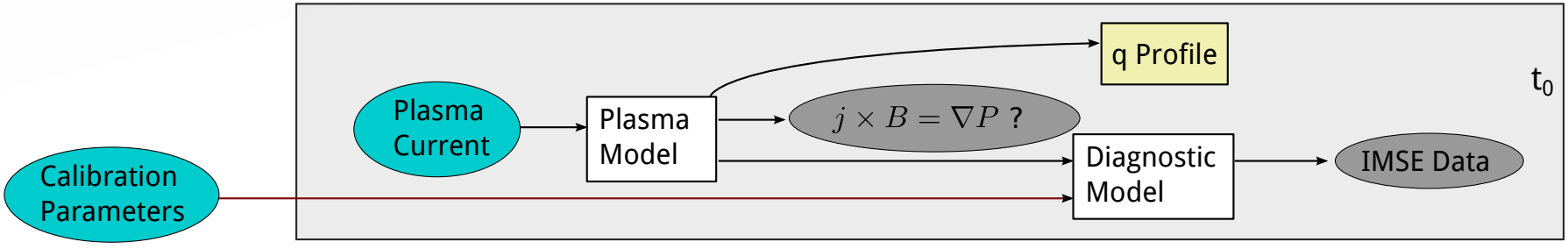

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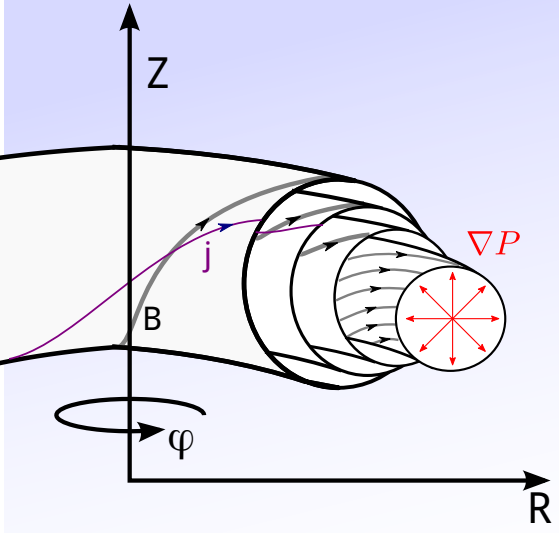

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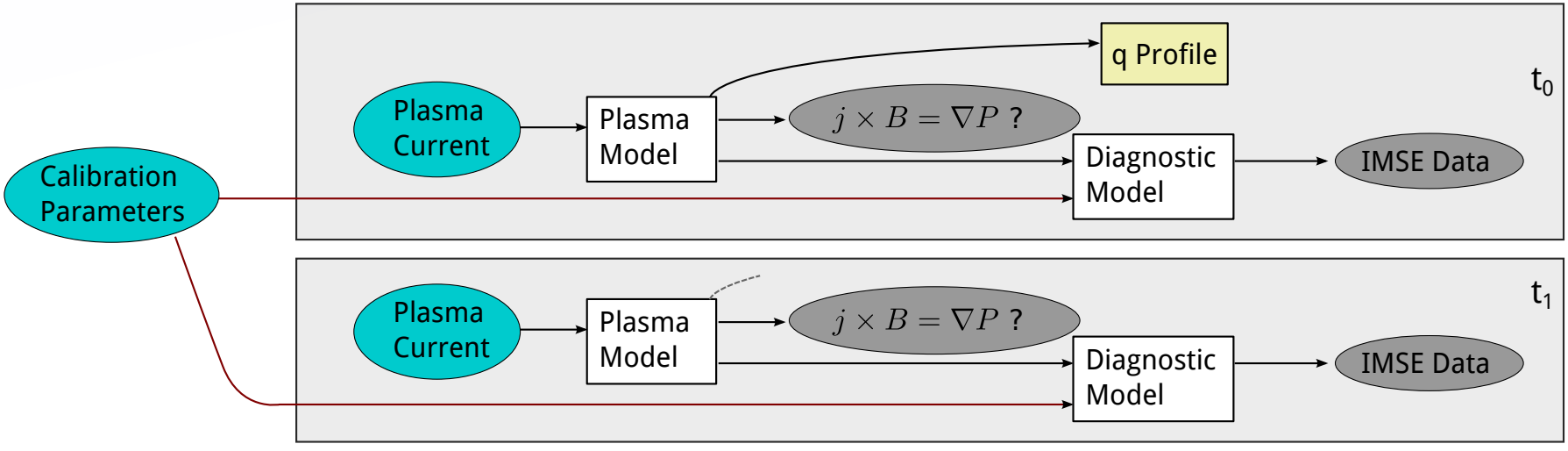

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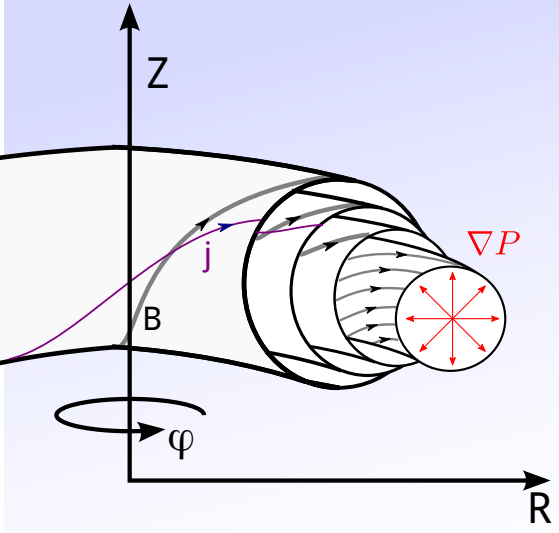

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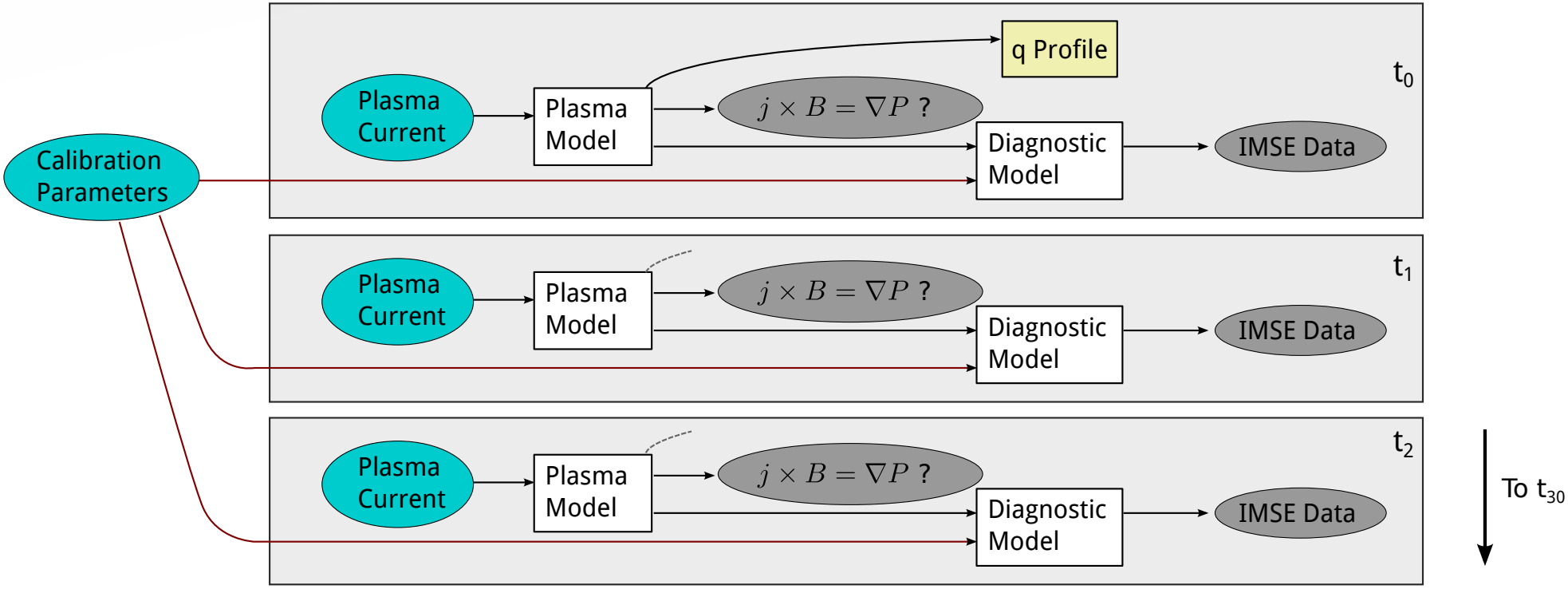

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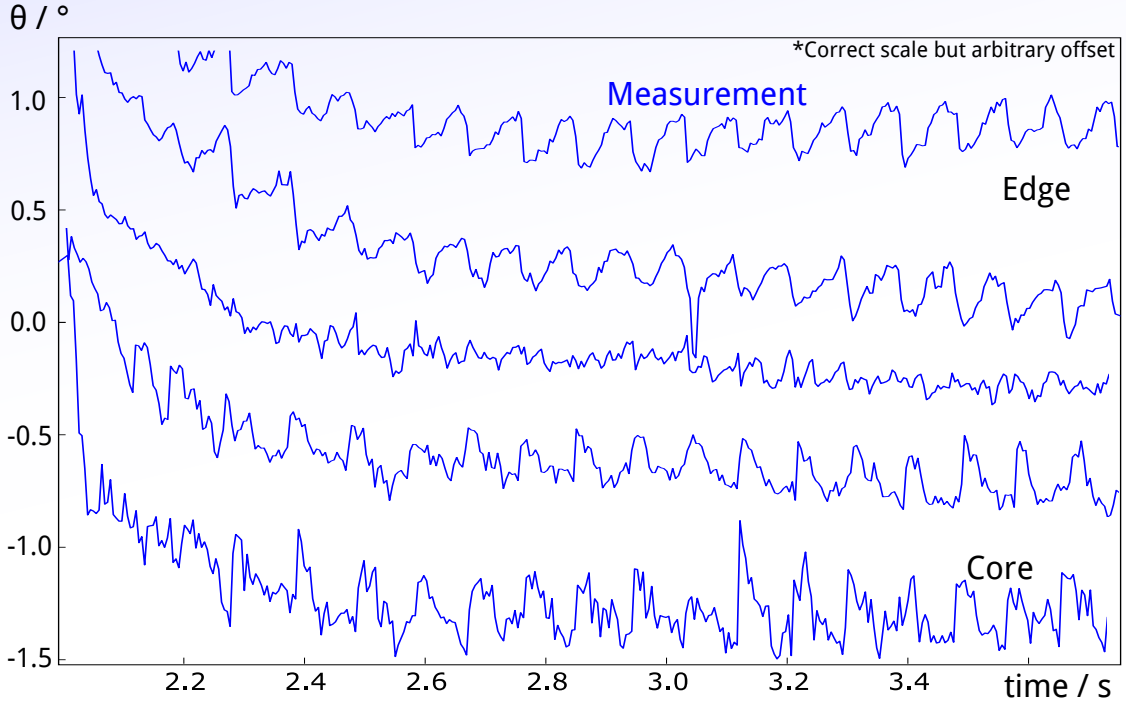
Measured sawtooth dynamics

What can we say about the Sawtooth crash?

Raw polarisation angle clearly shows the sawtooth pattern but this includes both q changes (current redistribution) and plasma movement (not interesting).



Core

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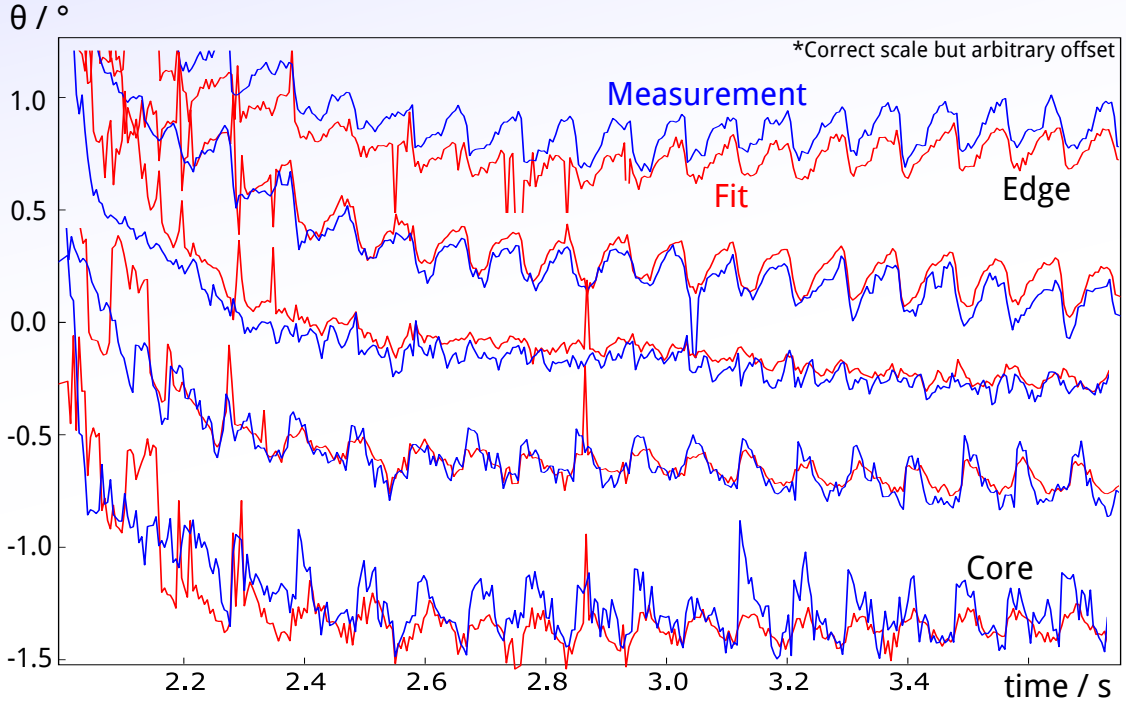

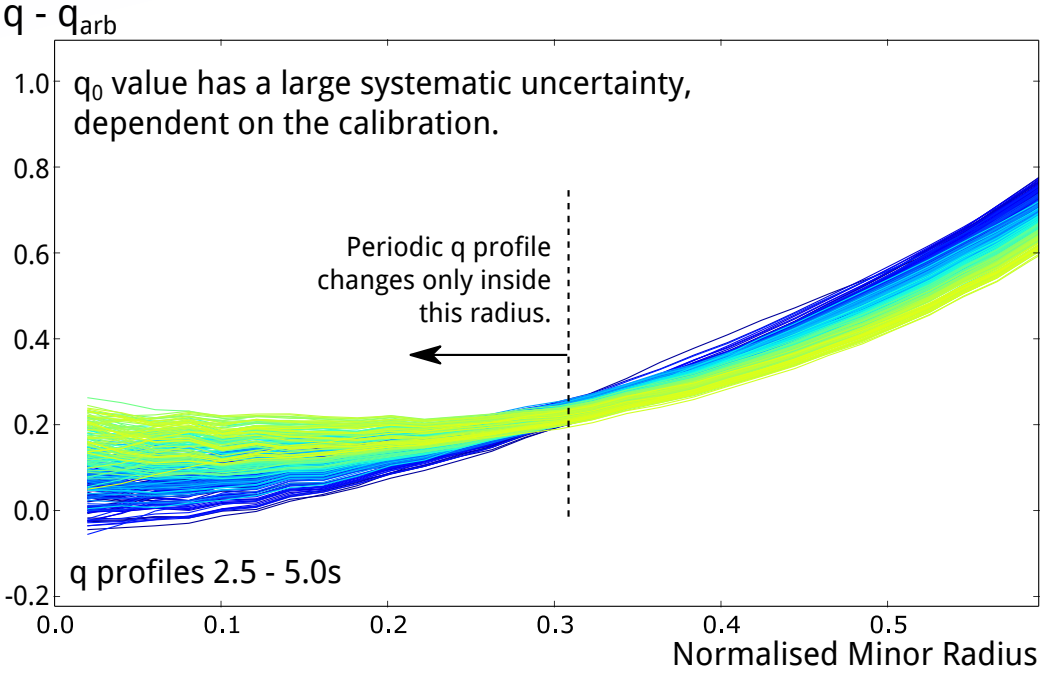

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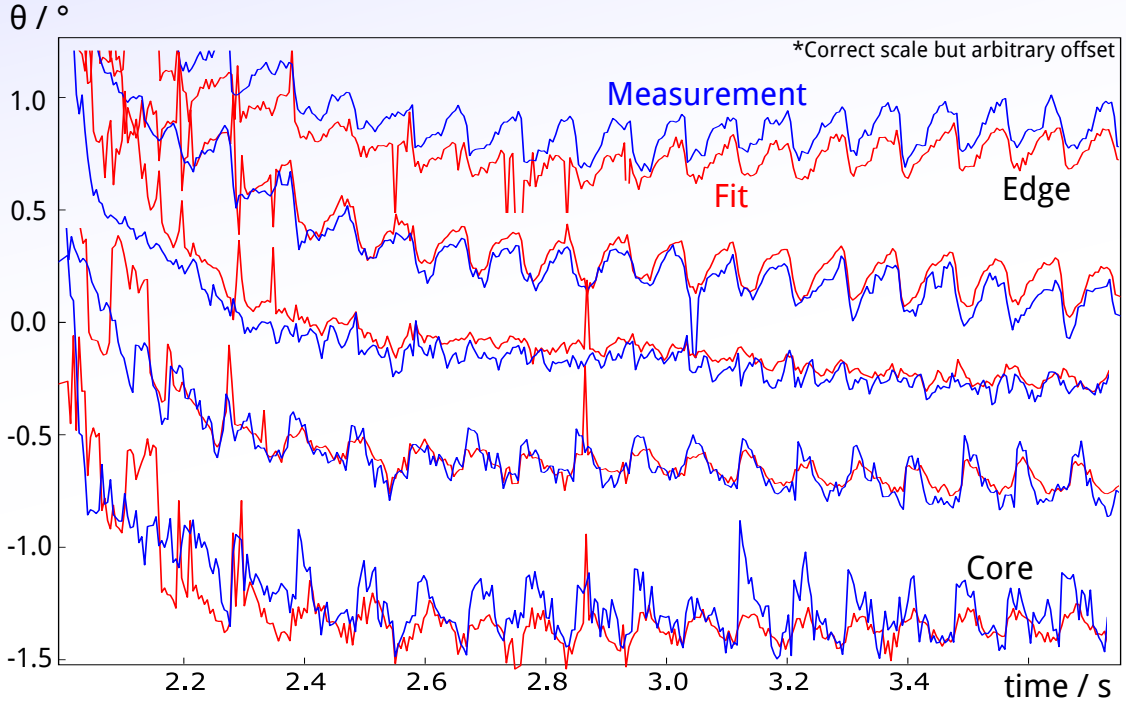

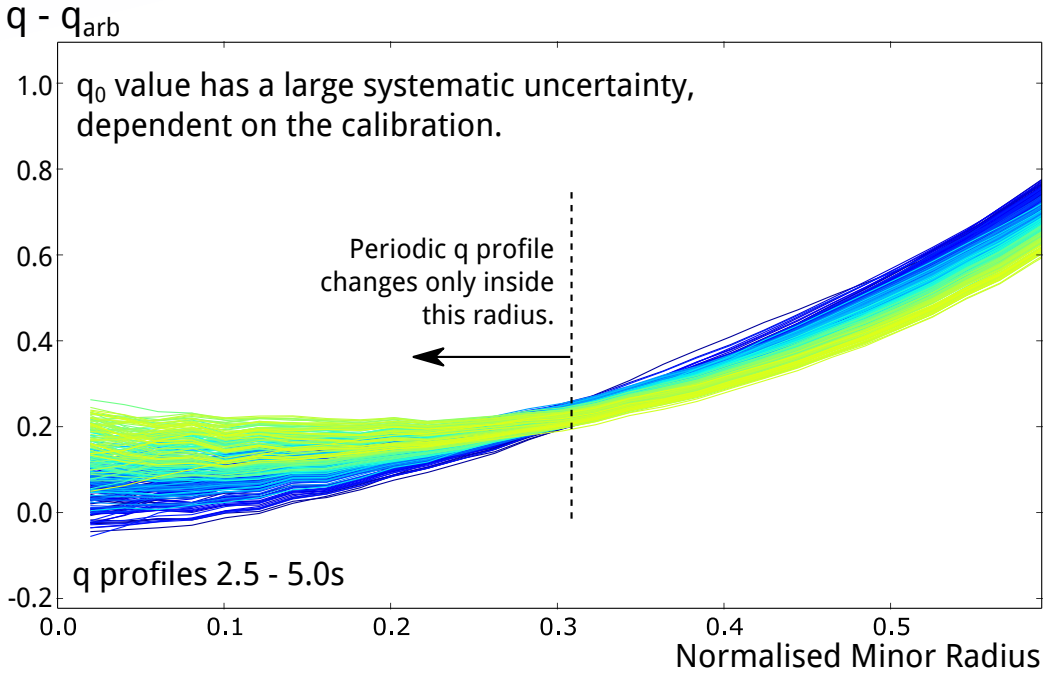

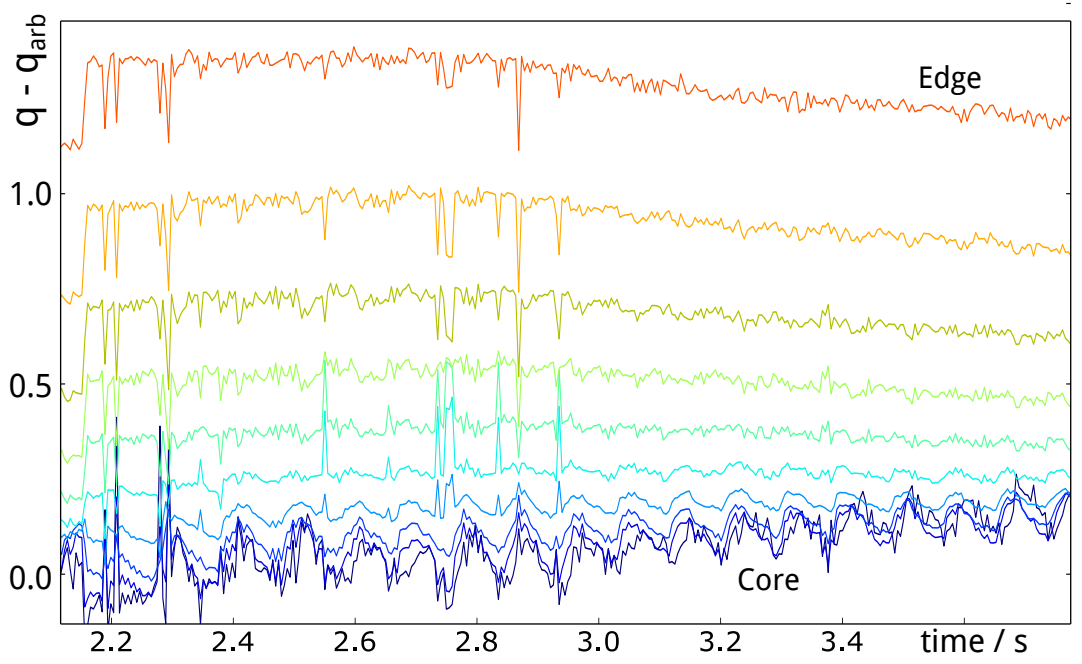

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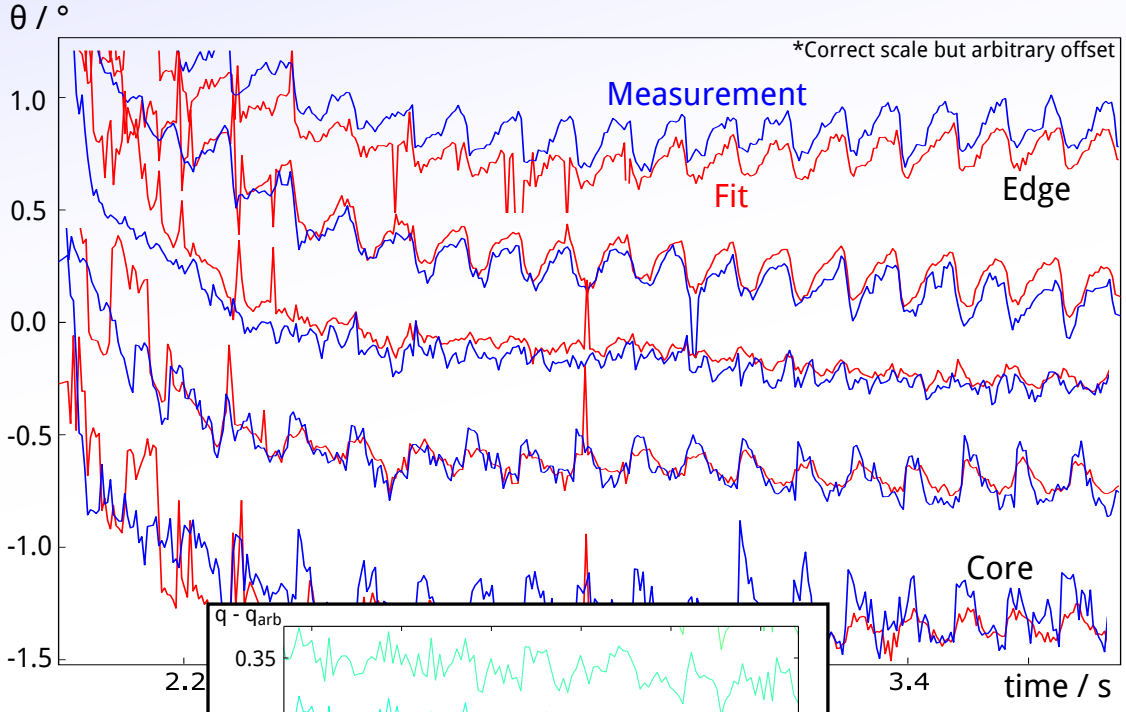

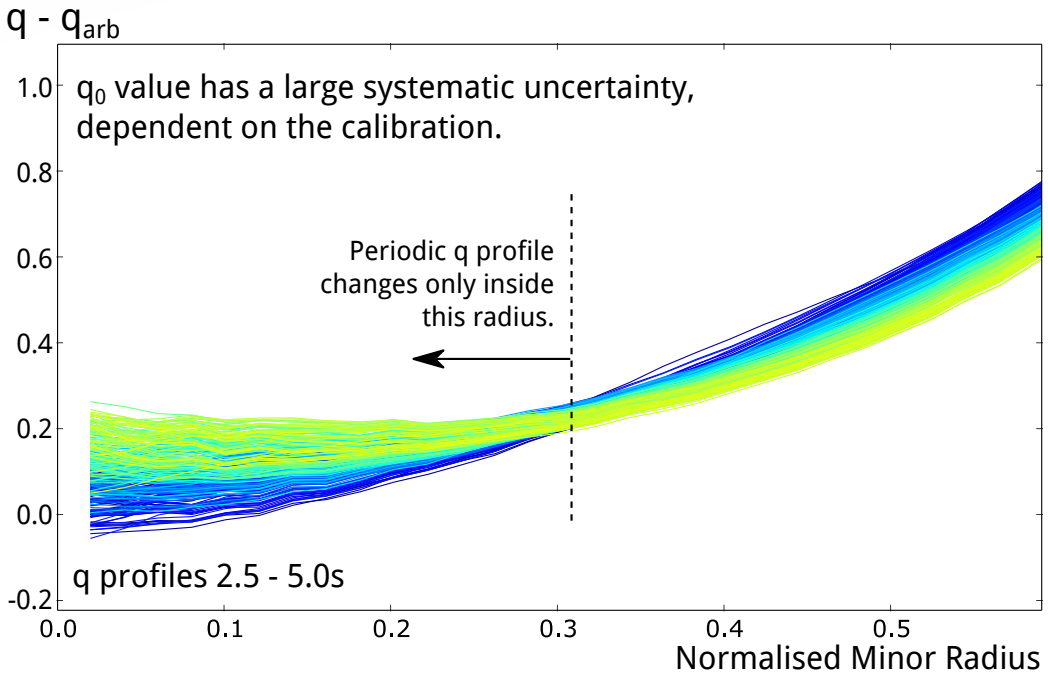

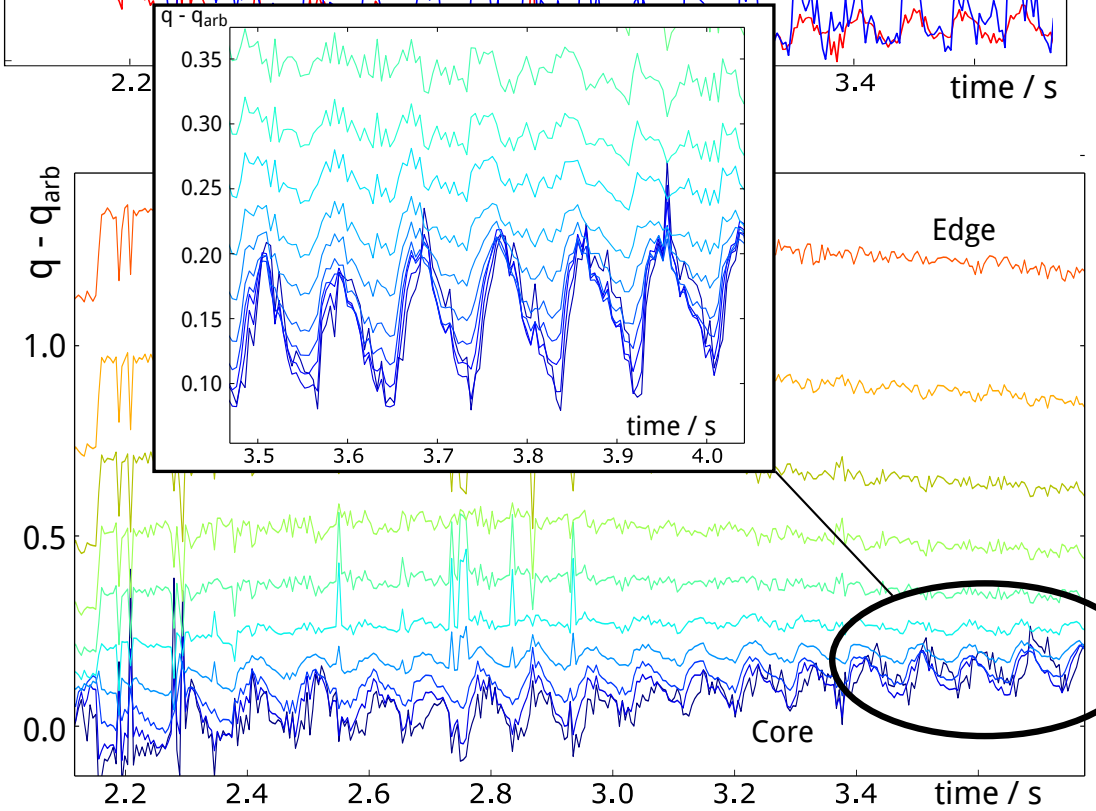

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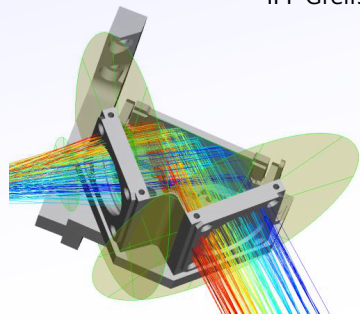
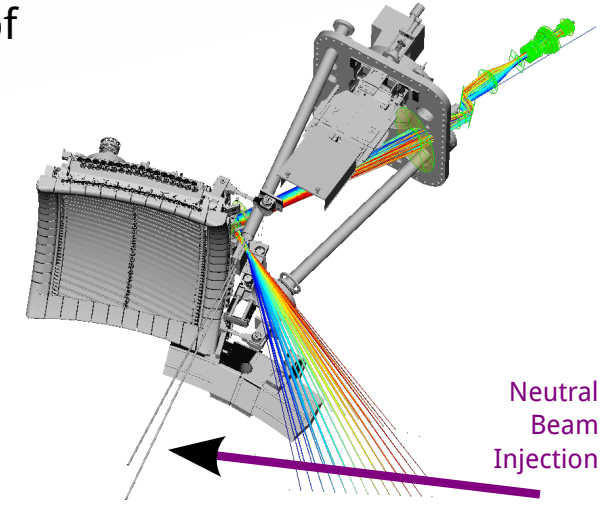
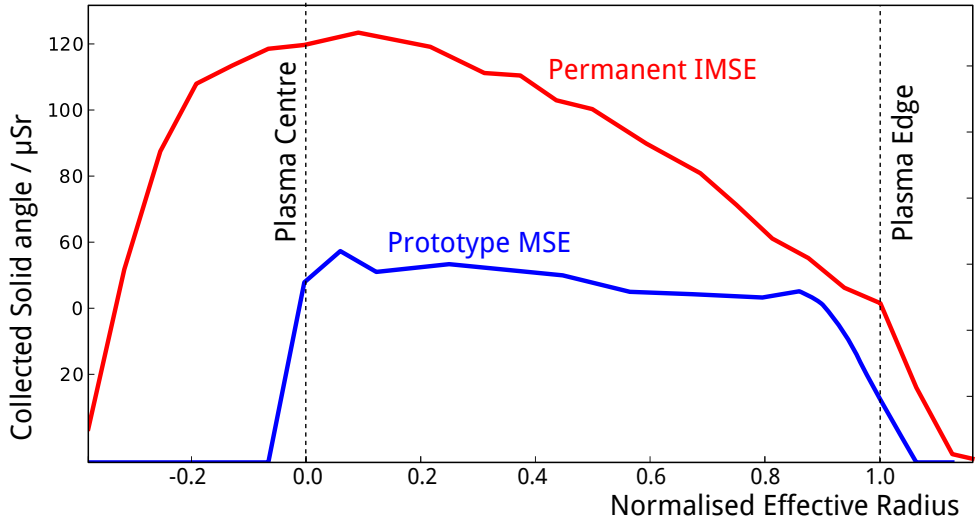
Permanent IMSE - 2015+

Given the promising results of the prototype, we are installing a permanent IMSE system on ASDEX Upgrade in May/June 2015 (Eurofusion funding).



- Special highly optimised optical design using custom ray tracing software.
- 10x better performance with 100x less light delivered - significant advantage of coherence imaging systems.
- Wider field of view for best use of the large quantity of data points.
- Dedicated system with lots of improvements for calibration.





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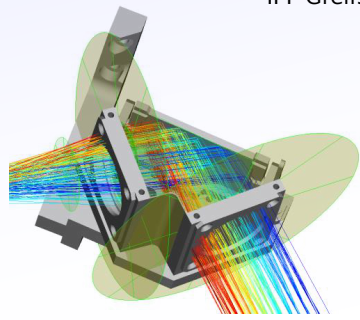

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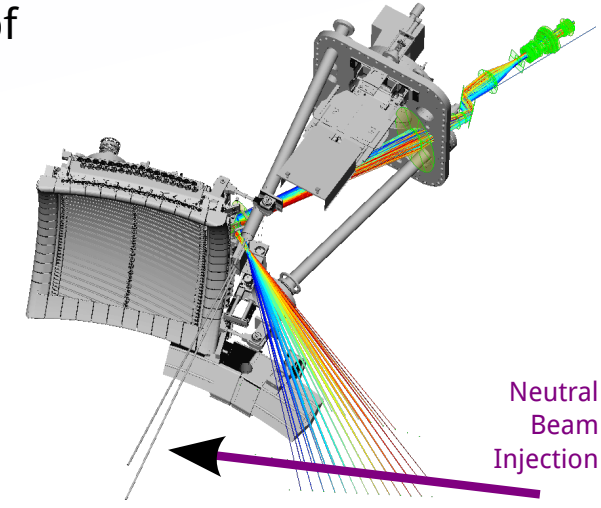
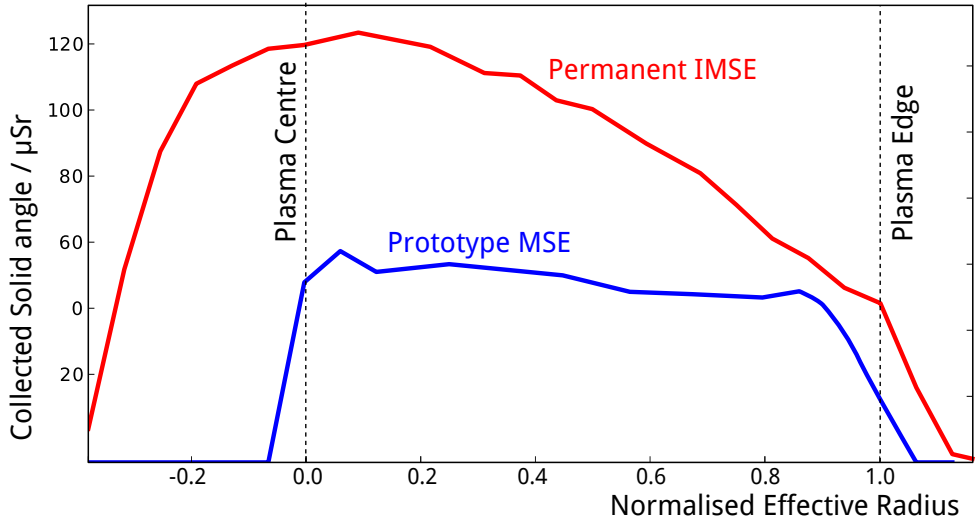


Scope for upgrade and lots of novel physics studies:

- Sawteeth
- Electric field measurements.
- Internal Modes
- Confinement and transport studies.
- Synchronous imaging.



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Future Work

ASDEX Upgrade IMSE:

Summer 2015 - Installation, calibration and performance qualification of new IMSE ASDEX Upgrade.
+ Analysis and publication of prototype results, sawteeth results, analysis technique.

Late 2015 - Full exploitation of new IMSE - general physics studies (possible Eurofusion MST1 funding / participation)

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2016+ - Application of synchronous imaging.

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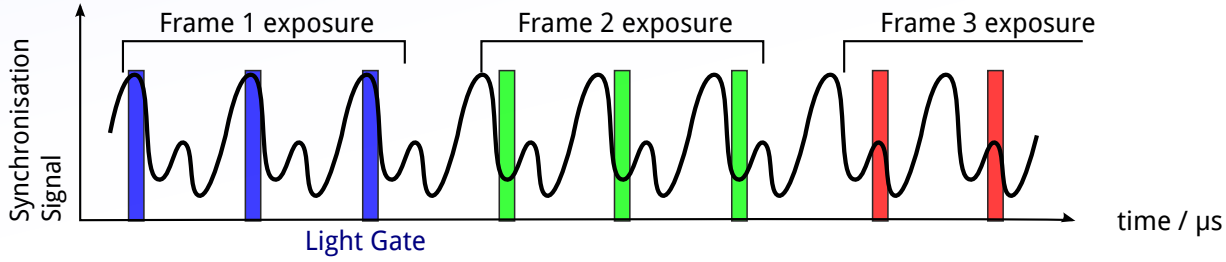

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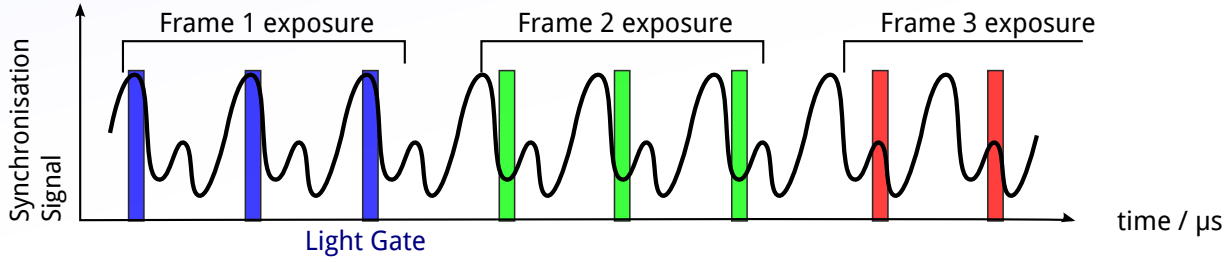


Many possible projects developing CI diagnostics for ASDEX Upgrade and Wendelstein 7X:

Doppler CI - Edge impurity density, temperature and flow.
Thomson Scattering - Electron density and temperature.
Charge Exchange Recombination Spectroscopy - Core ion/impurity density, temperature and velocity.
Zeeman Polarisation Imaging - Magnetic field vector and/or magnitude.
IMSE for Wendelstein 7X - Application to Stellarator requires special investigation.

Oliver Ford
IPP Greifswald

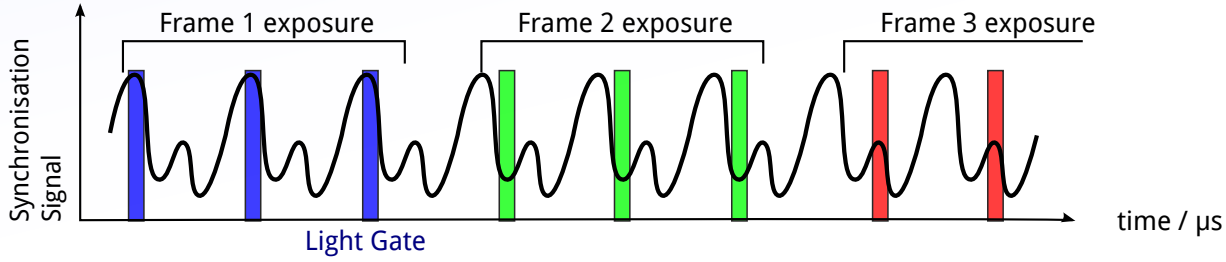
Future Work

ASDEX Upgrade IMSE:

Summer 2015 - Installation, calibration and performance qualification of new IMSE ASDEX Upgrade.
+ Analysis and publication of prototype results, sawteeth results, analysis technique.
Late 2015 - Full exploitation of new IMSE - general physics studies (possible Eurofusion MST1 funding / participation)
2016 - Upgrade IMSE sensitivity for further investigations (Within existing Eurofusion MST2 funding)
2016+ - Application of synchronous imaging.

Synchronous Imaging:

Collect light over multiple periods of high-speed plasma oscillations or repeated experiments.



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Application to laboratory and astrophysical plasmas.

Wherever images of polarisation and/or spectral moments are desired.
Need to discuss particular cases where the extra information/sensitivity will be most productive.

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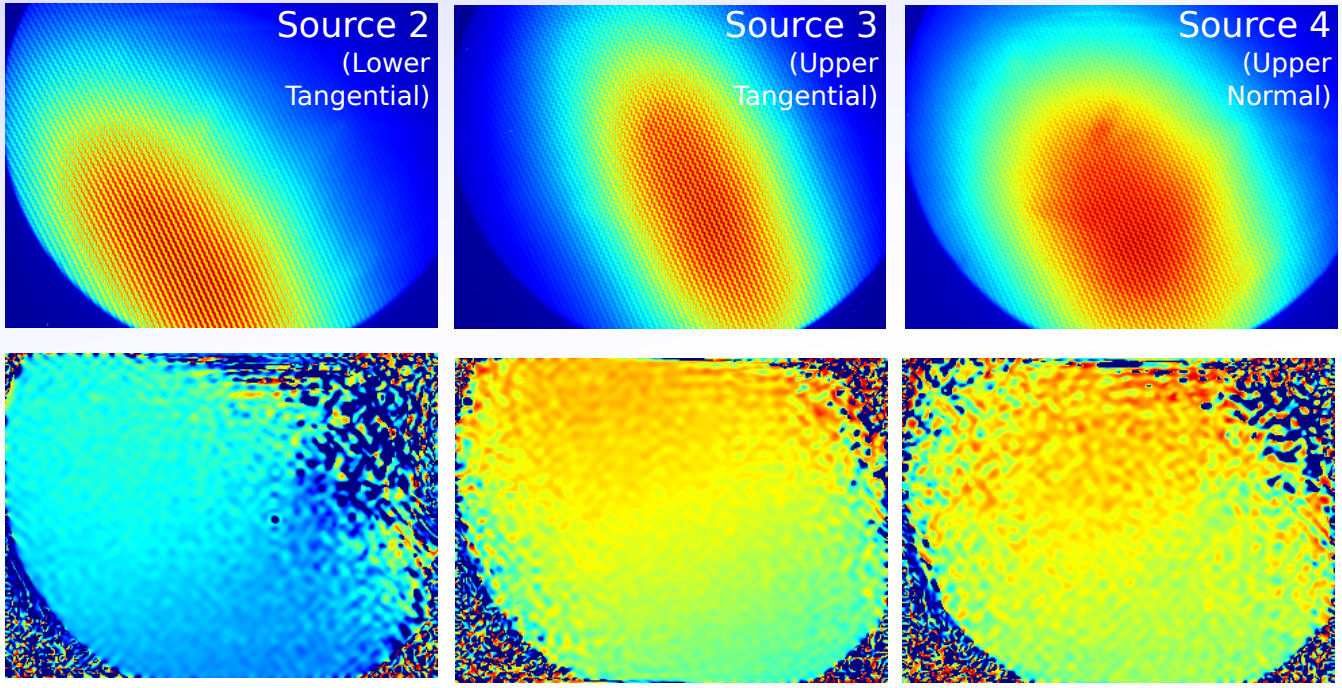
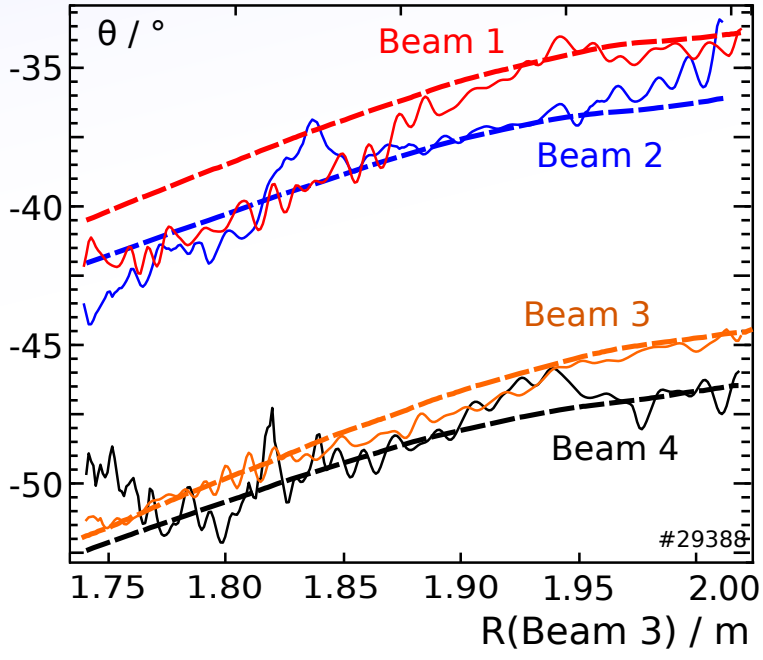
Beam Configuration Insensitivity

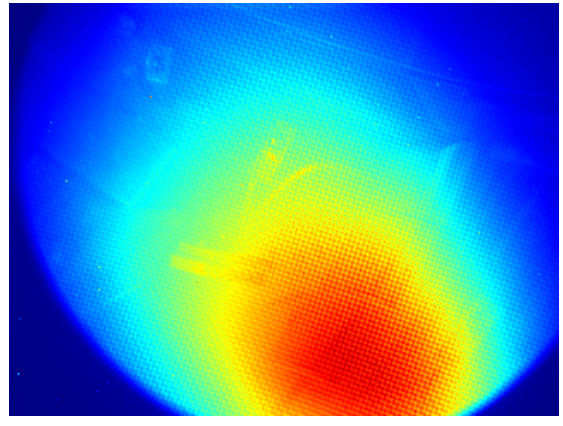
IMSE is insensitive to the spectrum so works on all 4 beam sources with both Deuterium and Hydrogen fuel:

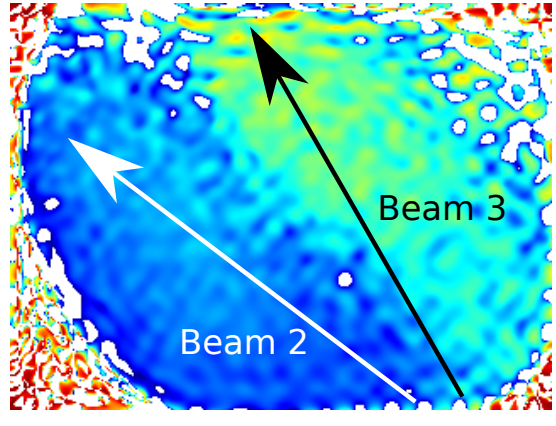




$\theta_3 - \theta_1$ is a fixed geometry value, so the agreement confirms the diagnostic linearity and beam geometry.
$\theta_3 - \theta_4$ (or $\theta_2 - \theta_1$) relate directly to Bz/Bφ and are unaffectd by fixed offset errors.

In principle, it is also possible to use data when multiple beams are on. The data is a complex average but can be analysed with the forward model if the beam geometry model is accurate.





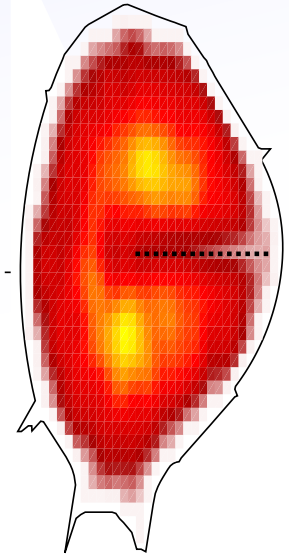
(Additional)

Motivation: Effect on Current Tomography

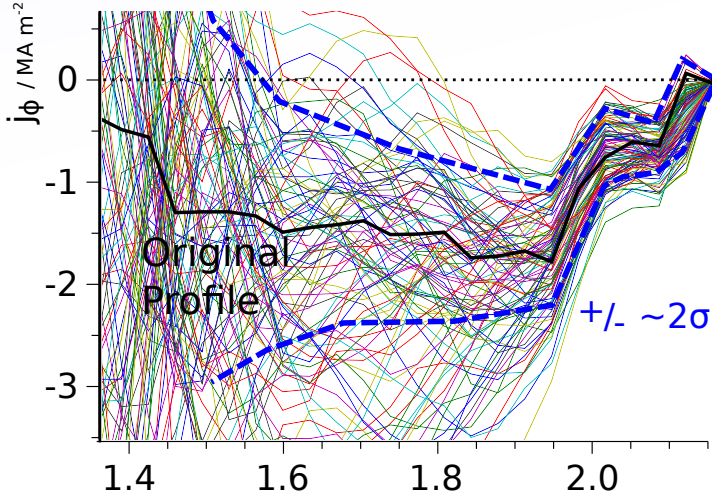
Magnetic configuration and current distribution are very important for many aspects of Tokamak physics.

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

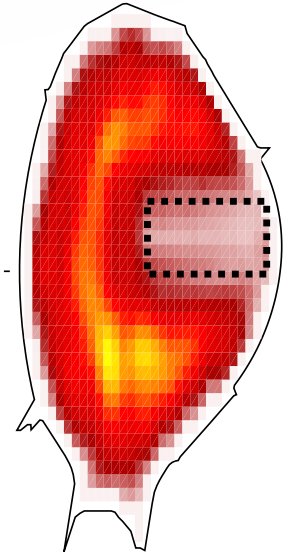
$j\phi$ Uncertainty



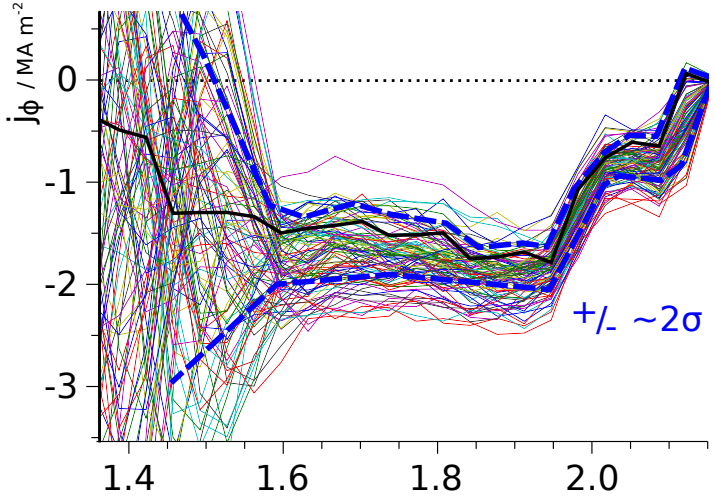
Magnetics + MSE system:
30 x *Bz* at 30 positions along NBI centre.



$j\phi$ Uncertainty



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



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

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

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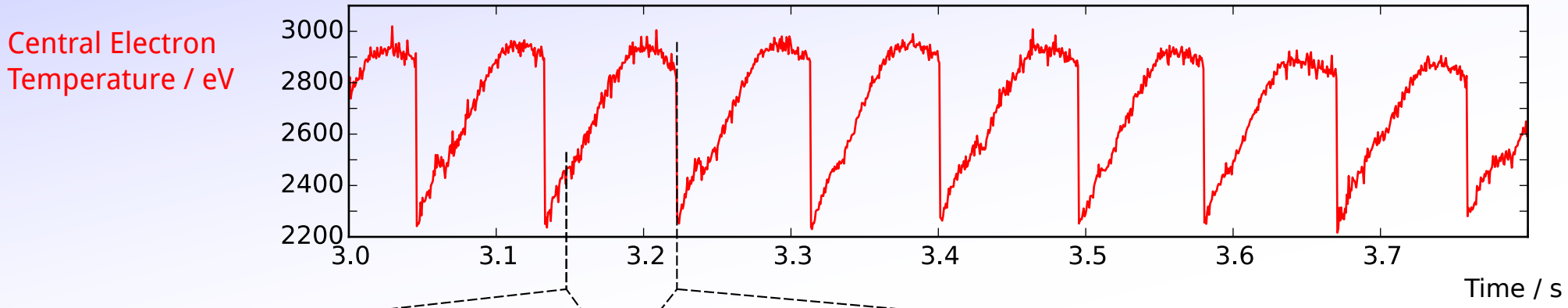
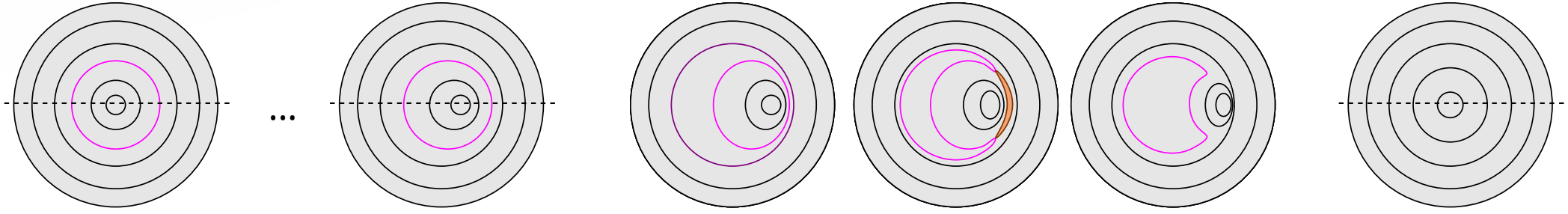
Sawteeth - Magnetic Reconnection

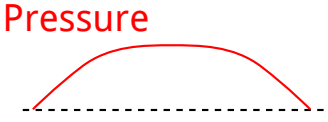


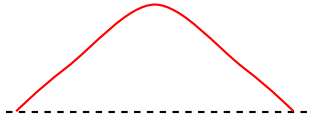
Slow build-up of pressure and current.

Fast magnetic reconnection event redistributes energy and particles outside q=1 surface.

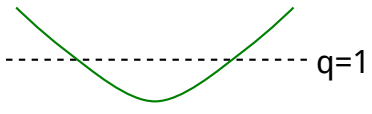
Cycle Repeats



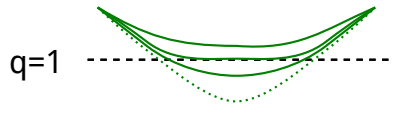




Reconnection observed is much faster than normal models allow (single-fluid MHD).



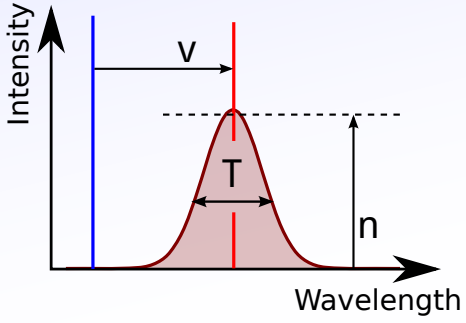
Many new models proposed, e.g. stochastic reconnection. Central question is always:
Does q_0 return to 1?



Fusion Diagnostics

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

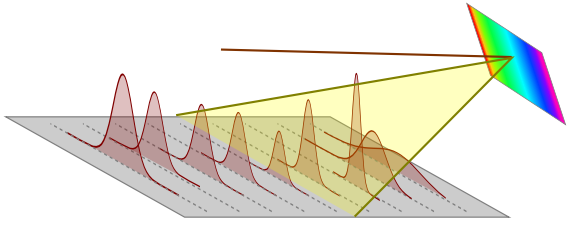
Doppler Spectroscopy: Observe atomic line emission from neutral hydrogen, impurities or laser light scattered by plasma particles.



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

Typical spectroscopy diagnostics:

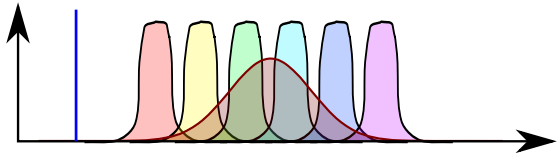
Diffraction grating and CCD camera, or individual detectors (PMTs/APDs)



Low light levels. 1D set of points.

or

Individual spectral filters and fast sensitive detectors.



Very complex setup per channel.
Low spectral resolution.

Techniques shared with plasma diagnostics from e.g. astrophysics