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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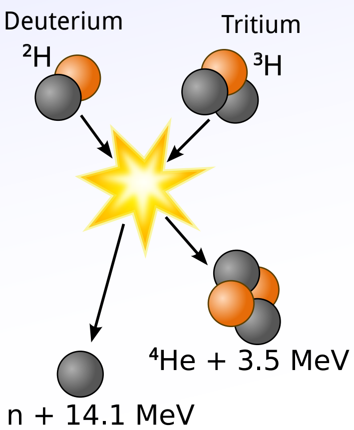
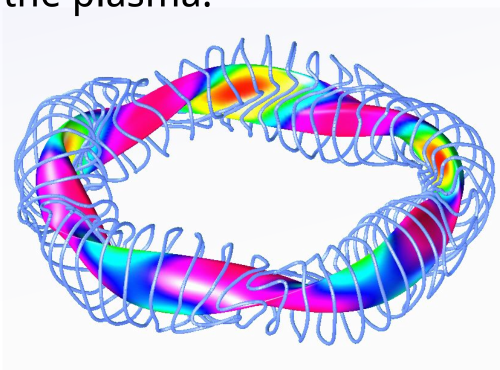
Magnetic Confinement Fusion

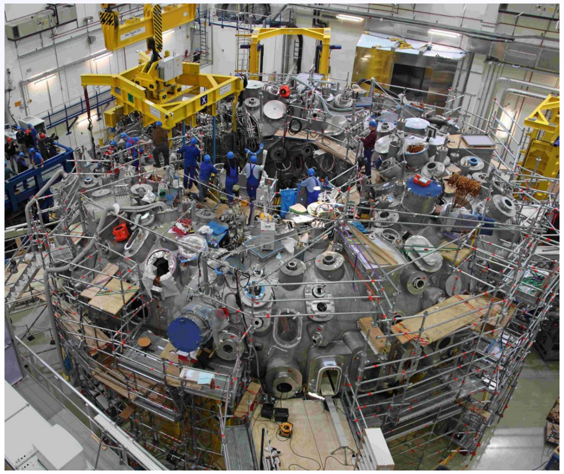
For controlled nuclear fusion, we need to confine a Deuterium/Tritium plasma for long enough and at high enough temperature to cause enough fusion reactions by thermal collisions.

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



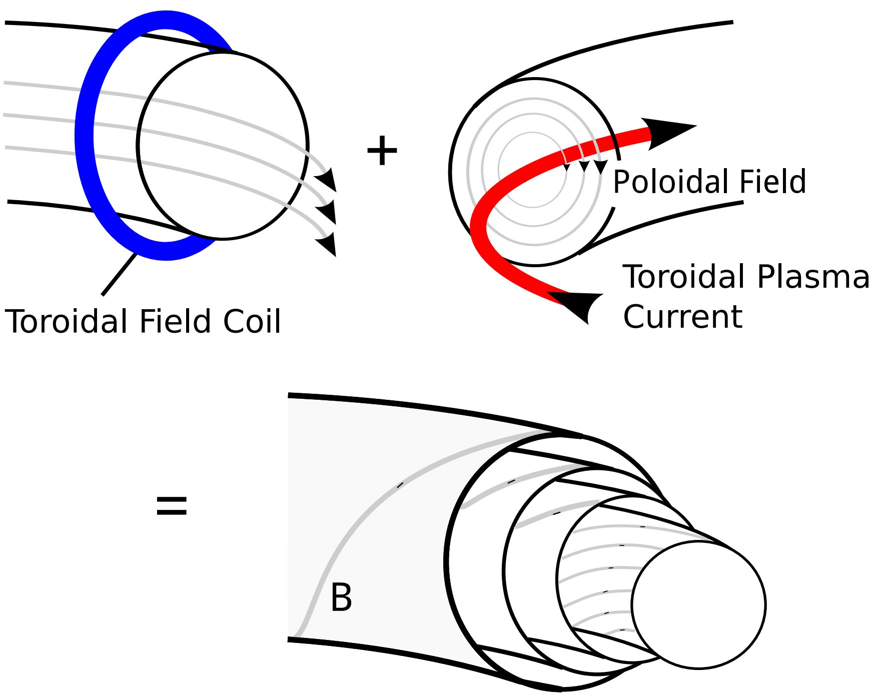
1) Stellarator:
External coils are complex twisted shapes to twist the plasma.

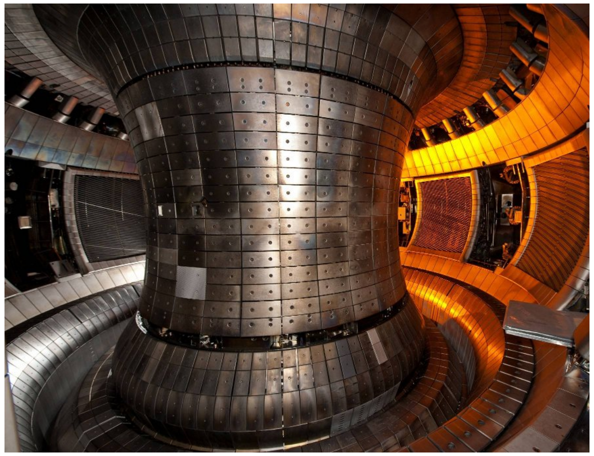




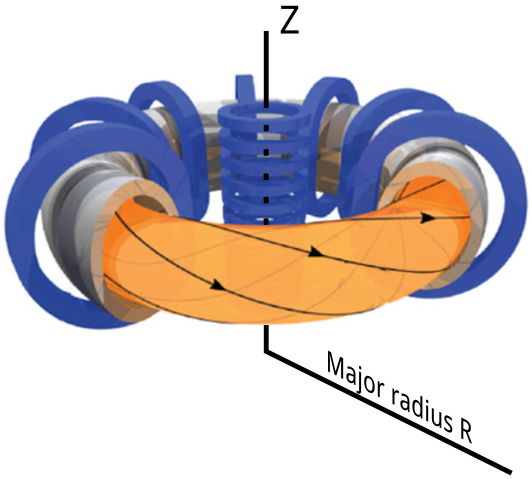
Wendelstein-7X (IPP Greifswald)

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

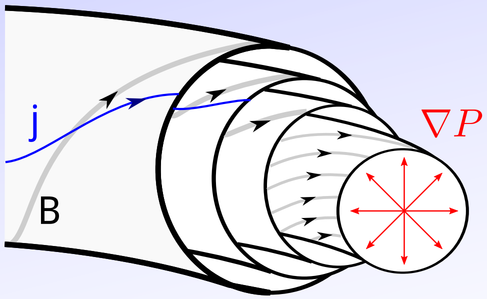




ASDEX Upgrade (IPP Garching)



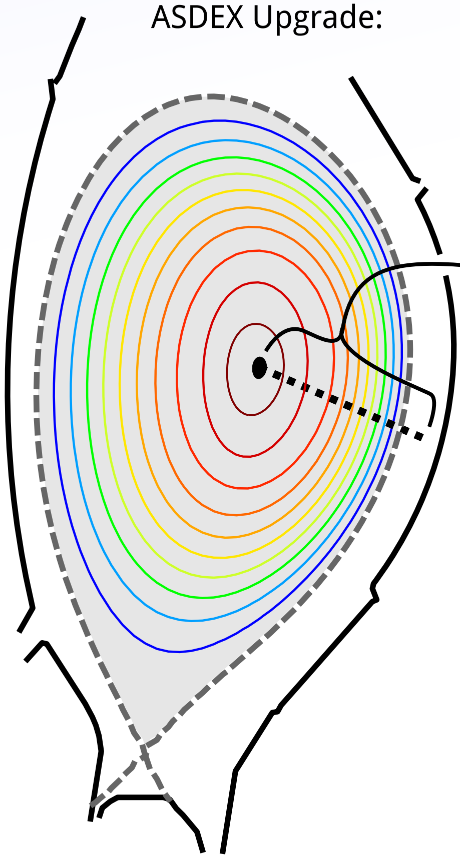
Magnetic Configuration

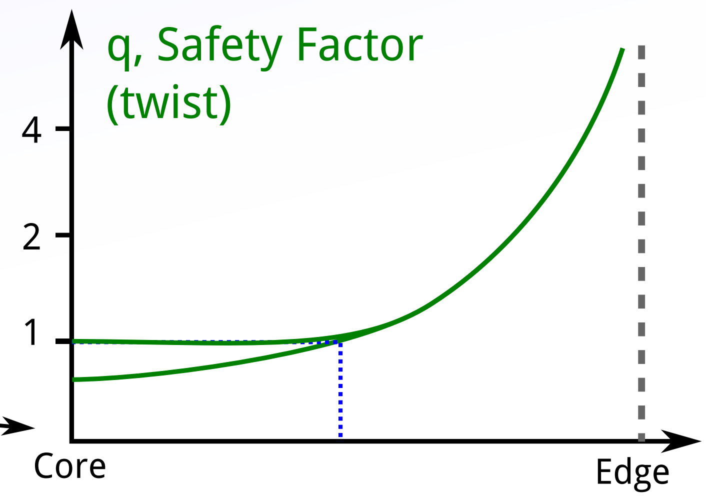


$$j \times B = \nabla P$$

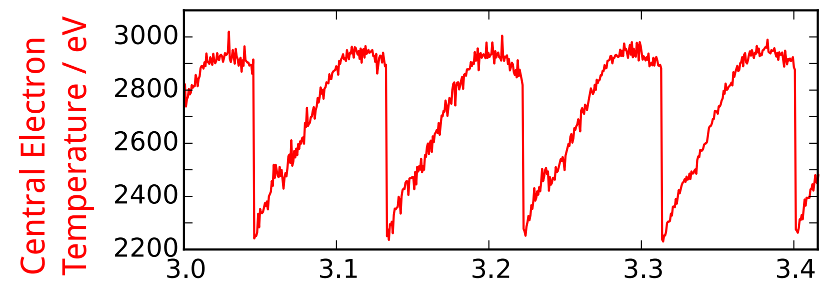
The current in the plasma is flowing through this field, and the Lorenz force must balance the pressure from the high temperature we are trying to confine, forming a stable equilibrium.

Real magnetic surfaces for ASDEX Upgrade:





The twist of the surfaces is important for the stability, and we call it the 'safety factor' q.



When the central q value falls below 1.0, the plasma core periodically suddenly expels particles and energy - shown as a 'sawtooth' crash. The crash is a magnetic reconnection event, which occurs far more rapidly than explained by simple theoretical models.

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

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

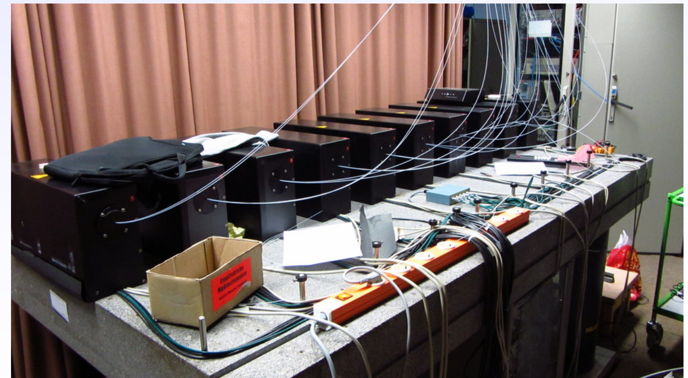
Stark/Zeeman Polarimetry

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

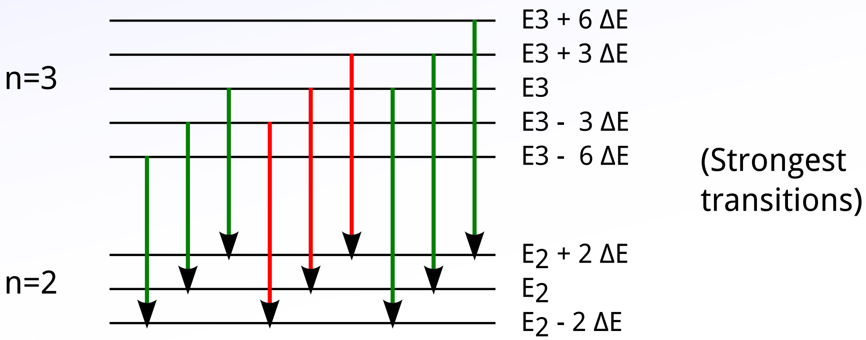
Zeeman Effect: Magnetic field.

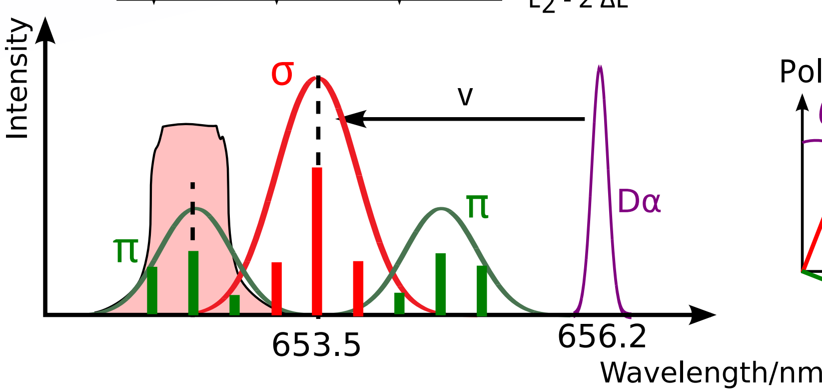
Stark Effect: Electric field.

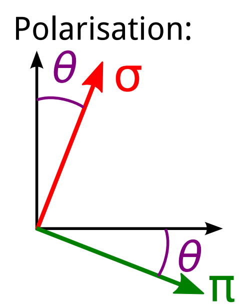
Motional Stark Effect (MSE)**:** Stark effect from Lorentz transformed **E** = **v** x **B** for fast injected neutrals.

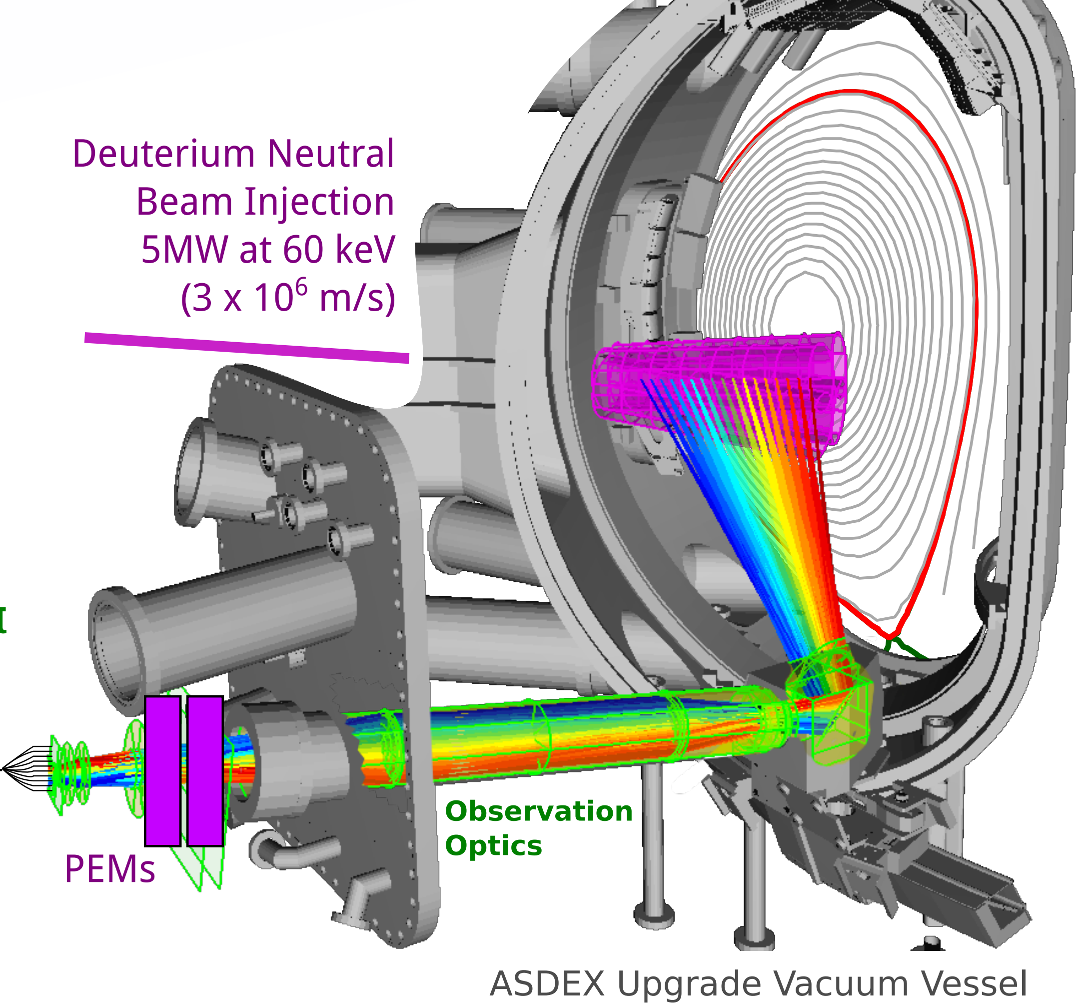


e.g: Deuterium Balmer-α (Dα):

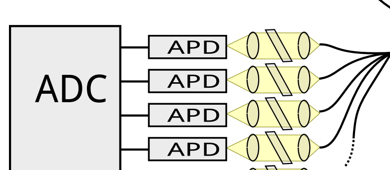






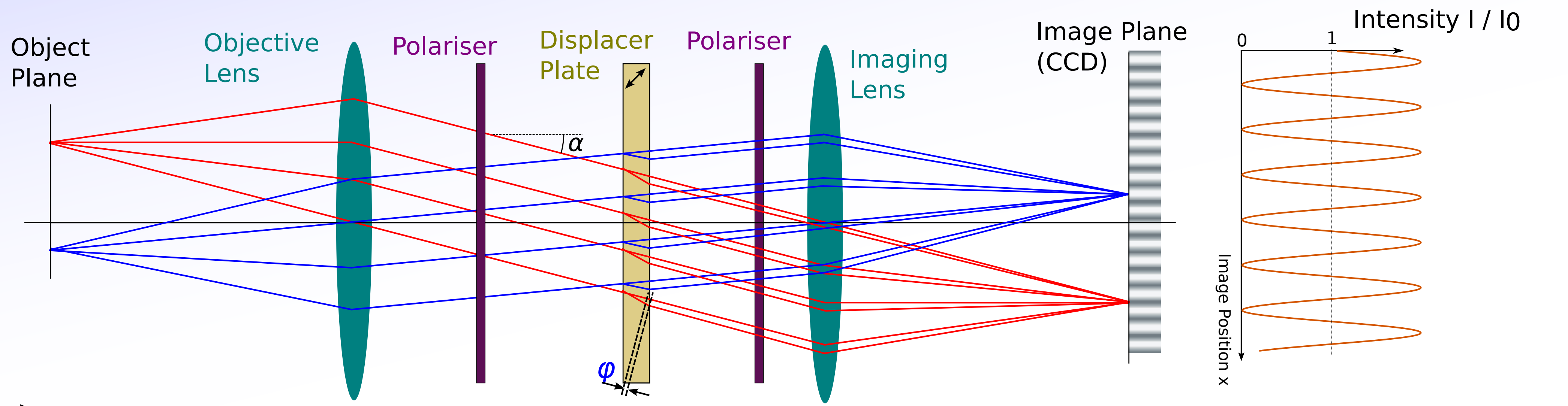


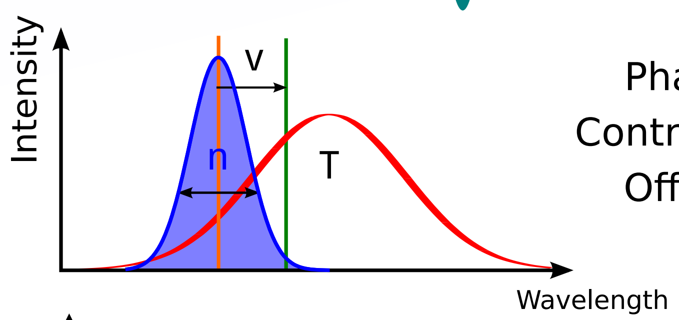
MSE is usually measured with Photo-elastic modulators (PEMs) or polarisers and individually tuned interference filters for each measurement (10 channels at AUG).



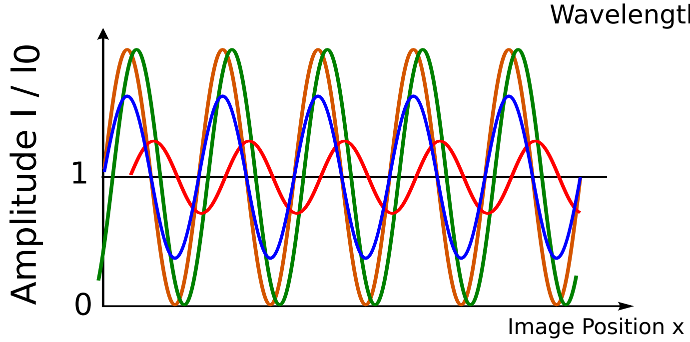
Coherence Imaging

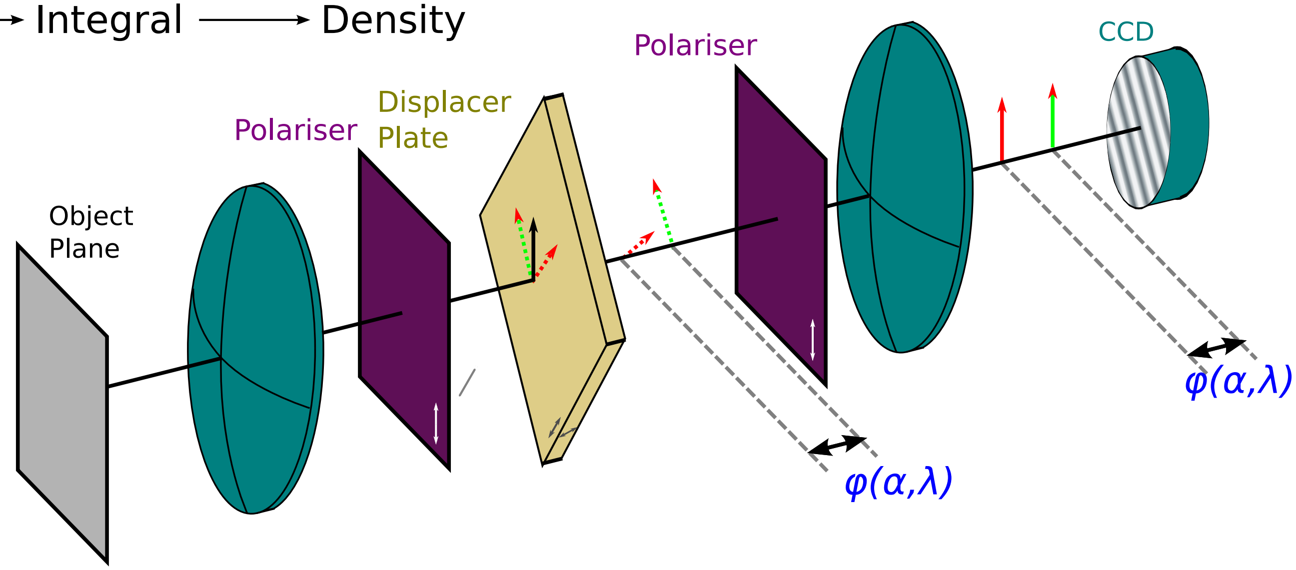
Coherence Imaging: Capture image with a CCD camera, modulated with interference pattern created by a 'Displacer plate' - Birefringent crystal with axis tilted with respect to surface.





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



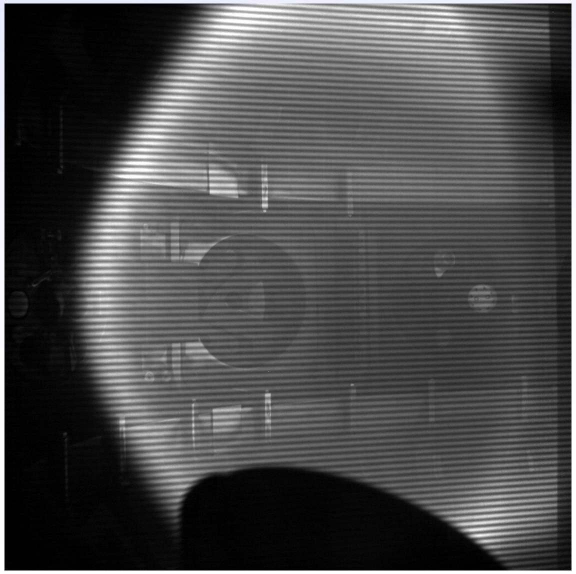


$$I \propto 1 + \zeta\, cos((\omega + \Delta\omega)x)$$

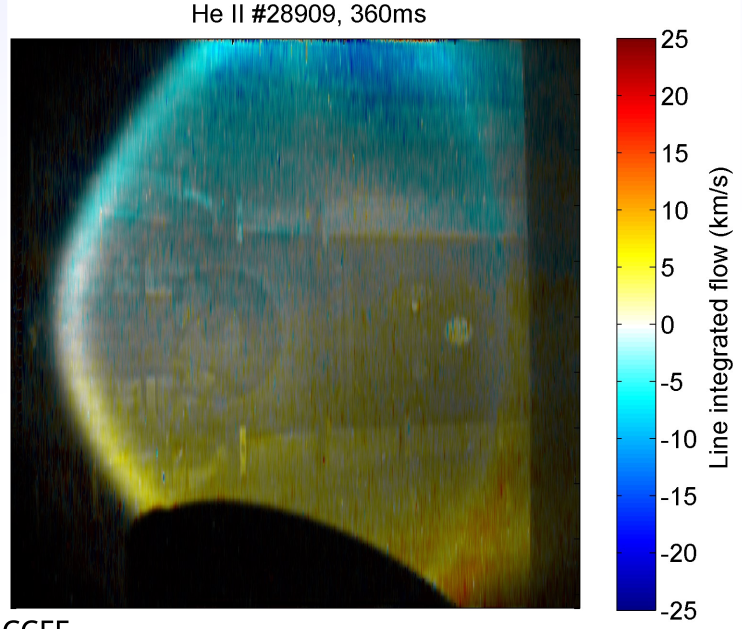
Doppler Coherence Flow Imaging

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

Raw Image:



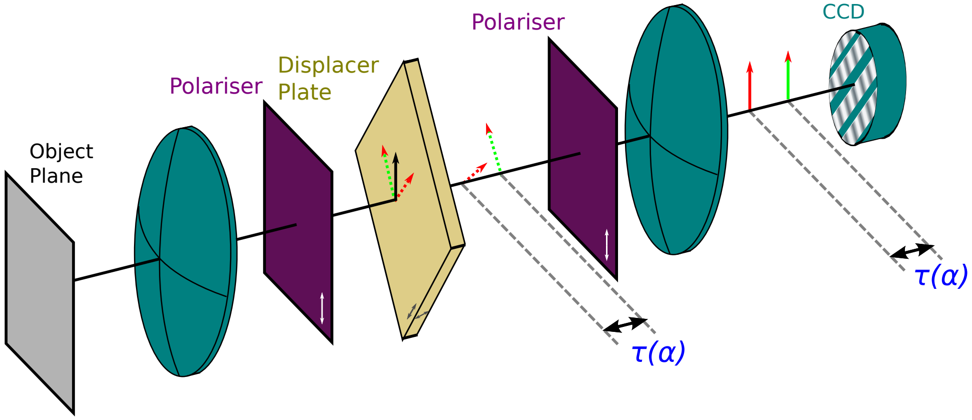
Helium Flow Velocity:



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]

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

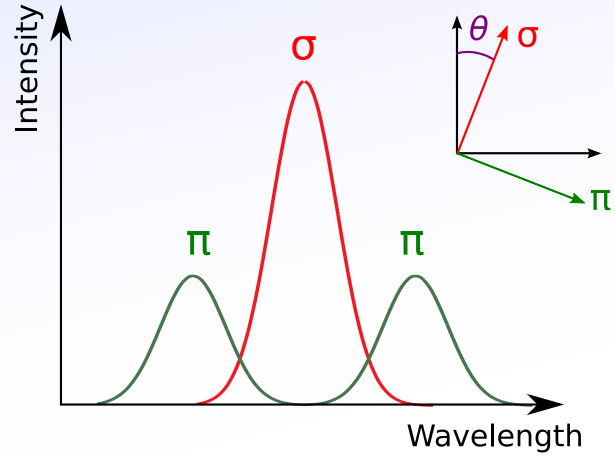


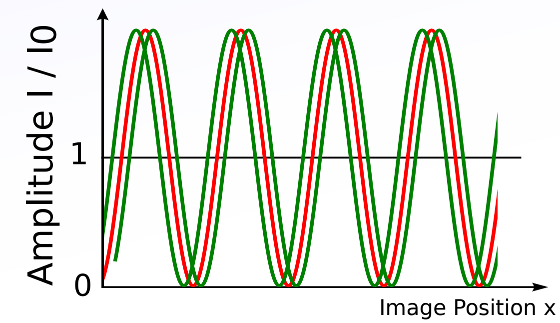
Multiplet Polarisation Coherence Imaging

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

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

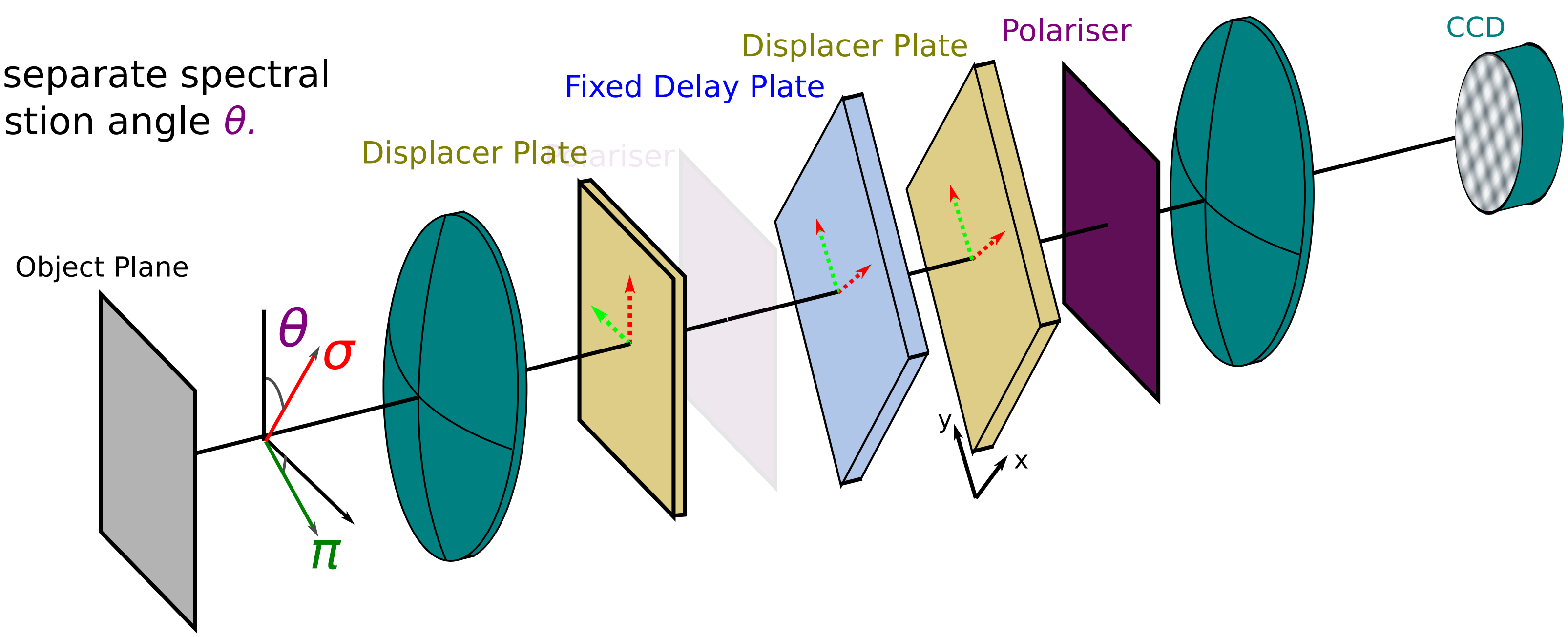
For the Stark/Zeeman spectrum, the π component is at 90° to σ, introducing a 180° phase shift, so they would cancel.





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.

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



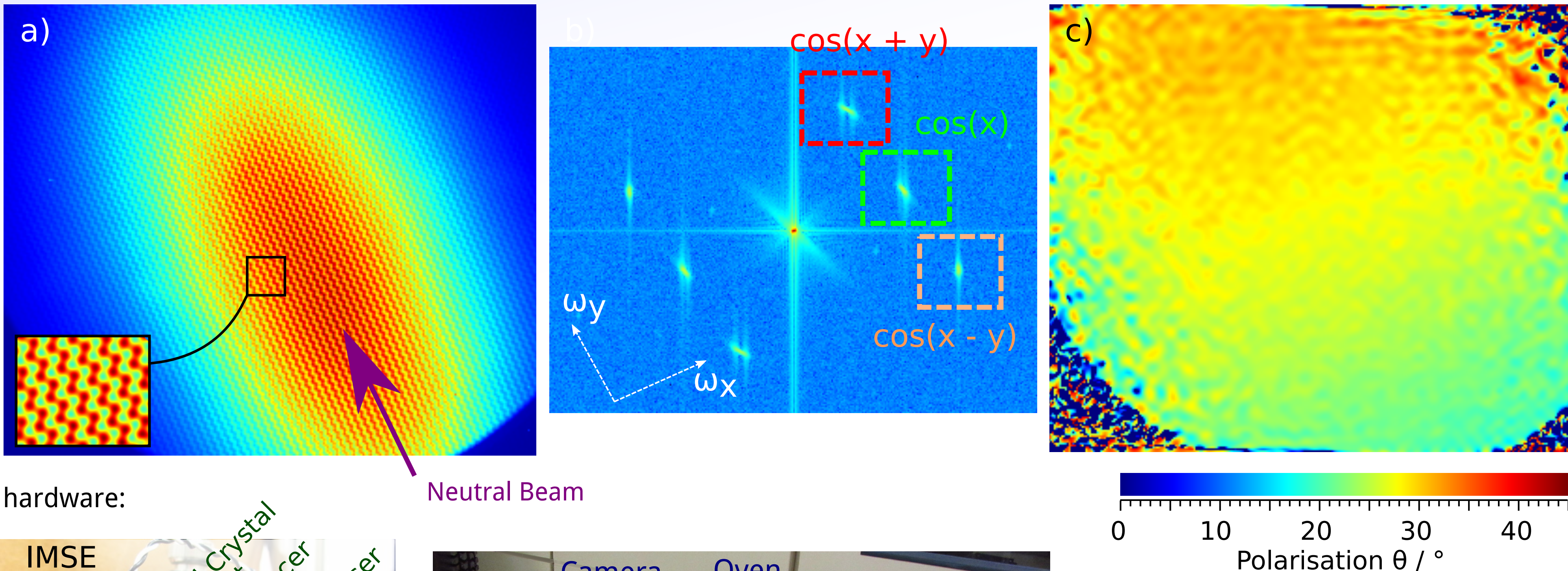
add another displacer at 45°. Combined effect adds 2 extra terms:

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

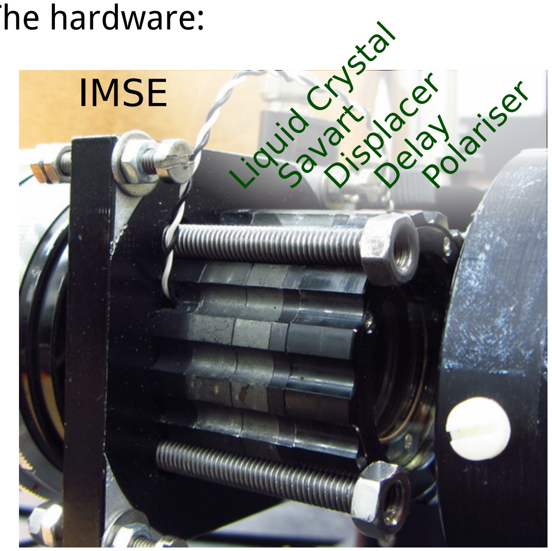
Image Demodulation

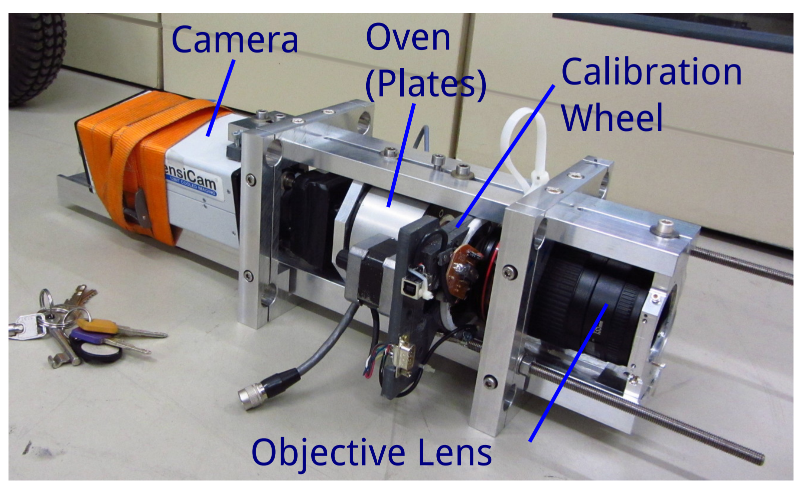
The two orthogonal interference patterns give 3 components in the Fourier transform. We can filter these from the FT and extract the polarisation angle θ:

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



The hardware:





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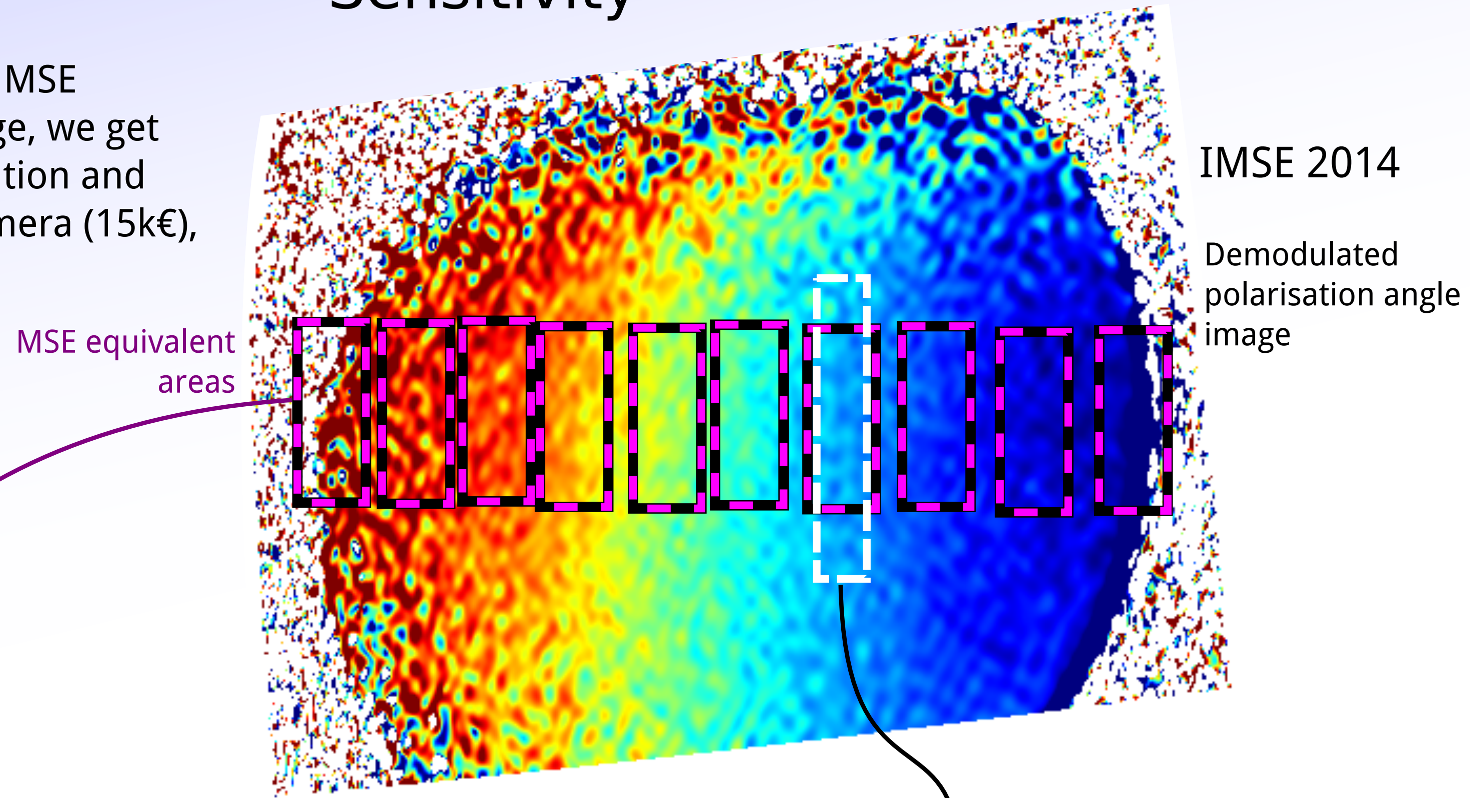
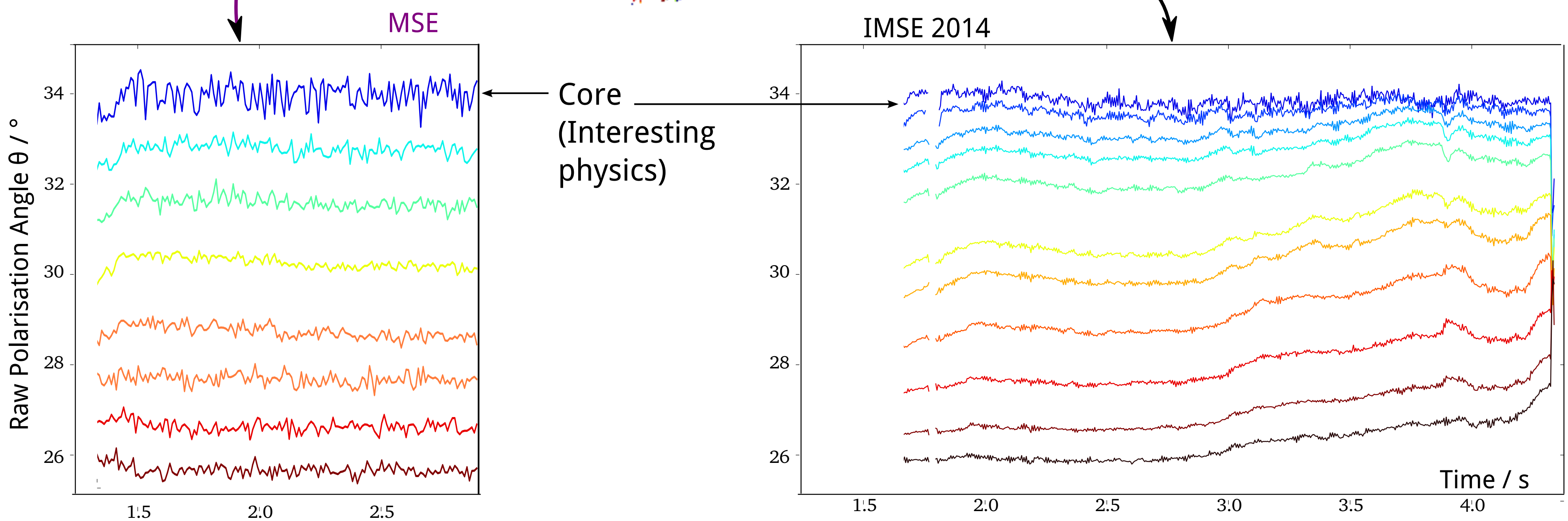
Sensitivity

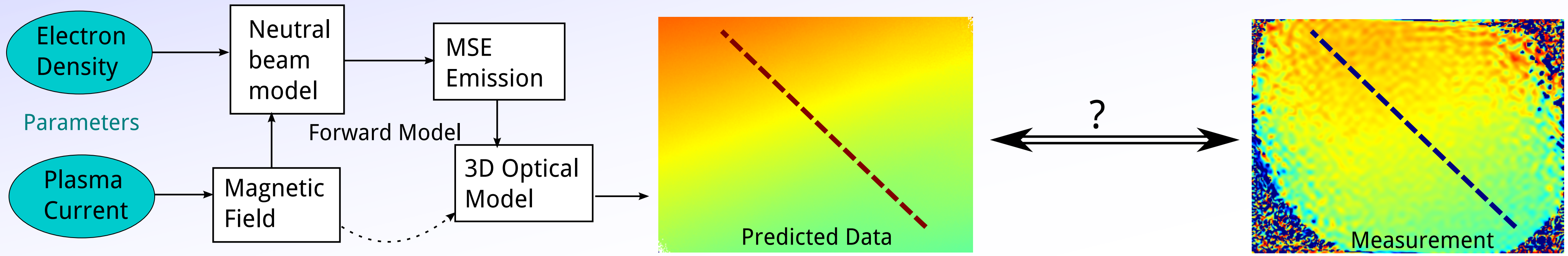
Comparing the new IMSE to the old MSE system on a similar plasma discharge, we get good agreement, higher time resolution and with a new a fast CMOS imaging camera (15k€), a much higher sensitivity.



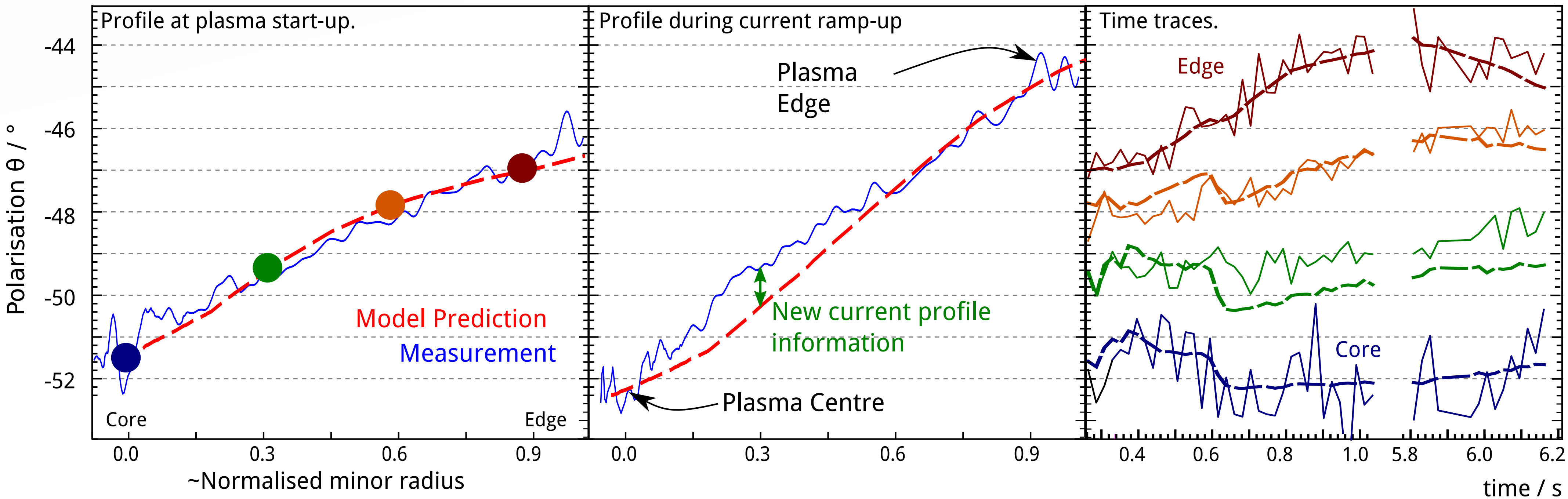


Comparison with Forward Model

First results in 2013, compared against a detailed forward-model of the diagnostic and relevant plasma physics:



Except for a 0.7° offset, the results agree with the modelling of a relatively 'predictable' plasma. The small differences is the new information that the IMSE provides:



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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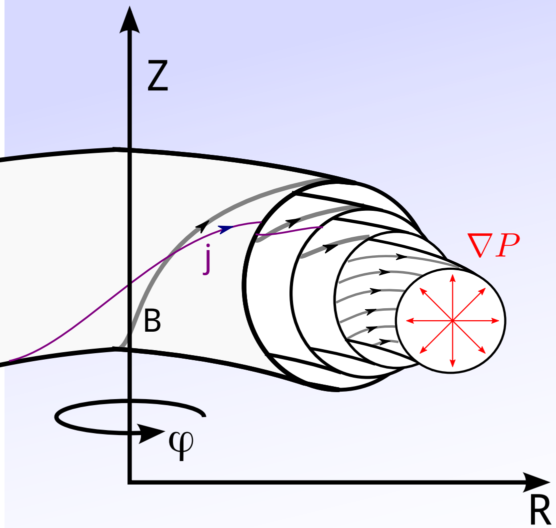
Data Analysis - Equilibrium Solutions



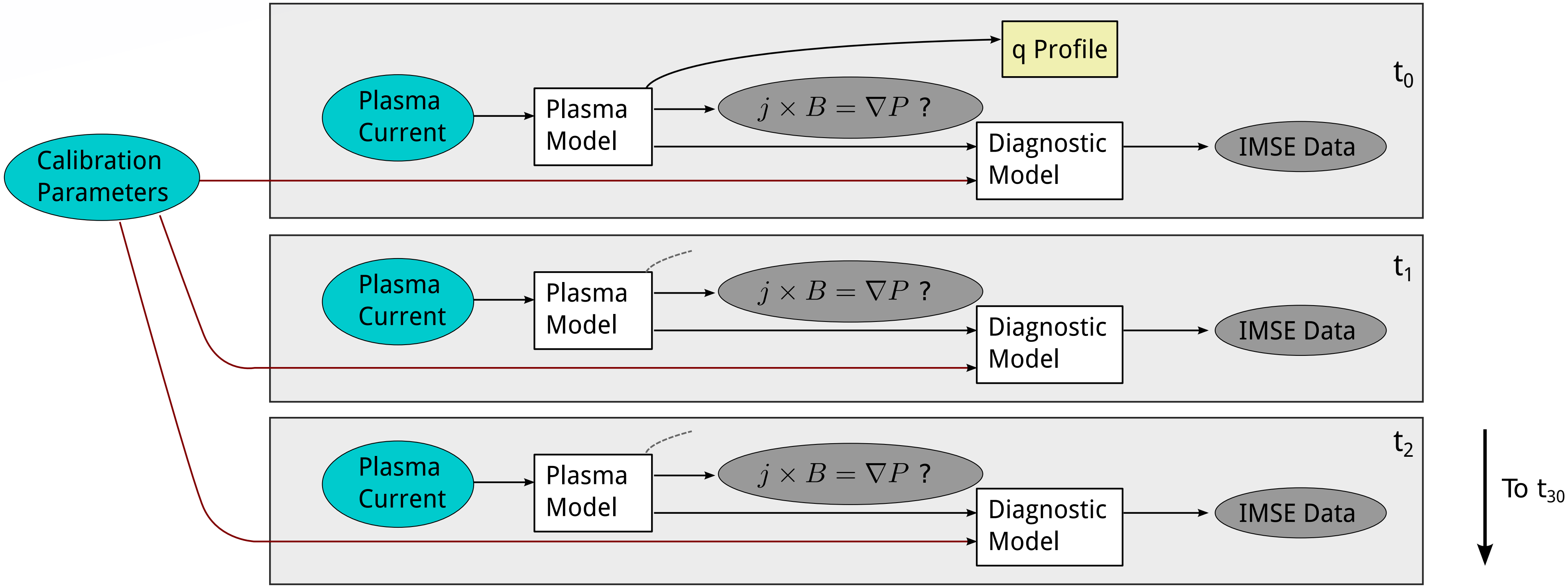
To obtain q, we need to find a solution to the plasma equilibrium that predicts the IMSE diagnostic data.

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

+ Pressure constant on magnetic surfaces
+other assumptions

Equilibrium solvers usually require an accurate calibration for diagnostics that mesure the pitch of the magnetic field - (which unfortunately we don't have yet)

The flexibility of our data analysis tools (based on Bayesian Equilibrium Analysis, PhD Work), allows us to simultaneously solve equilibria at multiple time points for the whole discharge using a common set of free calibration parameters:



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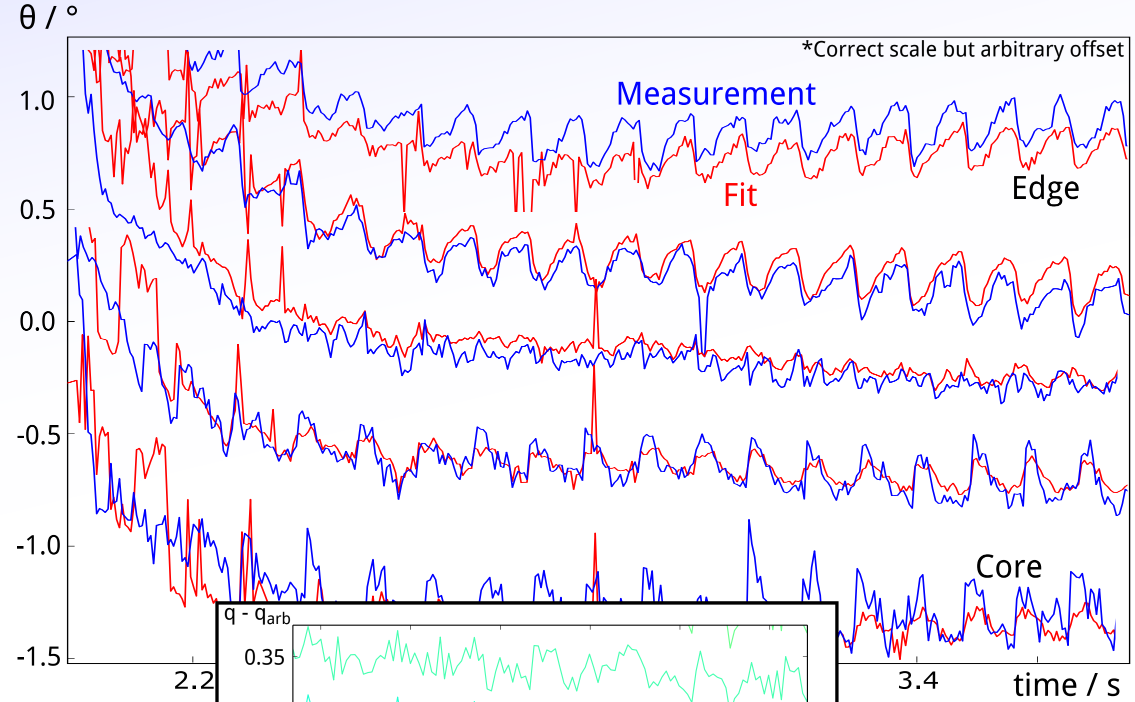
Measured sawtooth dynamics

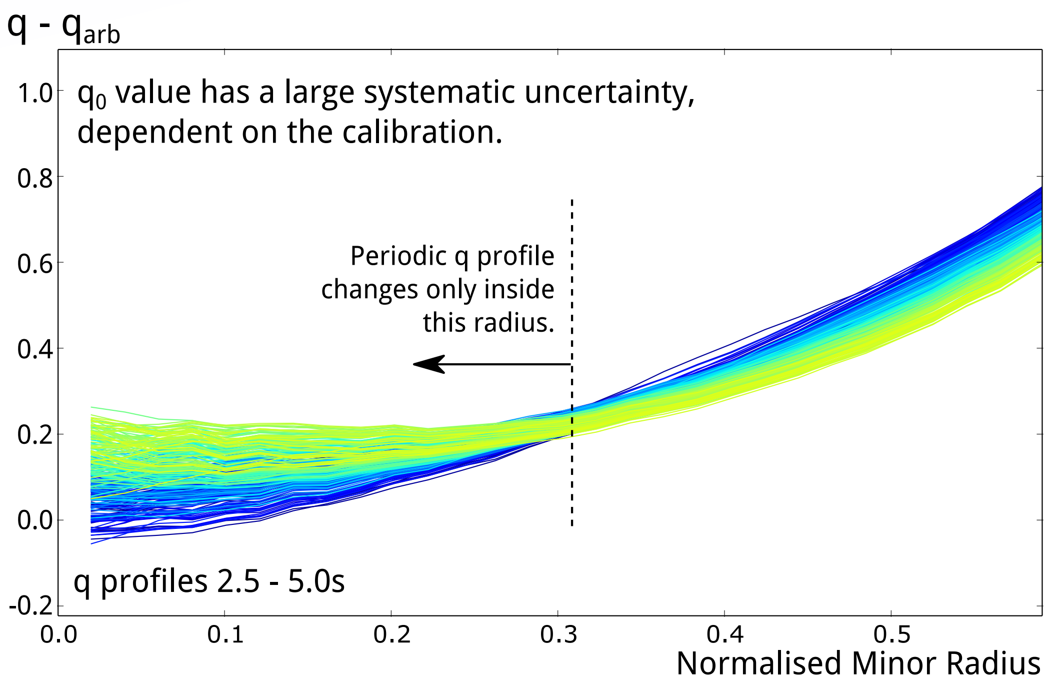
What can we say about the Sawtooth crash?

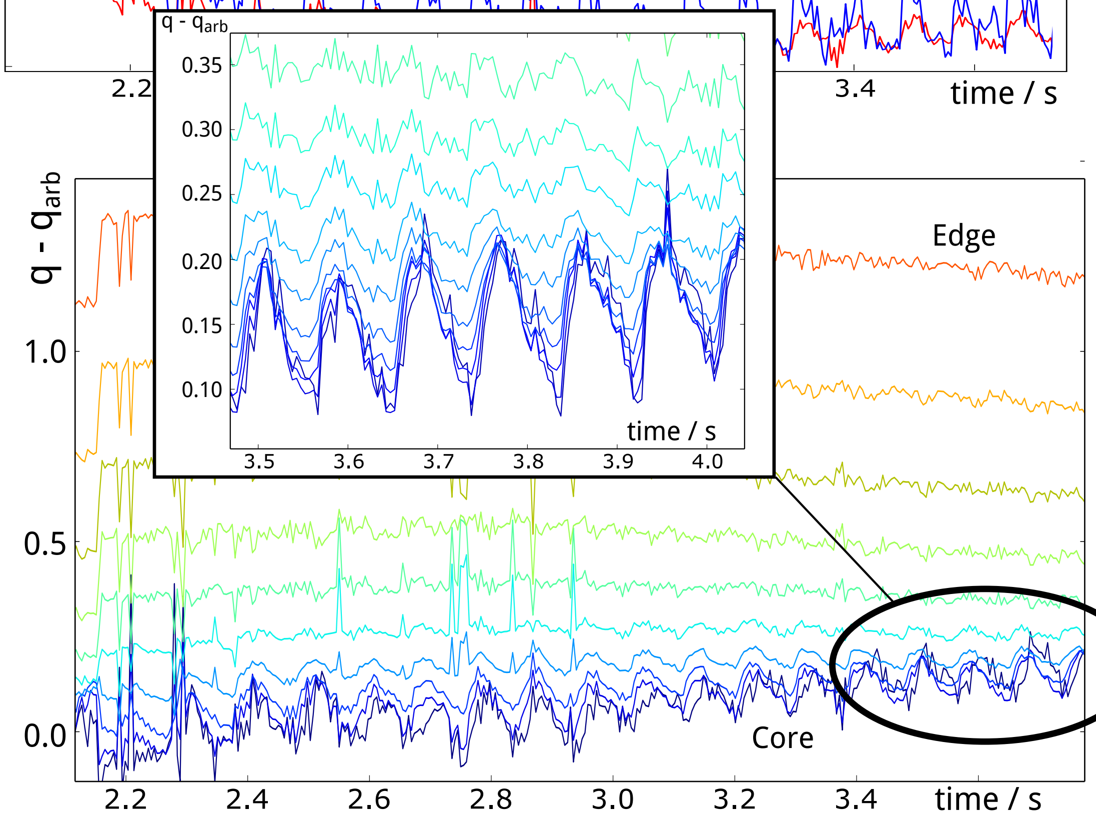
Raw polarisation angle clearly shows the sawtooth pattern but this includes both q changes (current redistribution) and plasma movement (not interesting).

- Sawtooth behaviour is clearly resolved by IMSE and behaves qualitatively as expected by most models.

- Systematic uncertainty on q_0 is still much larger than we need to answer the most important plasma physics question - will be improved!







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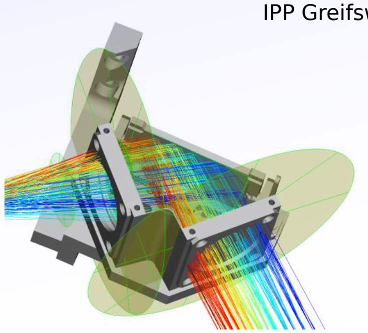
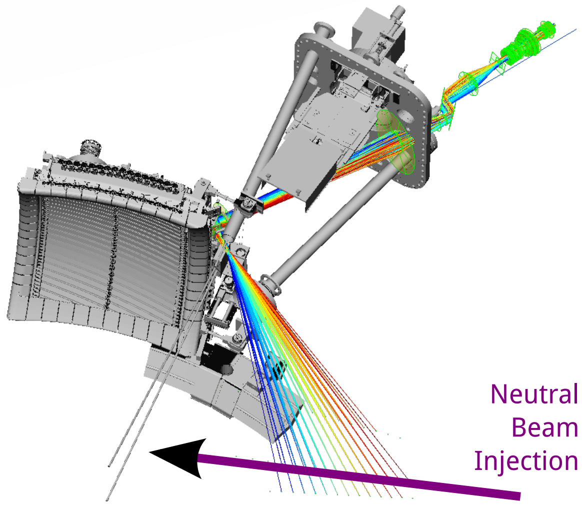
Permanent IMSE - 2015+



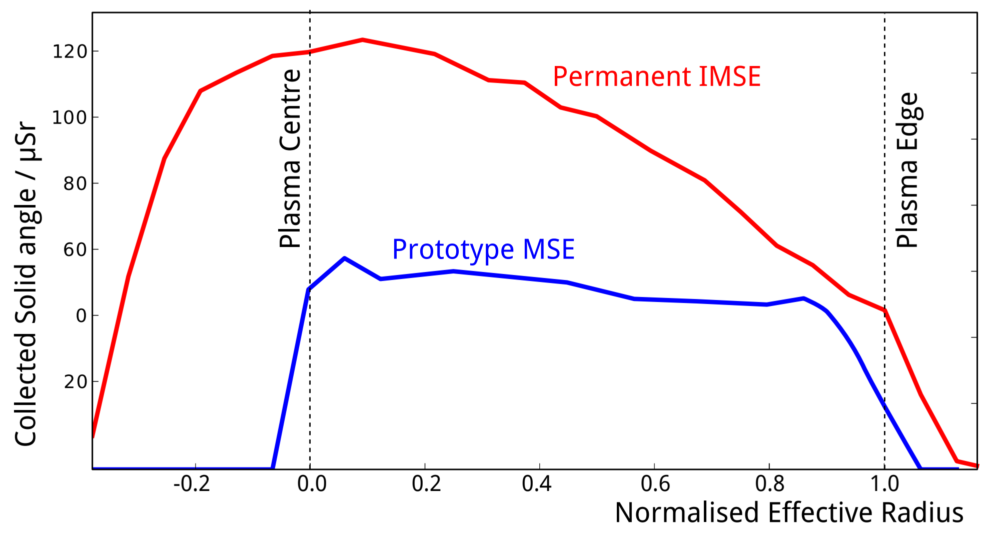
Given the promising results of the prototype, we are installing a permanent IMSE system on ASDEX Upgrade in May/June 2015 (Eurofusion funding).

- 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.



Scope for upgrade and lots of novel physics studies:

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



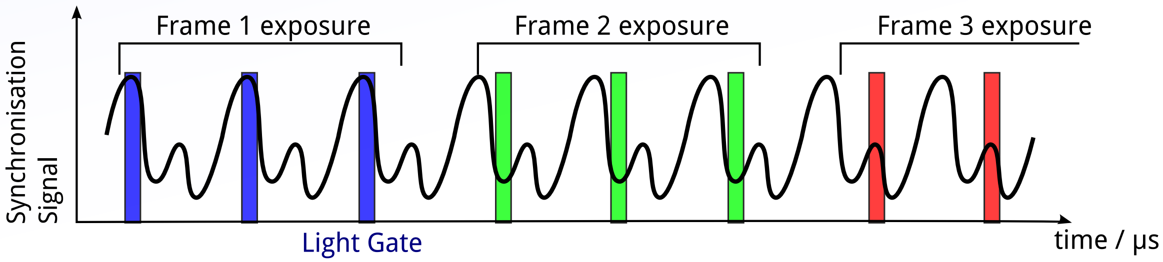
Future Work

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.



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.

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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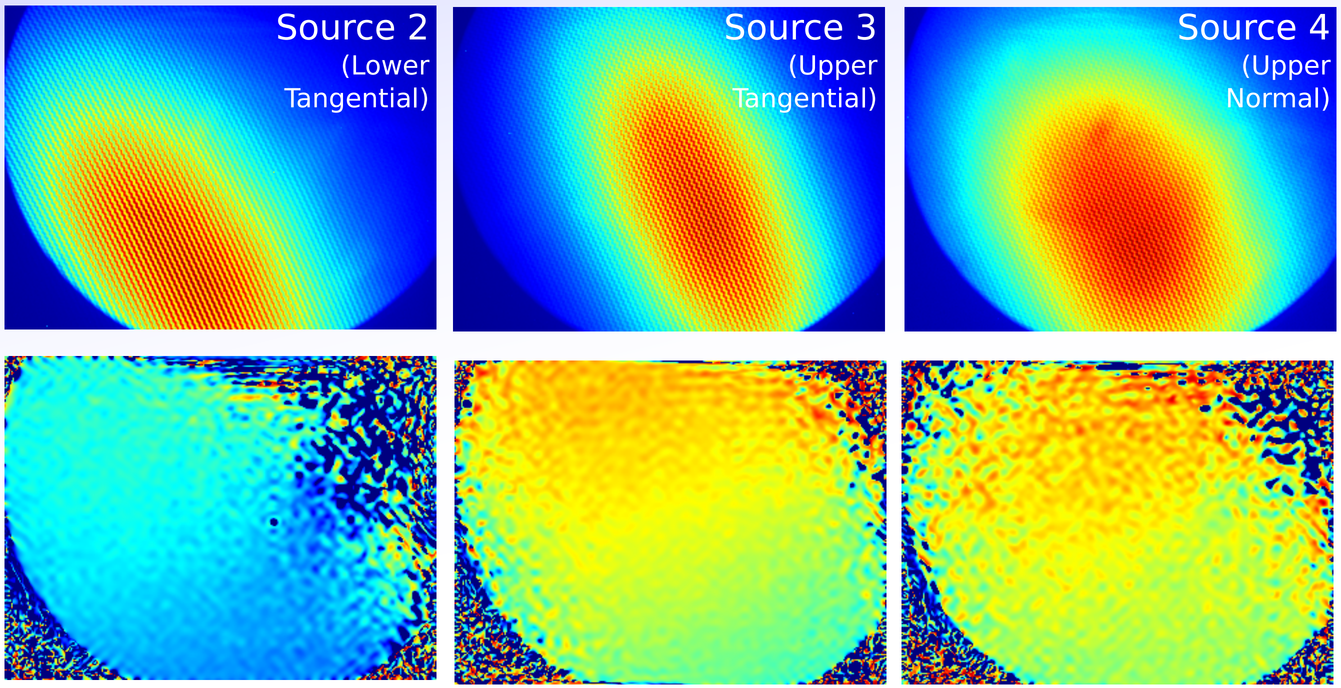
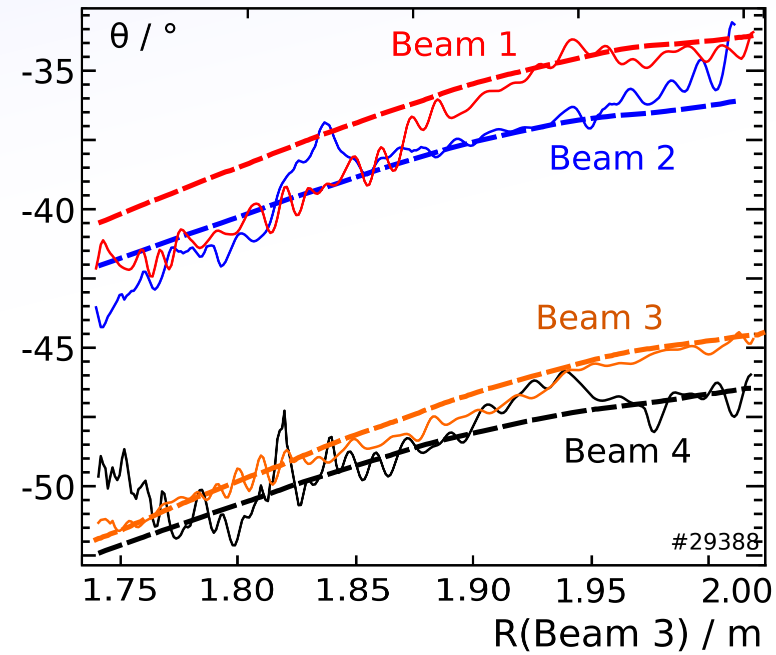
Beam Configuration Insensitivity

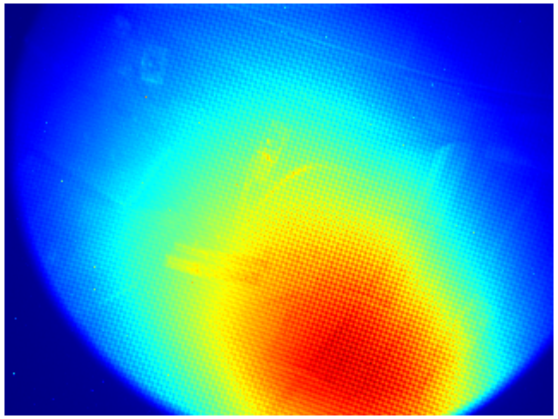
IMSE is insensitive to the spectrum so works on all 4 beam sources with both Deuterium and Hydrogen fuel:

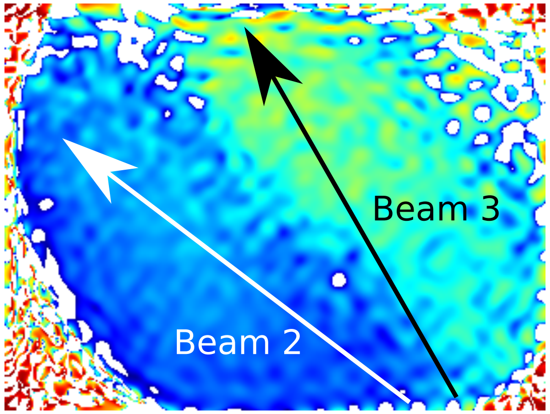




$\theta_3 - \theta_1$ is a fixed geometry value, so the agreement confirms the diagnostic linearity and beam geometry.
$\theta_3 - \theta_4$ (or $\theta_2 - \theta_1$) relate directly to B_z/B_φ and are unaffectd by fixed offset errors.

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)

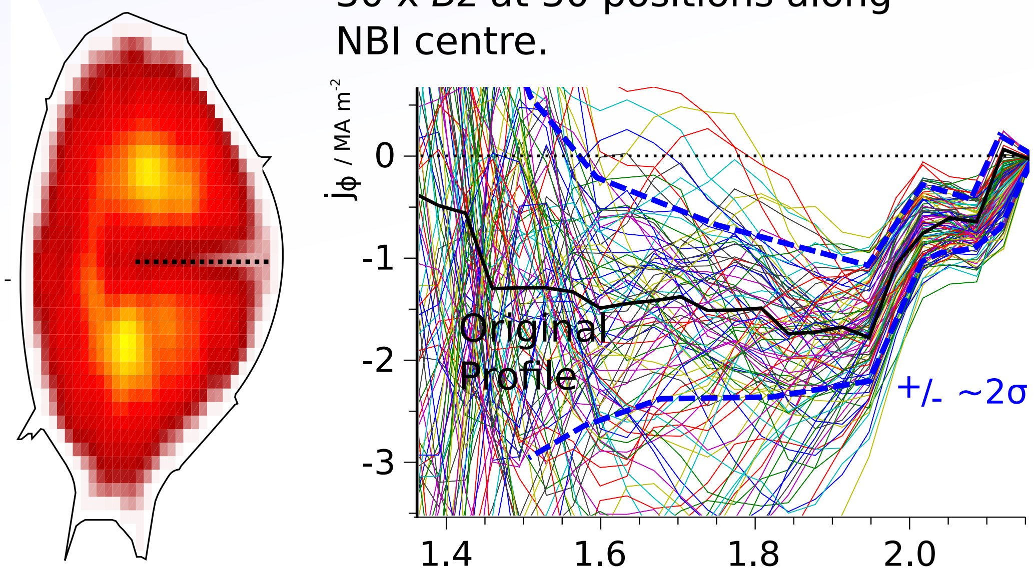
Motivation: Effect on Current Tomography

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.

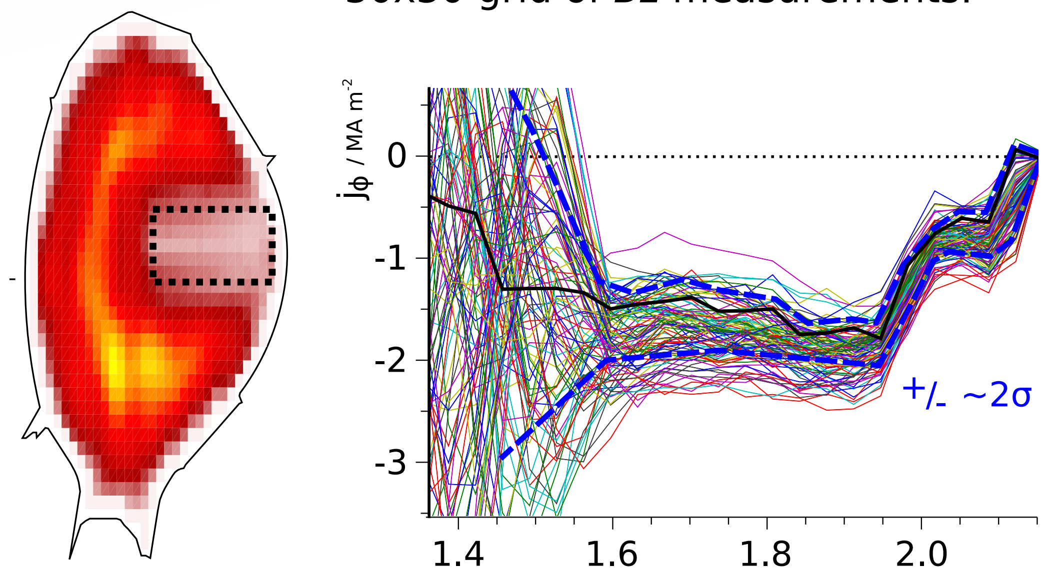
jϕ Uncertainty

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



jϕ Uncertainty

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



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

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

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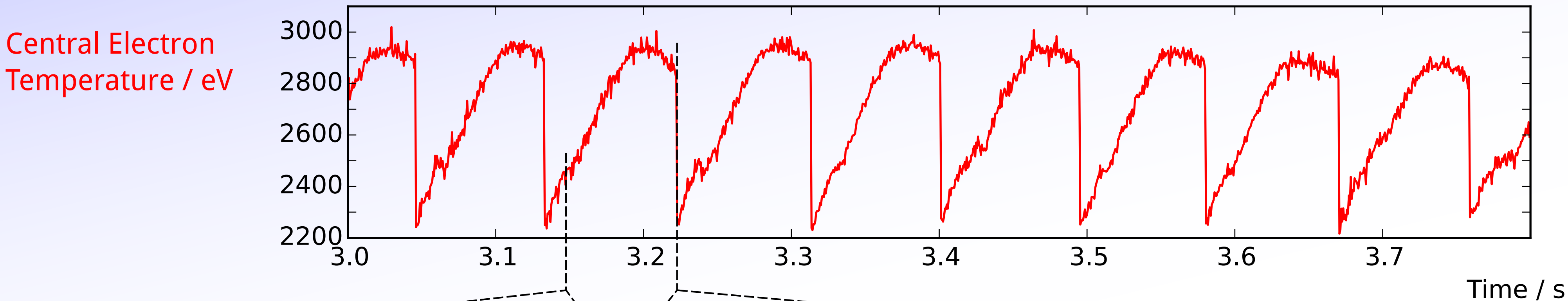
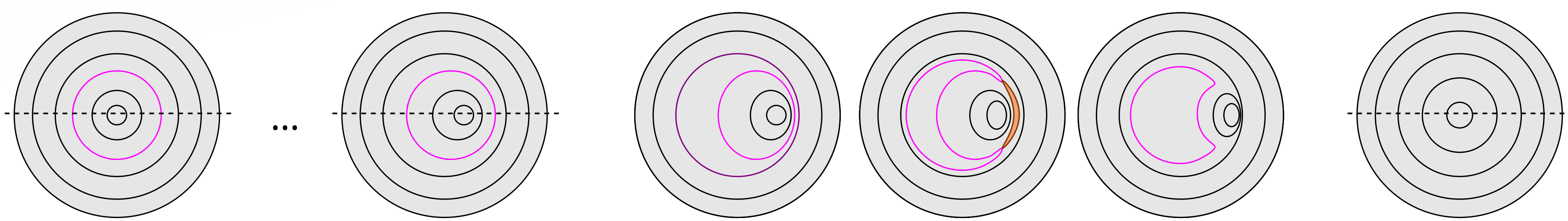
Sawteeth - Magnetic Reconnection

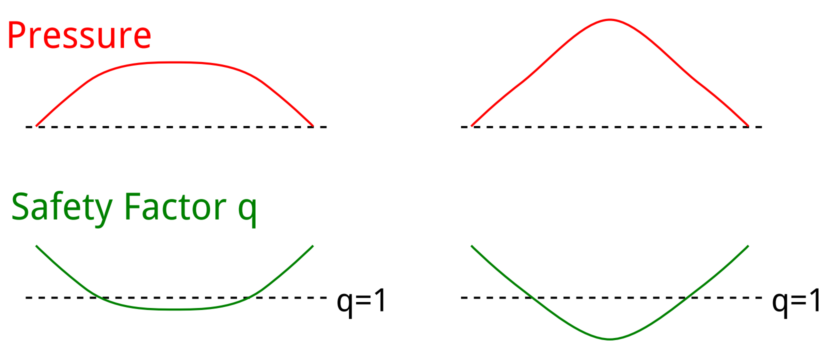


Slow build-up of pressure and current.

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

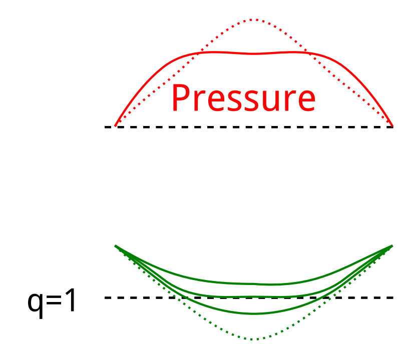
Cycle Repeats





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

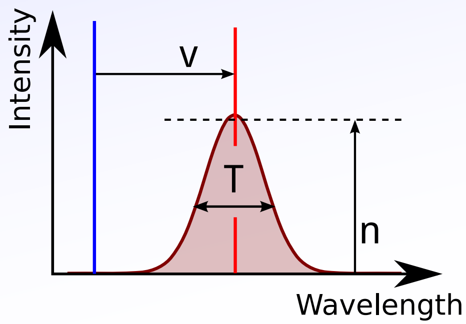
Many new models proposed, e.g. stochastic reconnection. Central question is always:
Does q_0 return to 1?



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:

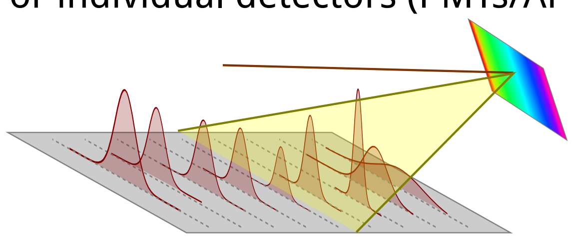
Doppler Spectroscopy: Observe atomic line emission from neutral hydrogen, impurities or laser light scattered by plasma particles.



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

Typical spectroscopy diagnostics:

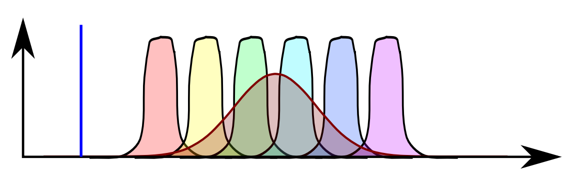
Diffraction grating and CCD camera, or individual detectors (PMTs/APDs)



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