Motional Stark Effect Imaging for ASDEX Upgrade:

Performance Tests and Expected Capabilities

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- Basic Principle
- Concept and Accuracy Tests
  - Test Spectrum
  - Polarisation angle measurement
  - Spatial variation
  - Unpolarised background
  - Ellipticity

  [K-STAR results]
- Jφ Inference

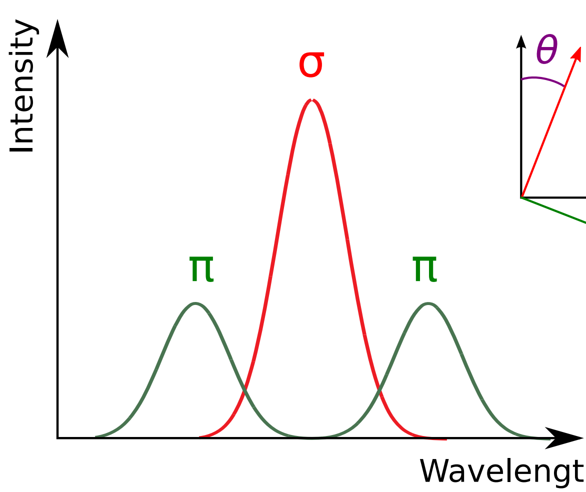
Motional Stark Effect at AUG

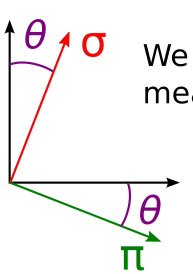
The IMSE system fits to the back of the the existing MSE optics, in place of the conventional MSE fibre bundle.

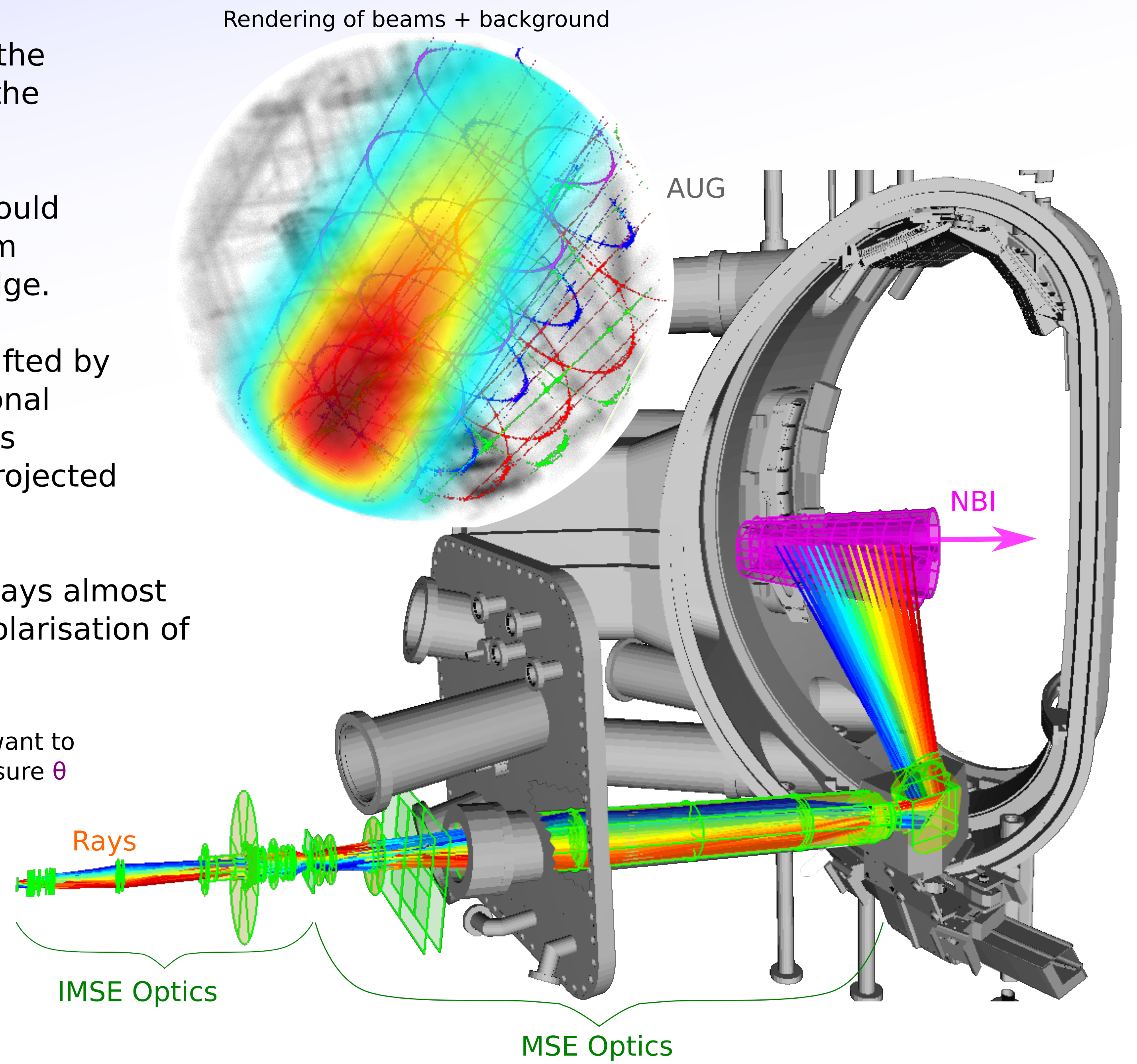
Ray tracing of optics shows IMSE should record a view of all 4 SE beams, from the plasma centre, to the plasma edge.

Hα/Dα beam emission is Doppler shifted by beam velocity and split by the Motional Stark Effect into π and σ components which is polarised perp/parallel to projected ***v*** *x* ***B*** direction.

The polarised component of σ is always almost exactly perpendicular to π, so net polarisation of entire spectrum is always 0. .

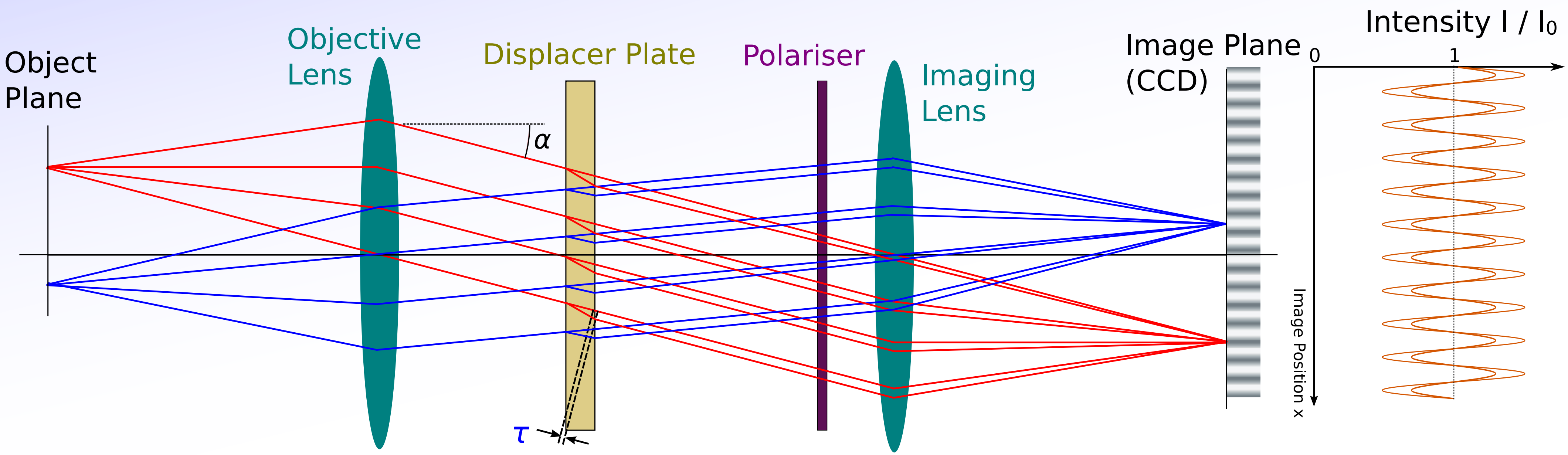






Coherence Imaging with Displacer Plates

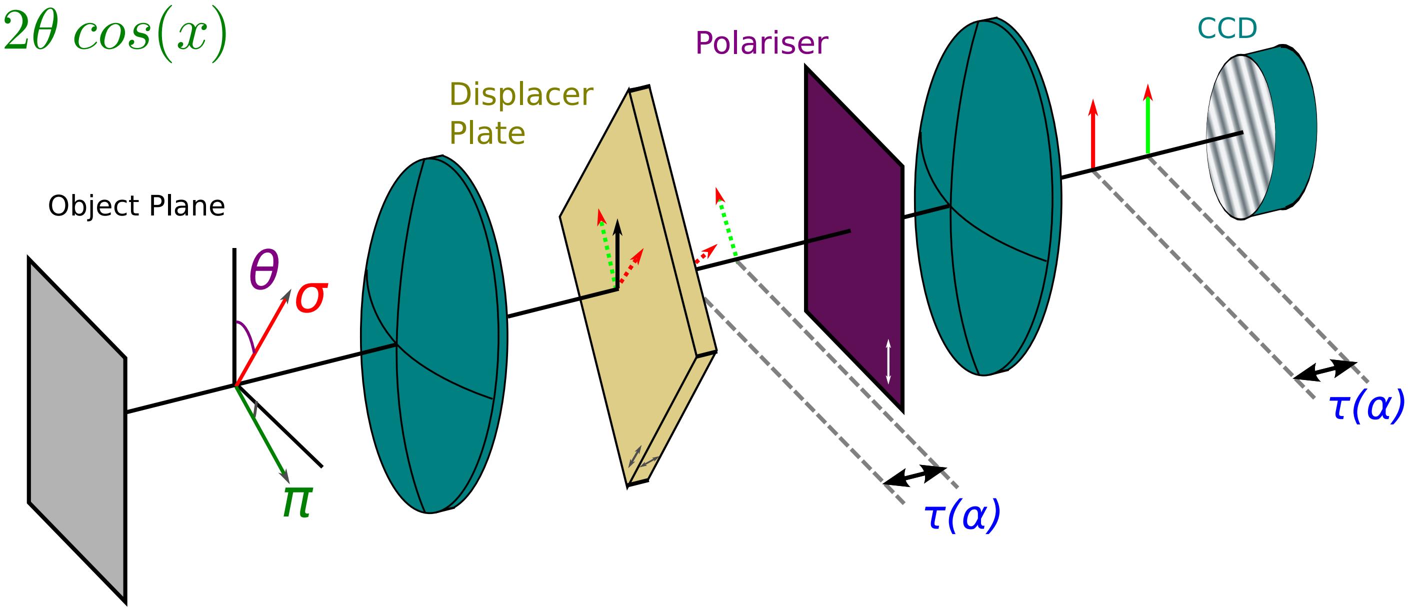
Displacer Plate: Angle dependent phase shift --> Interference pattern across image.



Oscillation amplitude proportional to polarisation angle.

$$I \propto 1 + \cos 2\theta \, \cos(x) - \cos 2\theta \, \cos(x)$$

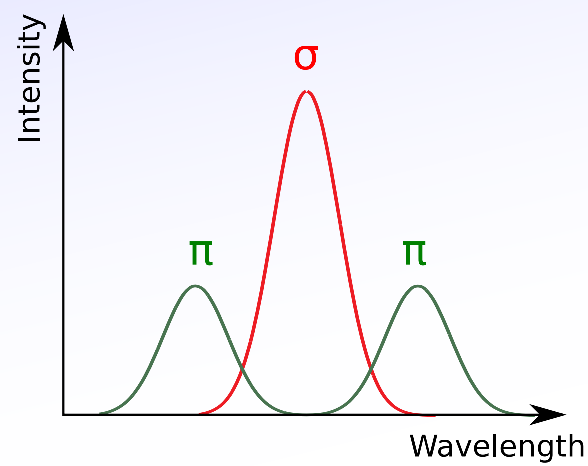
but σ and π are orthogonal.
If they were monochromatic,
they would cancel out...

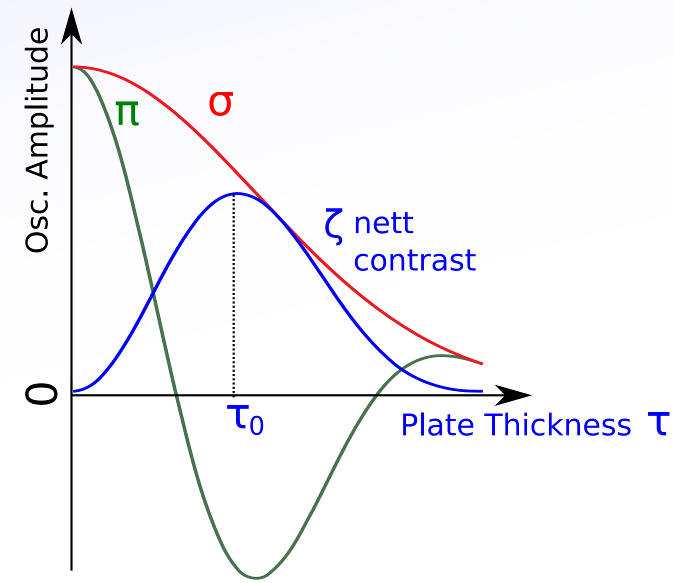


Spectral Coherence

Phase delay of a plate depends on wavelength. For large τ and finite spectral width, amplitude is reduced by decoherence.

For a specific τ, the phase of the π wings is 180° from σ. This cancels the 180° from the opposite polarisation, and the patterns add.



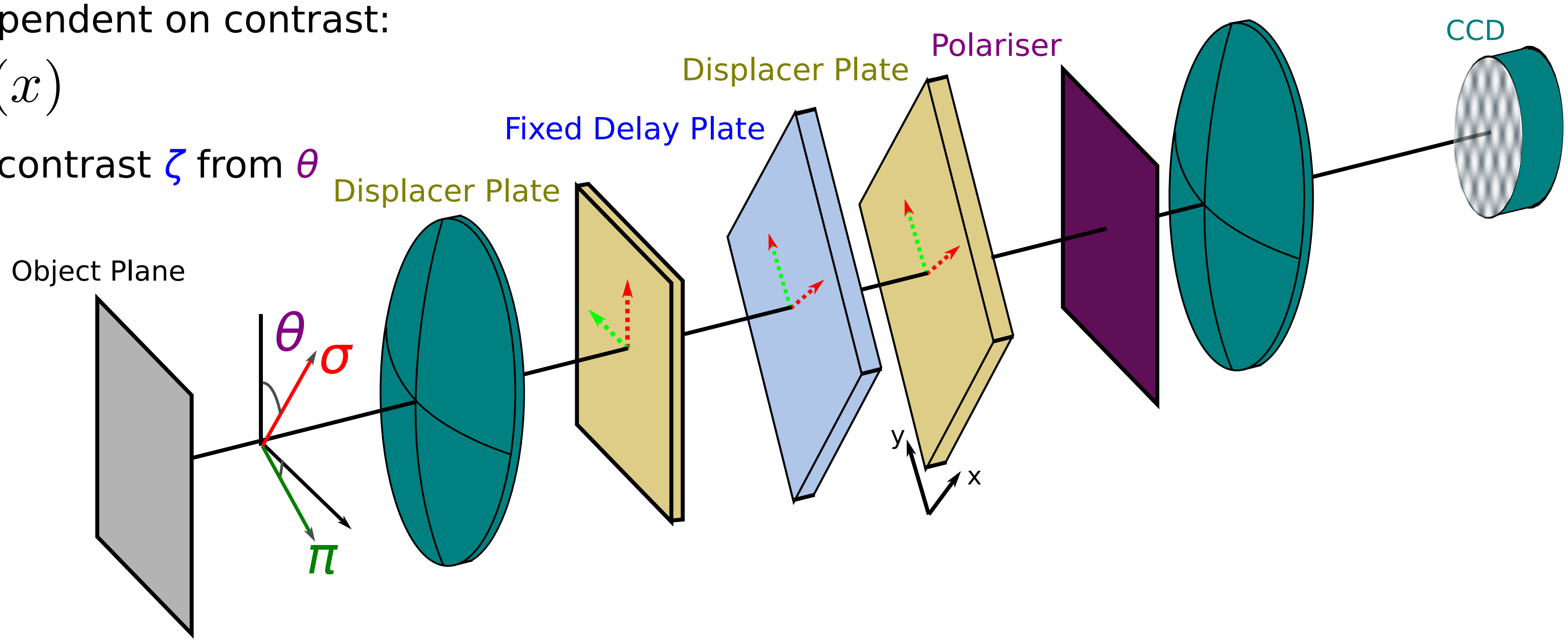


Add a delay plate to introduce the best τ_0 - where π and σ combine constructively.

but amplitude now also dependent on contrast:

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

Need to separate spectral contrast ζ from θ



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

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

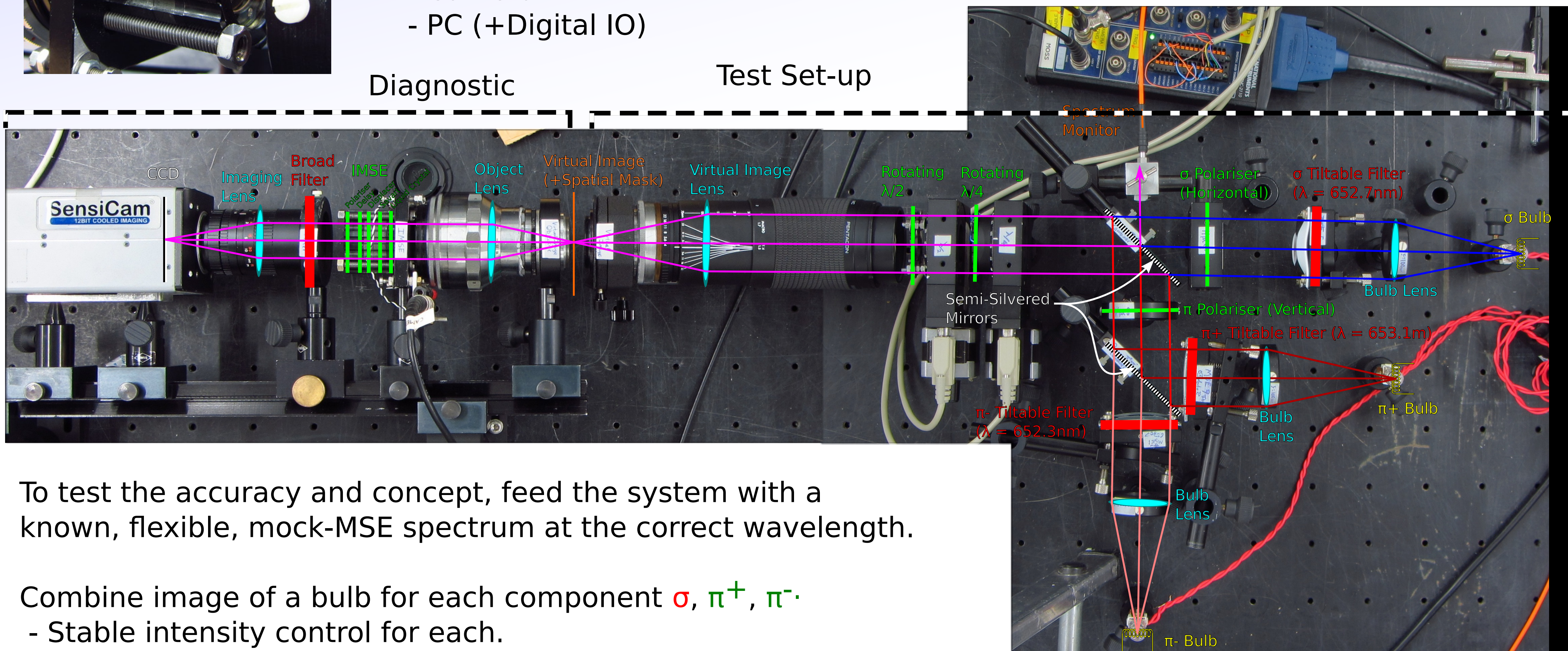
Test Setup

The IMSE hardware is very simple:

- 5 Plates
- Wide Filter (Dα Suppression)
- Two lenses
- Camera
- PC (+Digital IO)

Optional:

- Ferroelectric Liquid Crystal (FLC) for flexibility
- Temperature Cell (for temperature stability)

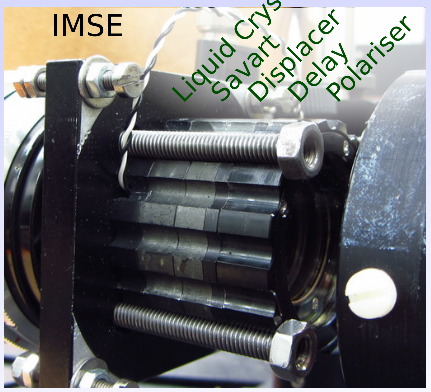


To test the accuracy and concept, feed the system with a known, flexible, mock-MSE spectrum at the correct wavelength.

Combine image of a bulb for each component σ, π^+, π^-.

- Stable intensity control for each.
- Independant tiltable filters (thanks M. Reich) for each.
- Separate polarisers for σ and π arms.
- Rotate whole result, or add ellipticity using motor controlled *λ/2* and *λ/4* plates.
- Lens to form virtual image similar to AUG optics.
- Optional mask at virtual image for spatial test.

Test Setup



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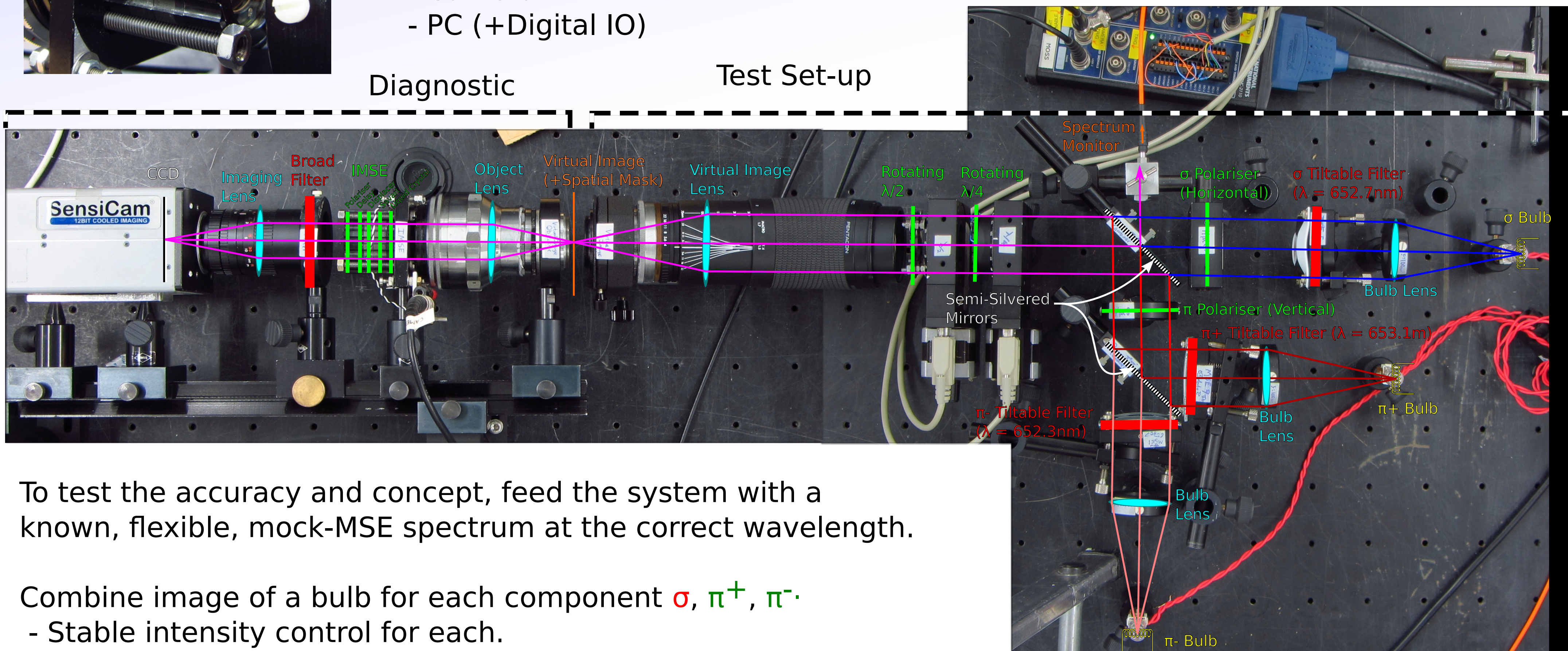

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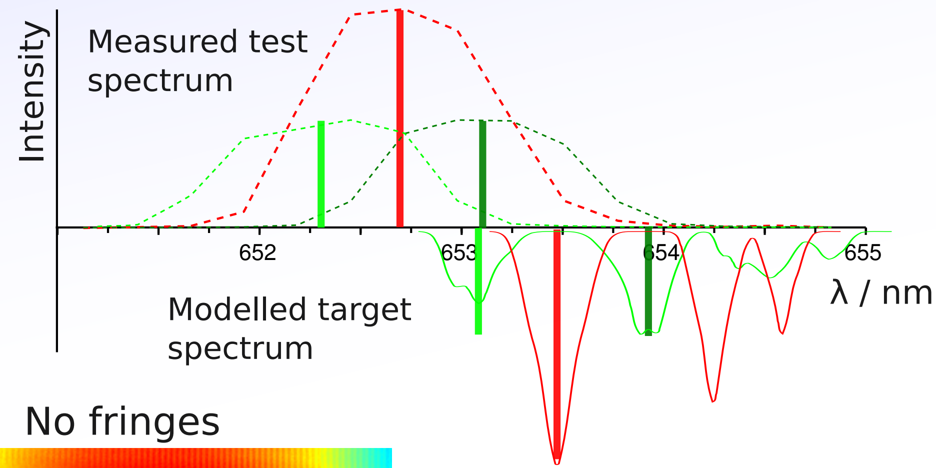
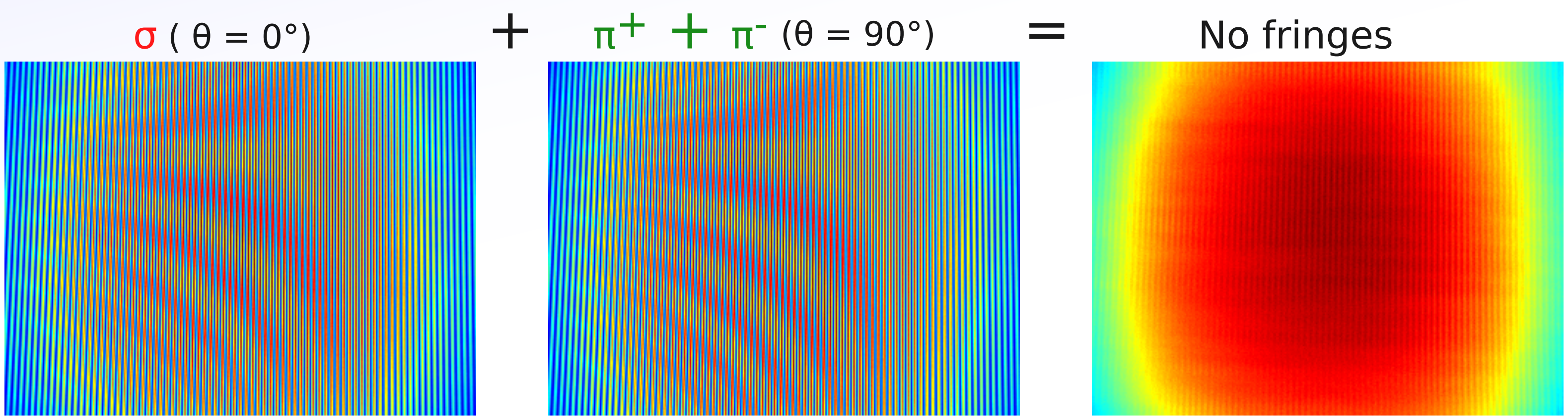
Test Set-up

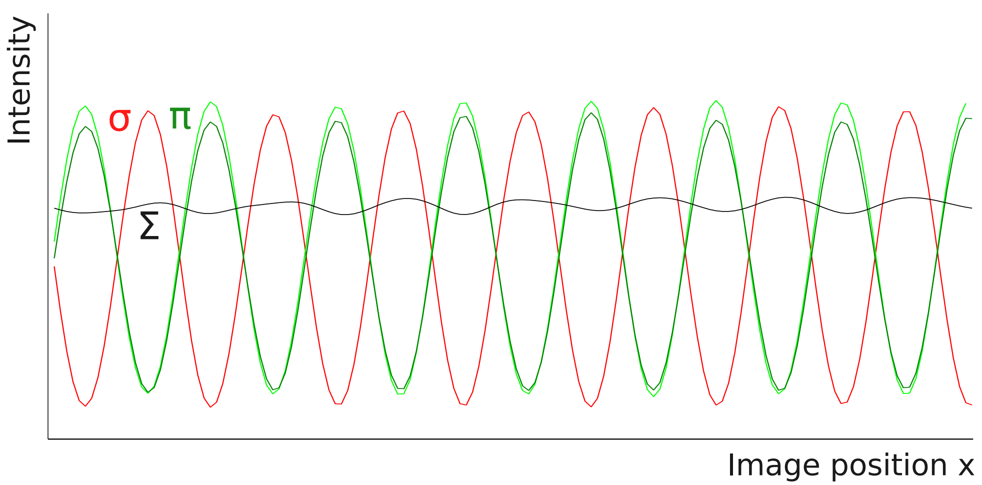
Spectrum is set up to roughly mimic AUG MSE spectrum.

(The test also confirms that the system is insensitive to the exact spectrum)

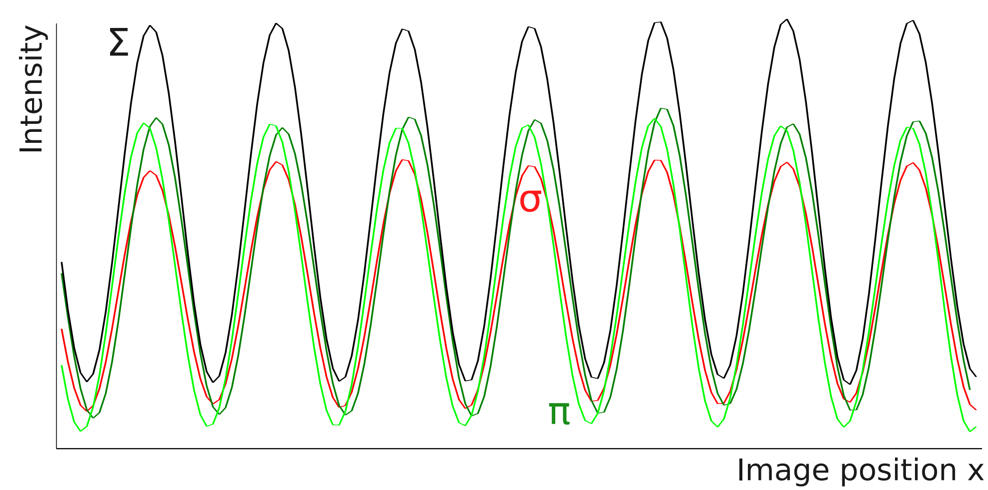


Fringes produced by a single displacer plate:





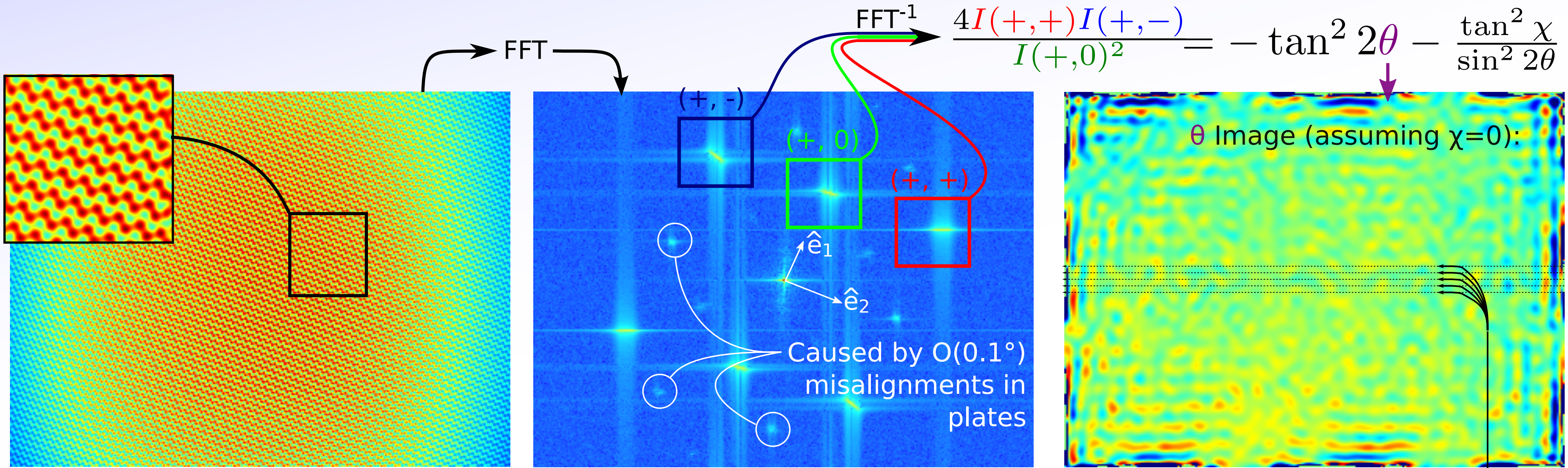
With delay plate, phase of πs roughly align to σ:



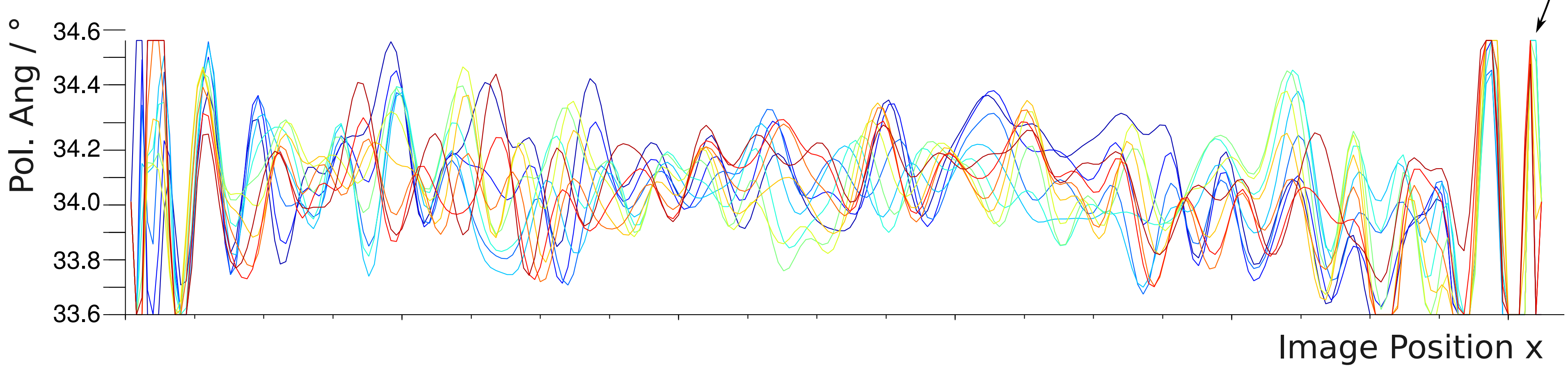
Full Fringes and Demodulation

Adding the 2nd displacer plate, gives the dual fringes:

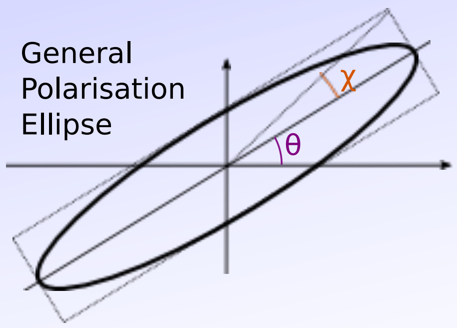
$$\frac{4I(+,+)I(+,-)}{I(+,0)^2} = -\tan^2 2\theta - \frac{\tan^2 \chi}{\sin^2 2\theta}$$

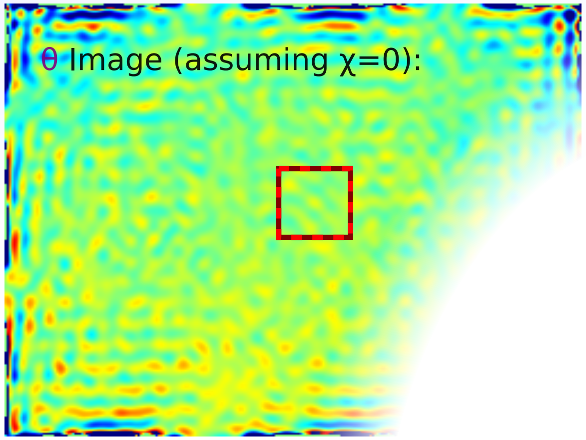


Pixel accuracy is degraded by edge effects etc. It might be possible to reduce this by improving the demodulation procedure later, but for now averaging 3-4 fringes works.

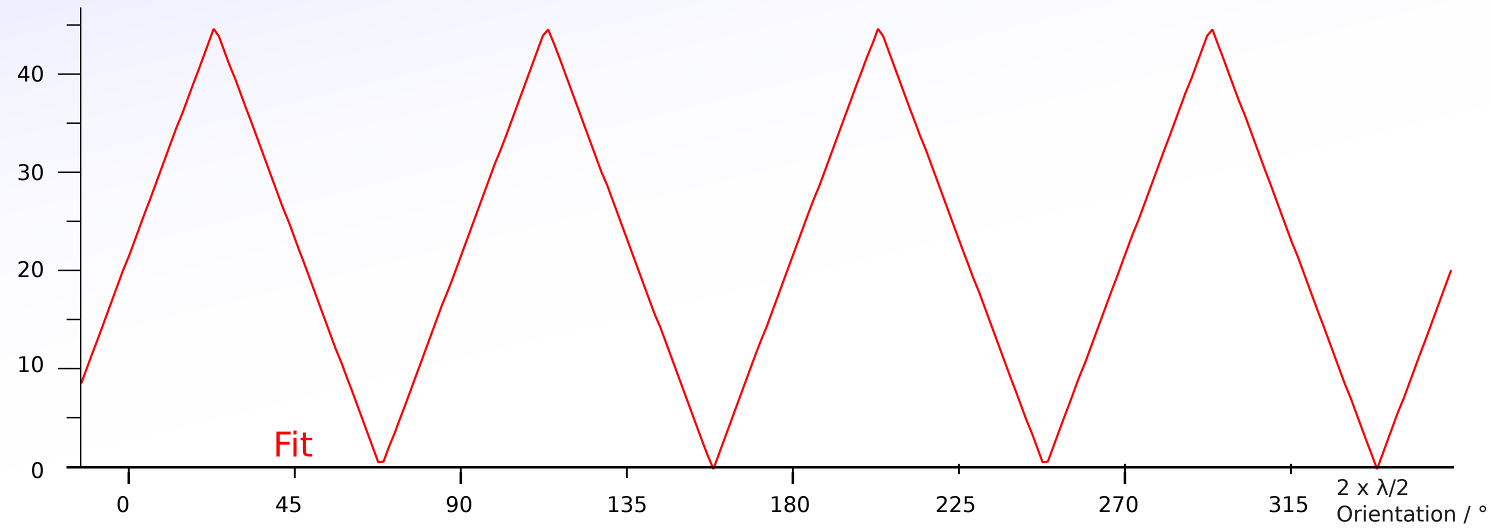


Calibration Sweep





Check linearity and systematic error by averaging a small area and scanning the λ/2 plate to rotate the polarisation.



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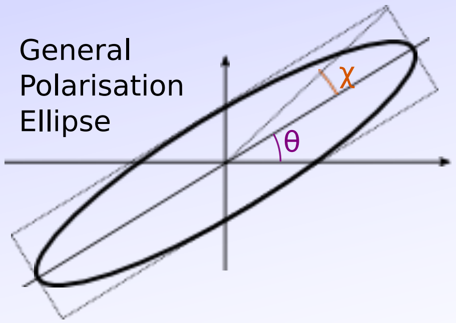

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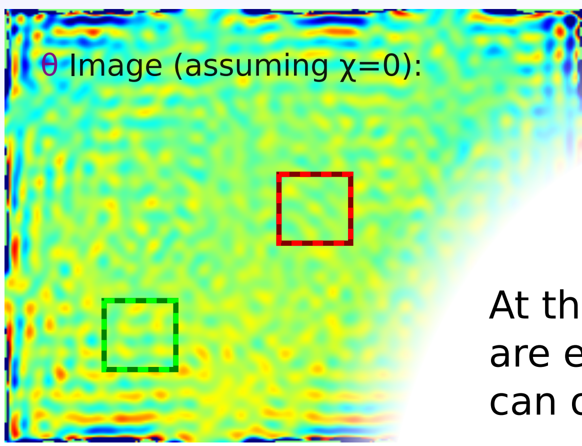
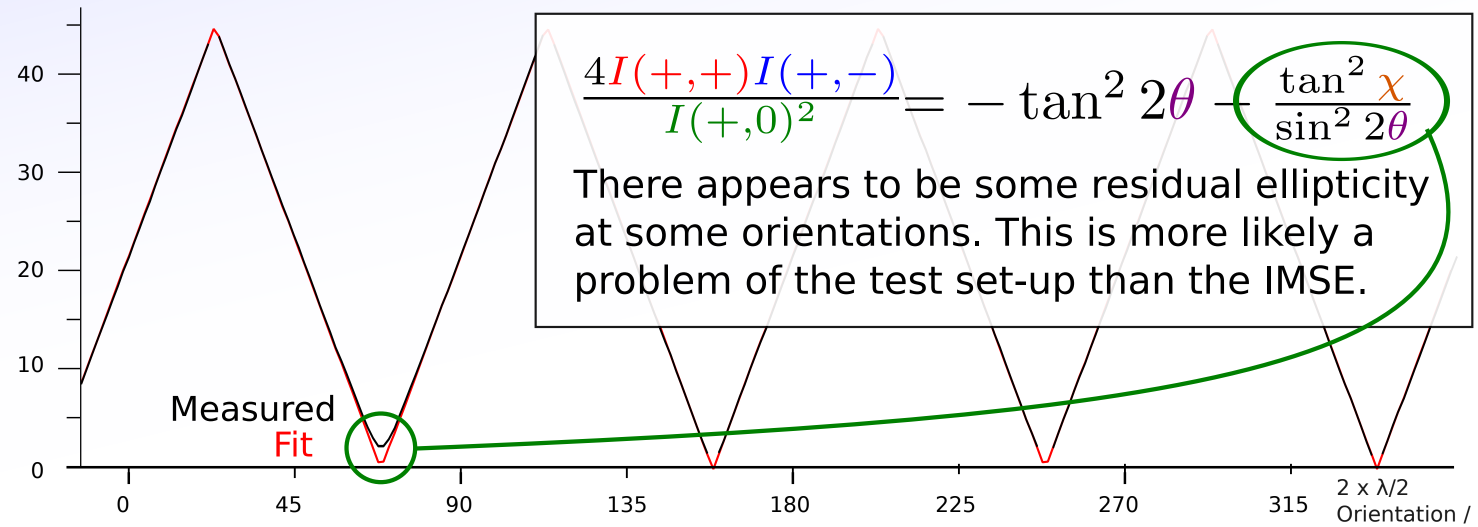
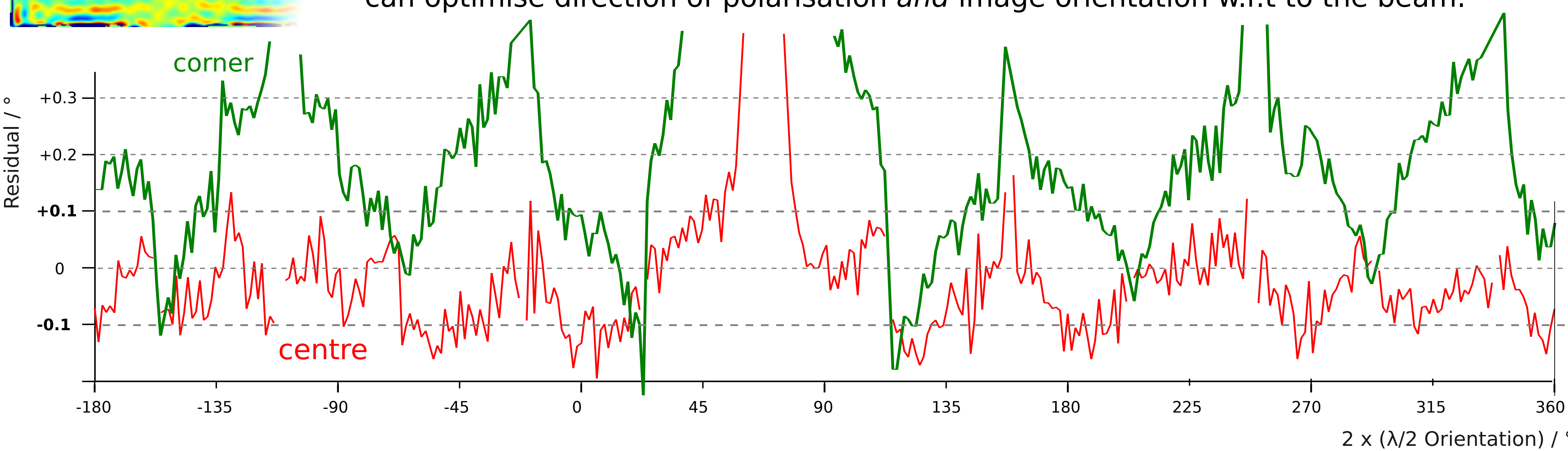




$$\frac{4I(+,+)I(+,-)}{I(+,0)^2} = -\tan^2 2\theta - \frac{\tan^2 \chi}{\sin^2 2\theta}$$

There appears to be some residual ellipticity at some orientations. This is more likely a problem of the test set-up than the IMSE.

At the centre of the image, the residual is at the desired ±0.1°. Two corners are equally good but the other two corners show stronger ellipticity. We can optimise direction of polarisation *and* image orientation w.r.t to the beam.

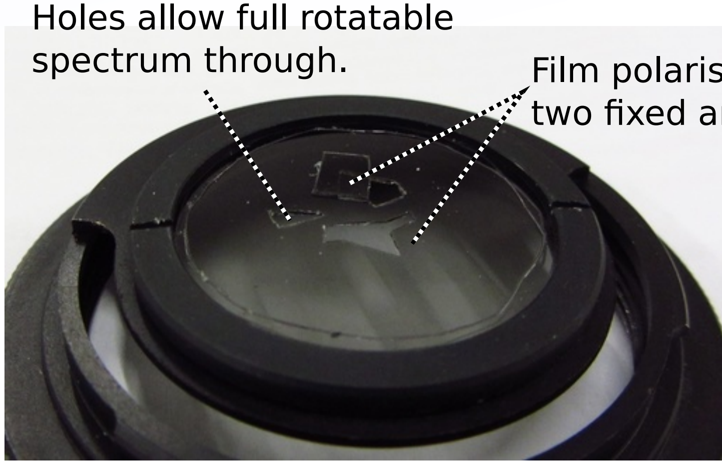


Background and spatial Variation.

The measurement should be impervious to unpolarised *or* broadband background. To test, introduce bright light after filters and polarisers (backlight spectral monitor):

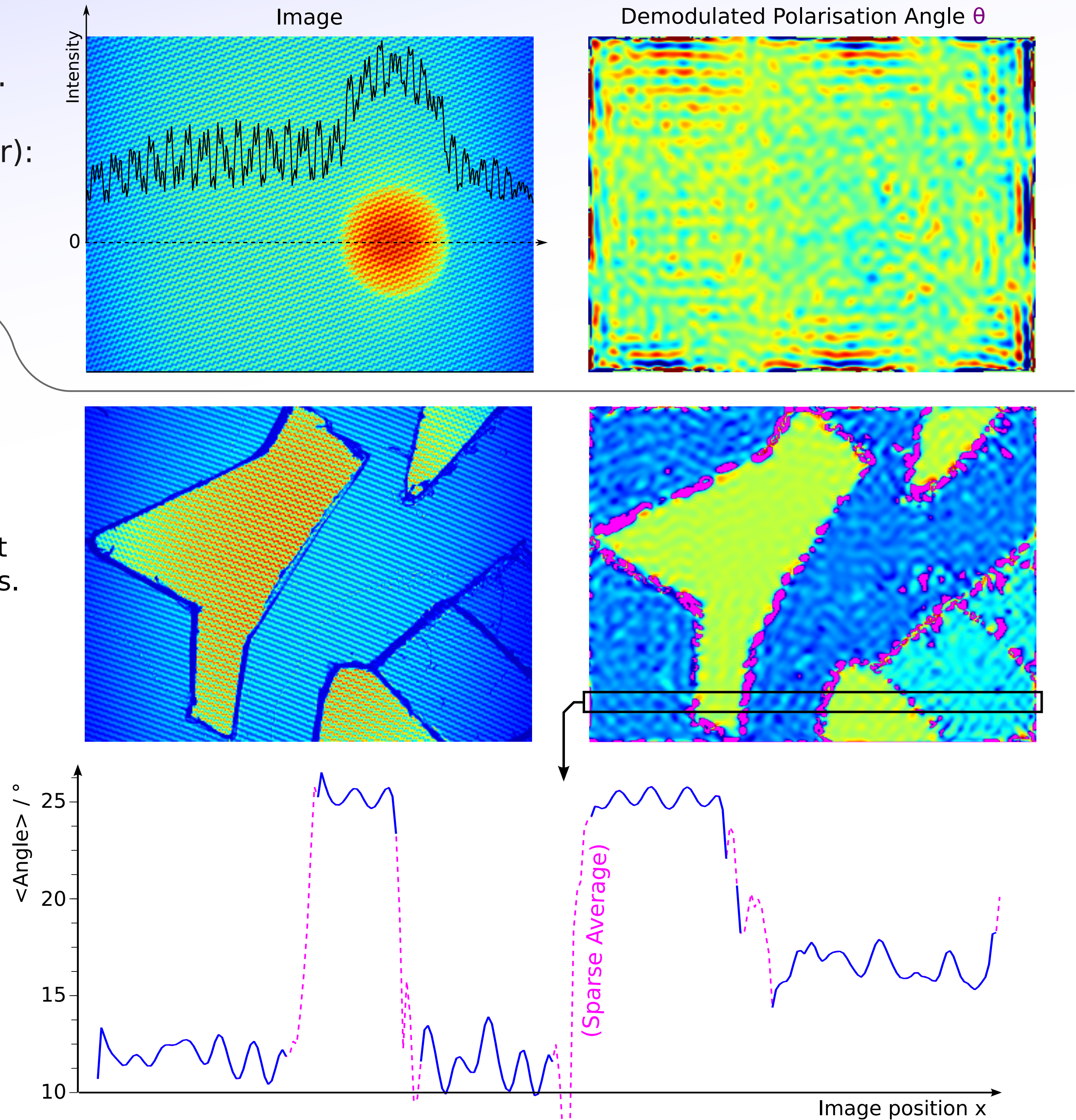
Effect on demodulated angle is smaller then existing noise level.

To test spatial variation of polarisation, insert a mask made of polarising film at the virtual image plane:



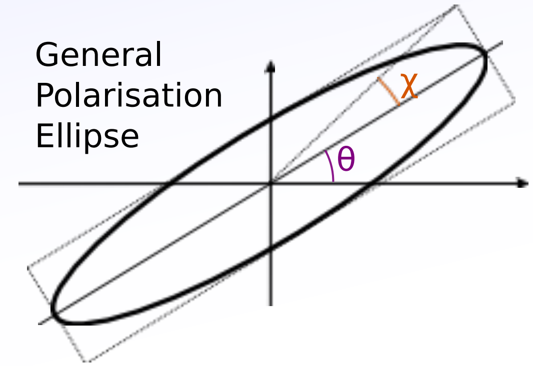
Spatial resolution is down to about 4x the fringe period. Sharp transition errors usually gives imaginary θ results.

Brightness through film polariser is much lower, so errors are larger.



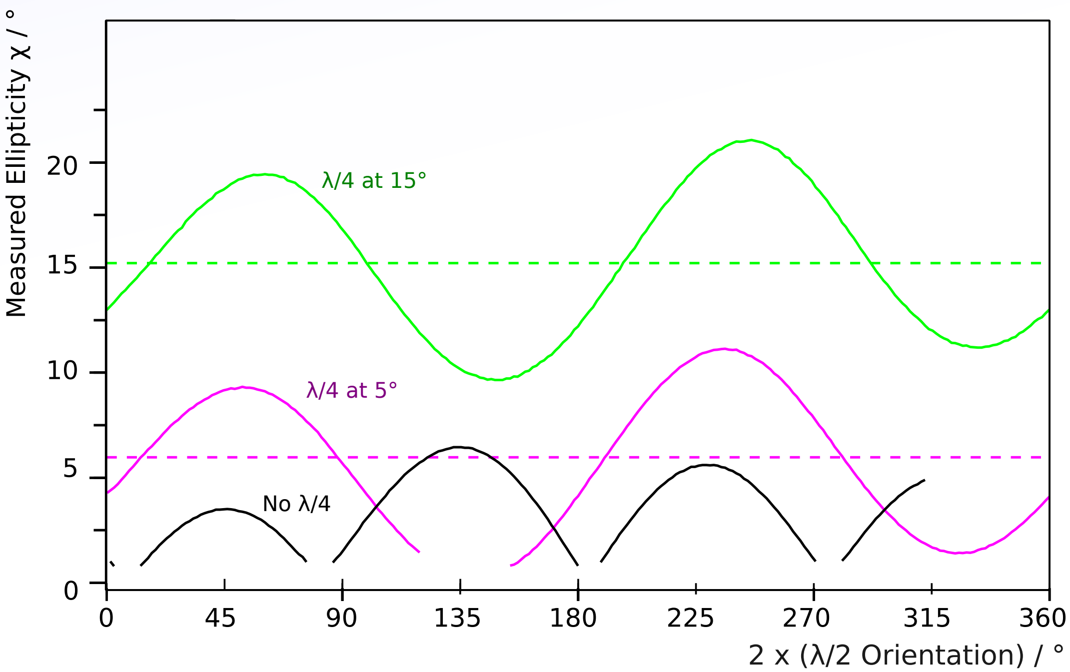
Ellipticity (in progress)

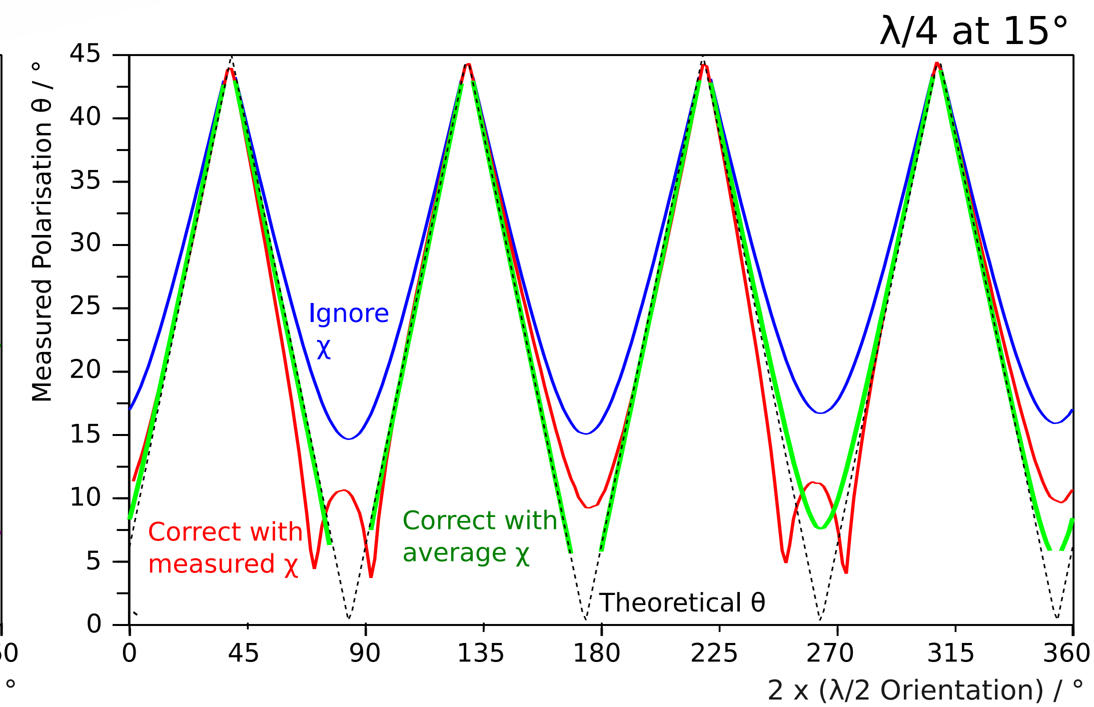
The λ/4 Ferroelectric-Liquid Crystal (FLC) gives different operating mode of the system. When on, the amplitude demodulation gives the ellipticity angle: *tan χ*.



If there is strong ellipticity from the Tokamak (either Stark-Zeeman coupling, or from the forward optics) we can in principle measure it, and remove the effect.

Currently, this only partially works:



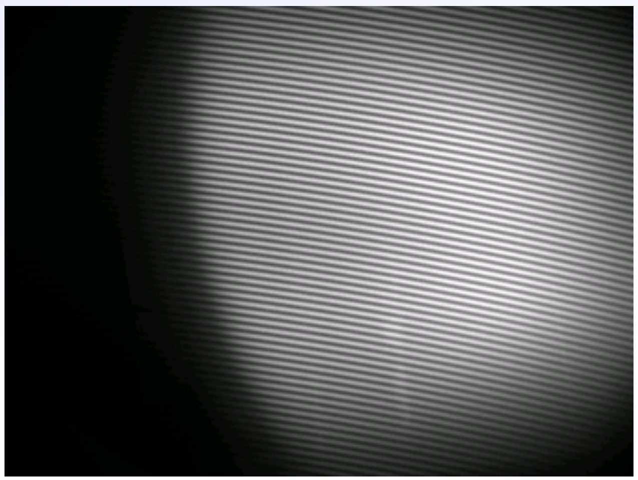


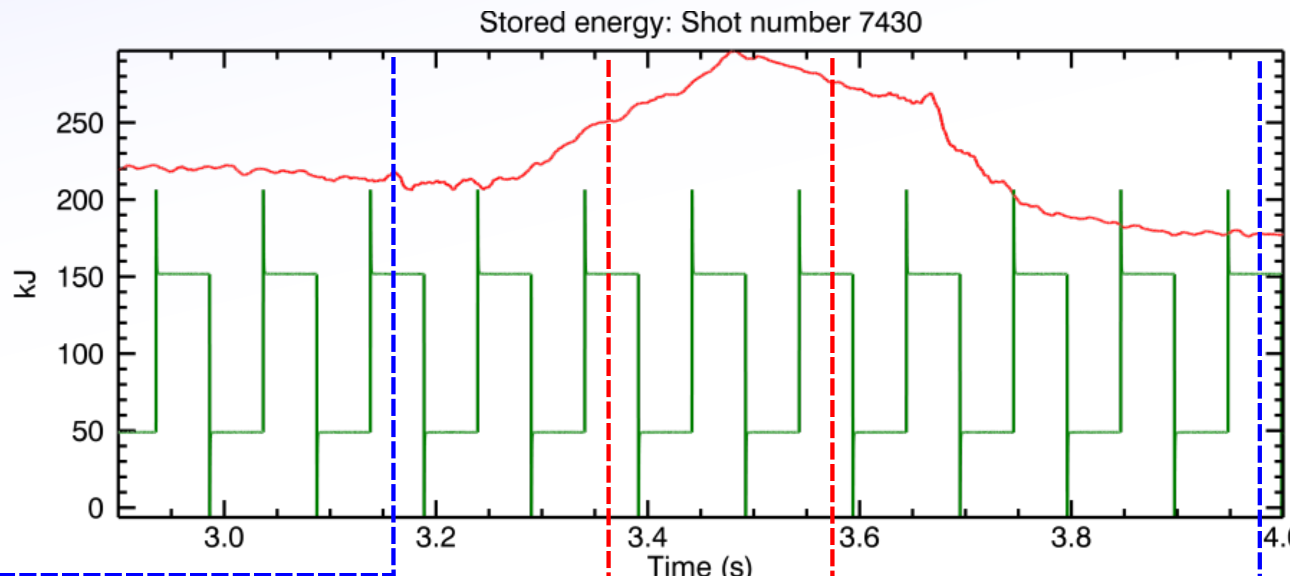
This is consistent with the λ/2 plate not being exactly λ/2 for the simulation wavelength (652.7nm)

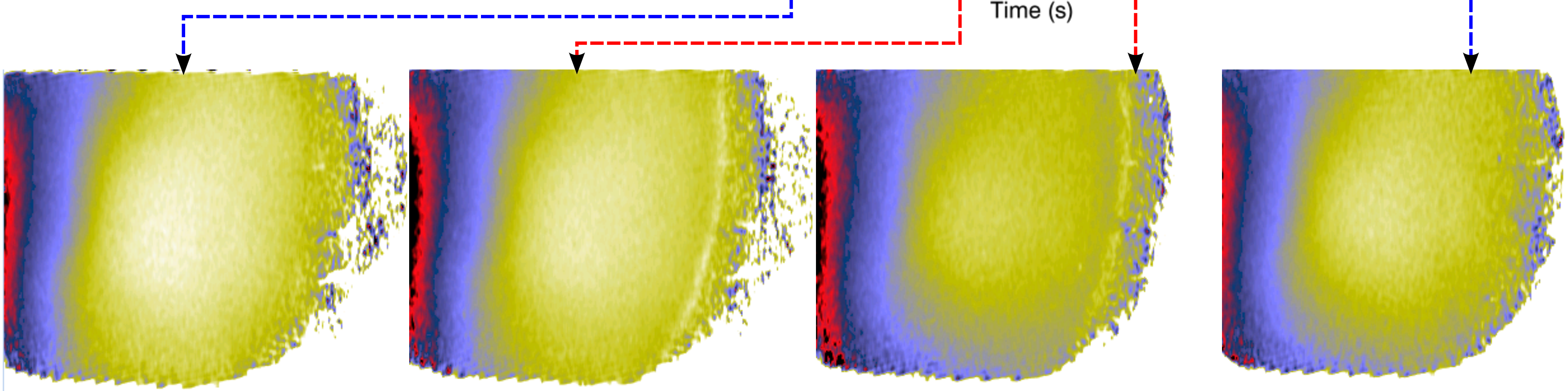
Some promising results from K-STAR

The λ/4 Ferro-Liquid Crystal (FLC) gives many extra options, including measurement of the polarisation angle without the 2nd displacer plate, so only 1 set of fringes.

This gives much better spatial resolution in 1 direction and is how John Howard currently has the K-STAR IMSE system setup:





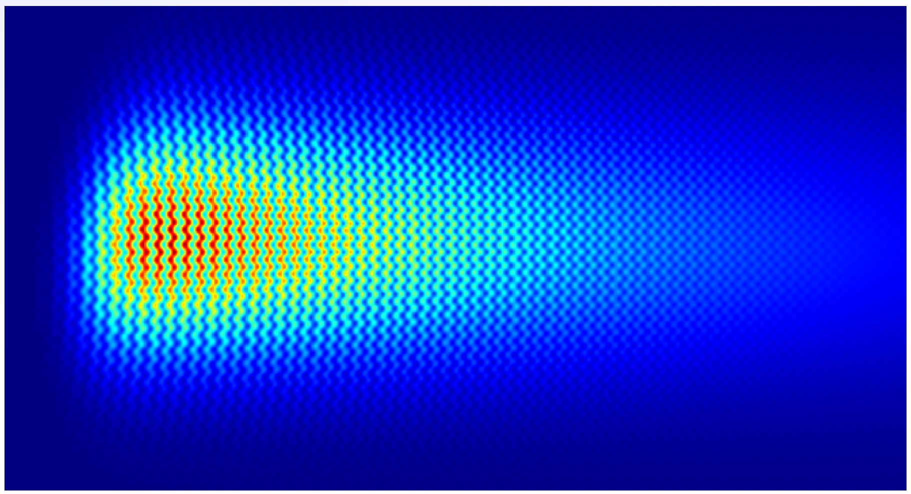


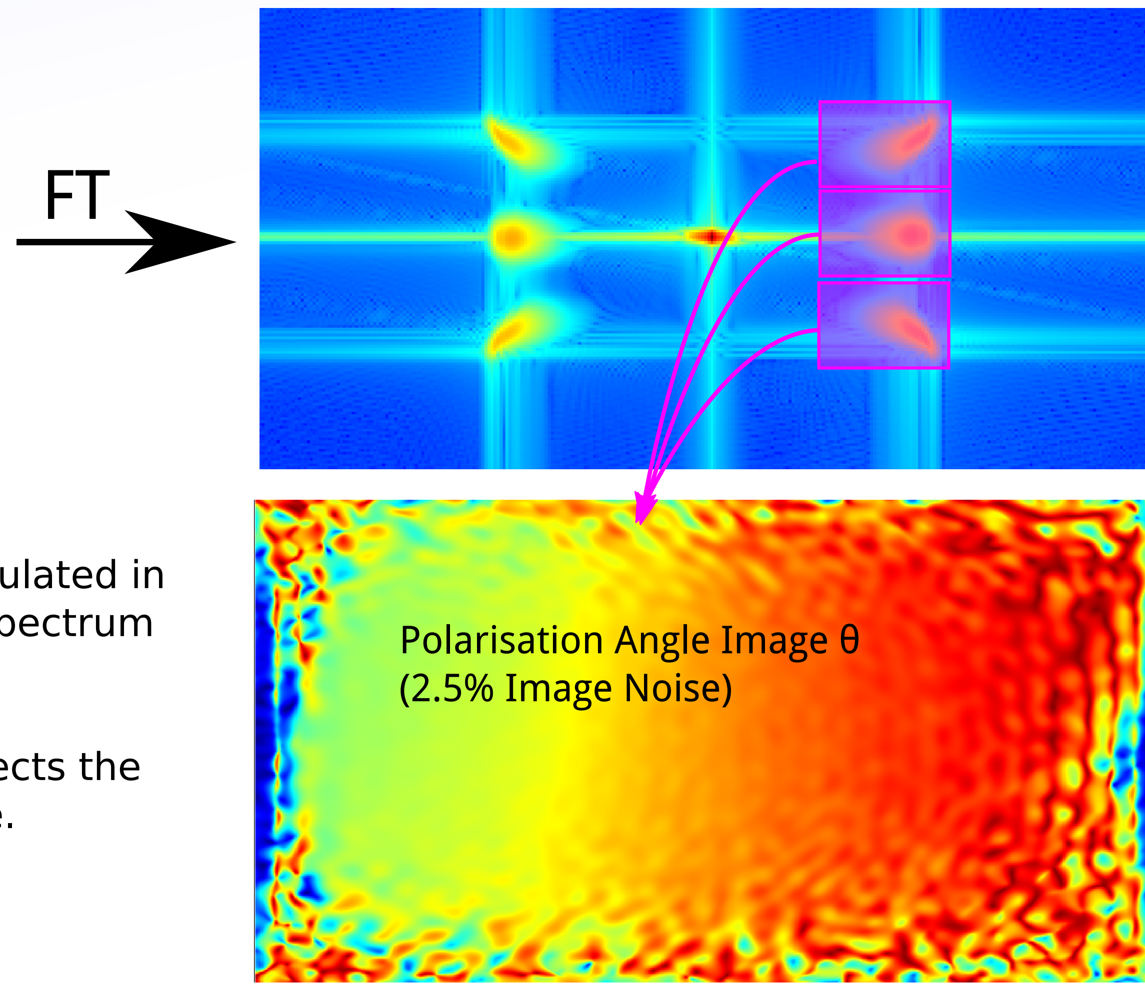
Angles are not yet calibrated, but H-mode pedestal is already clearly visible, and is probably a direct effect of the the pedestal current.

Simulations for AUG

With the hardware performance confirmed, what can we expect to see?

Earlier work included a detailed forward model for the AUG beams, MSE etc and showed a similar ability to demodulate the average polarisation angle, accurate to around 0.2°.





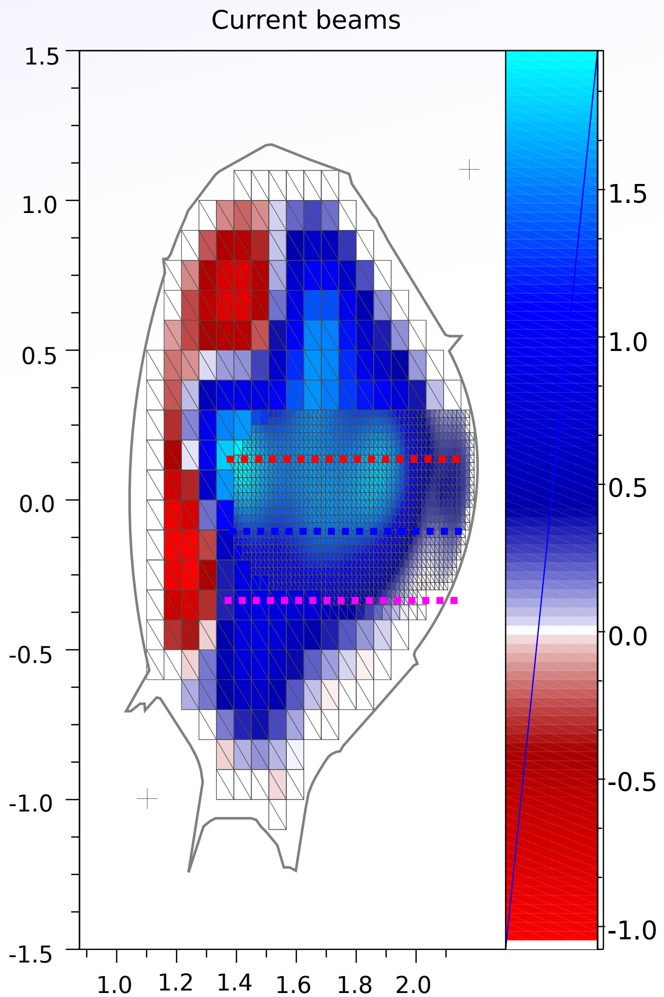
This includes an expected plasma effect not simulated in the hardware tests - the line integration of the spectrum over the beam width.

For AUG, the demodulated angle accurately reflects the (beam weighted) line average polarisation angle.

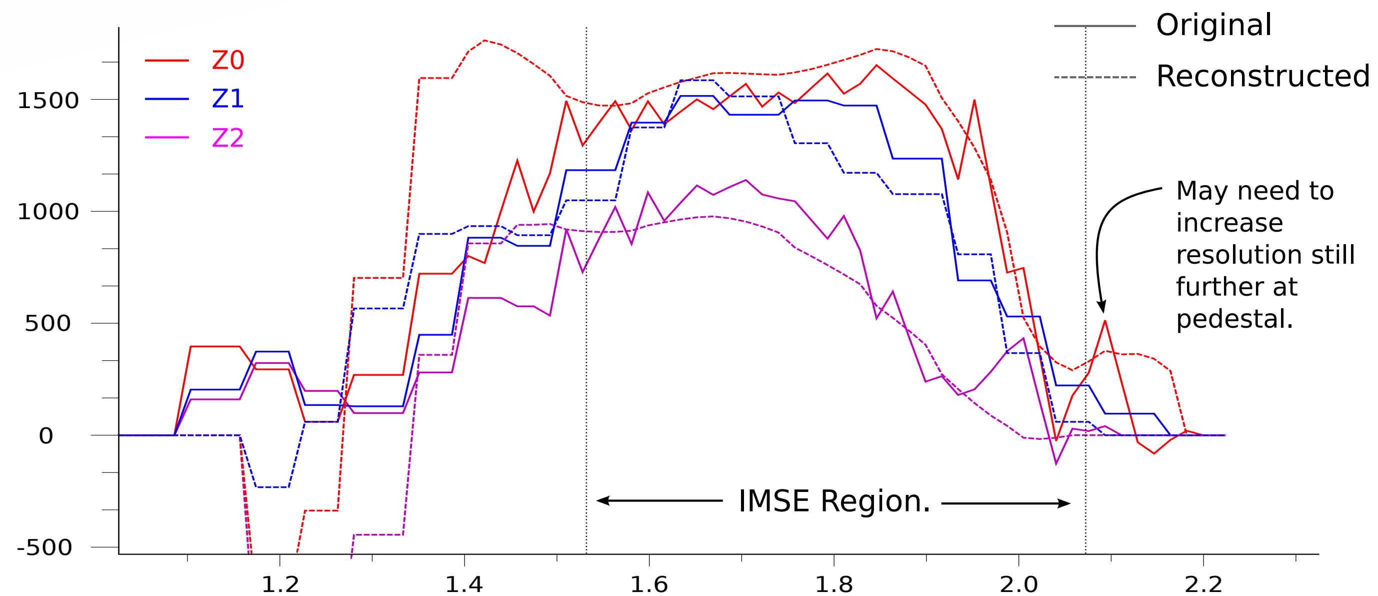
Inference of Jϕ

Calculation of pitch angle from polarisation angle is relatively straightforward, but not very useful. Unfortunately, even with 2D data, plasma current Jϕ cannot be calculated directly. The 2D data does however greatly improve the tomographic reconstruction of Jϕ (with or without equilibrium assumptions).

Magnetic Current Tomography (J.Svensson)
+ AUG Magnetic pickup data
+ Irregular grid support (My PhD)
+ Gaussian process priors (J.Svensson)
+ Parallel Bayesian Inversions (My PhD)
+ An unloaded Linux cluster



Simulate pickups and a 60x40 grid of IMSE polarisation measurements (θ) with 0.3° error then invert back to Jϕ:



Initial results indicate that it is possible to recover the $j_\phi(R, Z)$ to at least a good resolution for studying the bulk plasma (e.g. testing different equilibrium models etc). This is *much* better than is currently possible. Resolution is processing limited - Higher resolution may be possible, but computation cost rises with resolution as $\sim n^4$.

Oliver Ford
IPP Greifswald

Status

- ✔ The IMSE device for AUG is now built and ready to install.
- ✔ Concept and accuracy tests for polarisation measurement completed at target wavelengths.
- ✔ Modelling for AUG spectrum and view completed.
- ✔ Control, calibration, capture, demodulation and processing software all completed.

- ... Get support structure built (design is done)
- ... Fit to the Tokamak and get some data!

- ... Devise method of absolute angle calibration.
- ... Complete ellipticity recovery investigation (needs better test sources).
- ... Improve demodulation proceedure.
- ... Model Stark-Zeeman coupling (can ellipticity tell us something?)
- ... Deeper investigation of θ --> Jφ inference methods (including equilibrium codes)

- ✔ Modelling and image generation for W7X.
- ✔ Ability to infer polarisation angle for W7X images.
- ✔ Ability to infer parallel current for W7X.
- ✔ Modelling of AUG MSE emission spectrum/polarisation.
- ✔ Modelling of generated images and ability to infer polarisation angle images.
- ✔ Asses ability to infer axisymmetric current from polarisation images.
- ✔ Ray tracing of existing MSE optics to see the image delivered.
- ✔ Asses lens options for optics coupling.
- ✔ Calculate and order required crystals (for middle range of lenses)
- ✔ Calculate and order filter
- ✔ Investigate non-orthogonal fringes idea (works great)
- ~✔ Build polarisation test setup (simulated spectrum, OK, getting better filters).
- ✔ Measurement principal test (Zeeman splitting).

- ✔ Software/Methods for exact alignment of plates.
- ✔ Assess neutron damage probability to camera (not much info, but looks OK)
- ✔ Design support structure.
- ... Order optimal filter
- ... Model polarisation effects of MSE forward optics.
- ... Spectrum+Image model for MAST.
- ... Calculate expected absolute light level (hence max absolute frame rate).
- ... Find optimum optical setup (fielding etc).
- ... Interface to objective auto-focus .
- ... Lighting of background polarisers for absolute calibration.
- ... Plasma-based absolute calibration method/check.
- ... Add Stark/Zeeman coupling to forward model (Ellipticity).
- ... Reproduce non-linearity in ray tracer (requires full E/O ray splitting to work)
- ... Improve edge effect / non-periodic FFT demodulation problems.
- ... W7X assessment based on AUG results.