Max-Planck Institut
für Plasmaphysik

ANU

Motional Stark Effect Imaging for ASDEX Upgrade:

Status and Performance Tests

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- Concept and Accuracy Tests
  - Test Spectrum
  - Polarisation angle measurement
  - Spatial variation
  - Unpolarised background
  - Ellipticity
  - Waveplate and FLCs
  - The mysterious magic number.
- K-STAR results

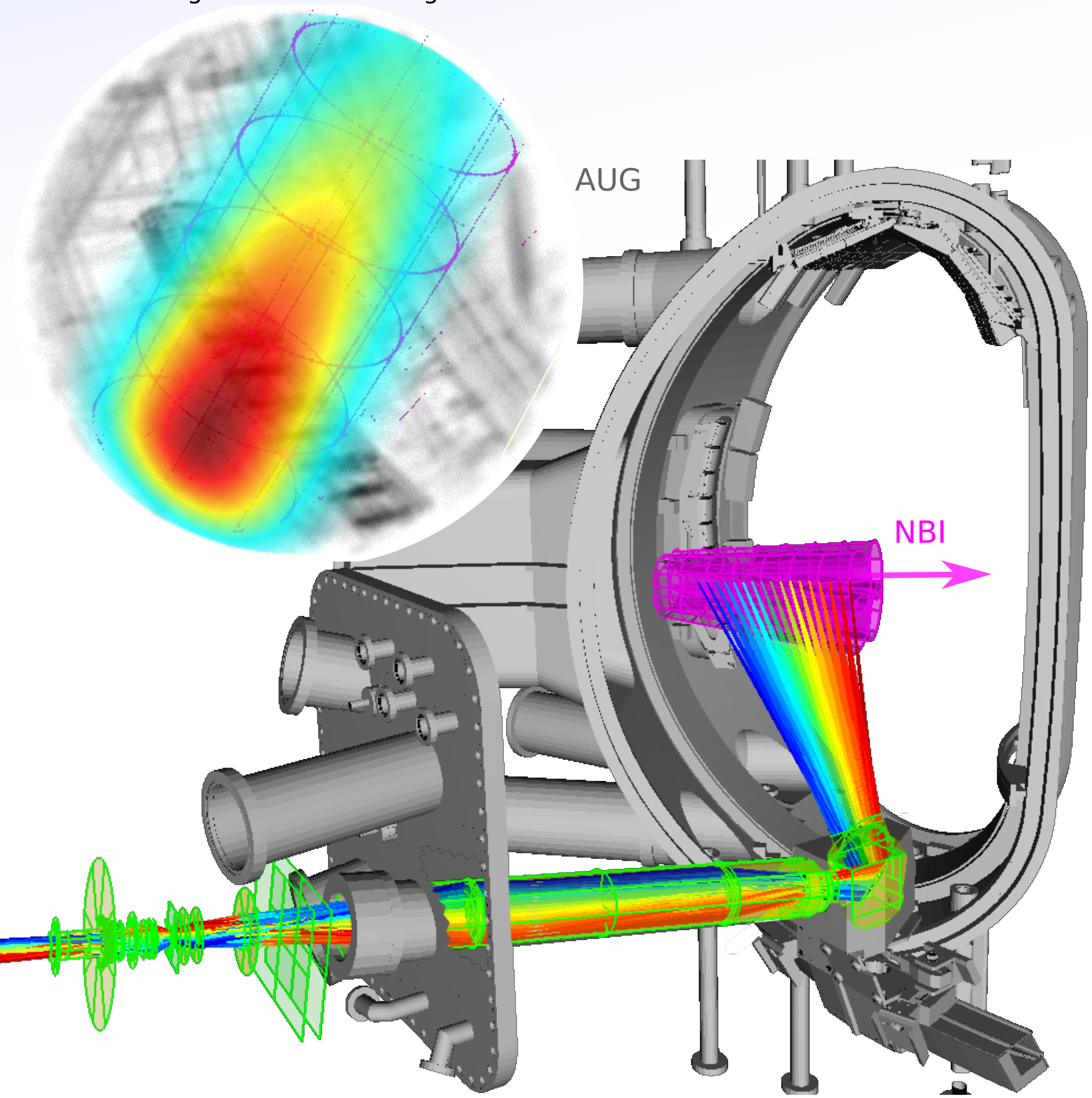
Motional Stark Effect at AUG

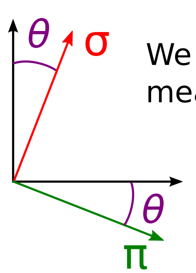
The IMSE system fits to the back of the the existing MSE optics, in place of the conventional MSE fibre bundle.

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

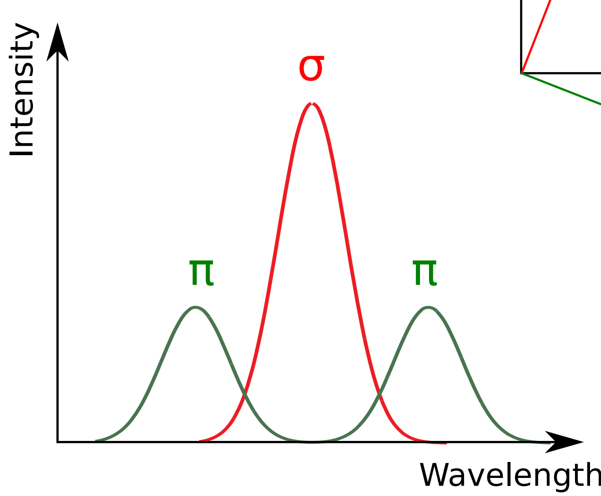
Hα/Dα beam emission is Doppler shifted by beam velocity and split by the Motional Stark Effect into π and σ components which is polarised perp/parallel to projected ***v*** *x* ***B*** direction.

Rendering of beams + background



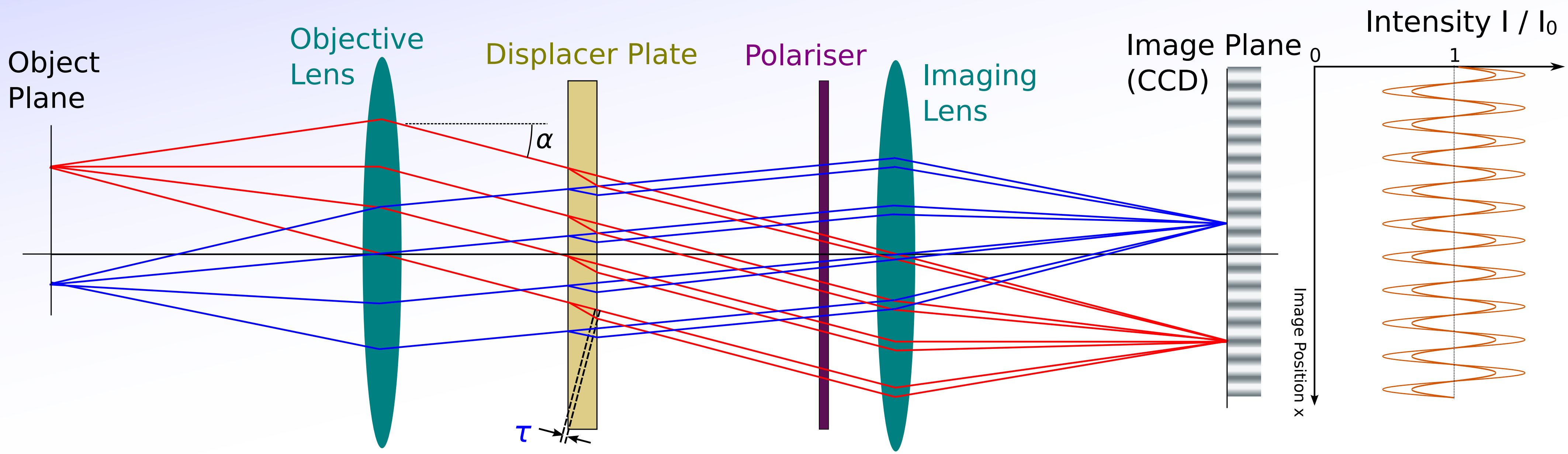


We want to measure θ



Coherence Imaging with Displacer Plates

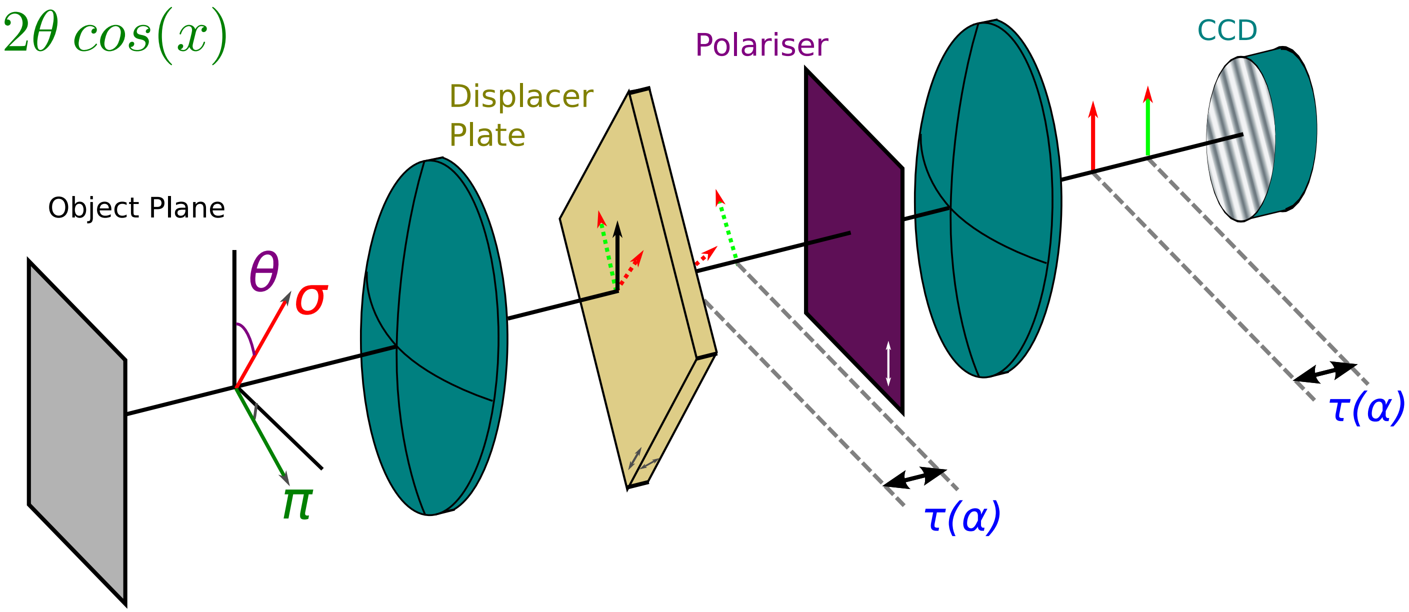
Displacer Plate: Angle dependent phase shift --> Interference pattern across image.



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...

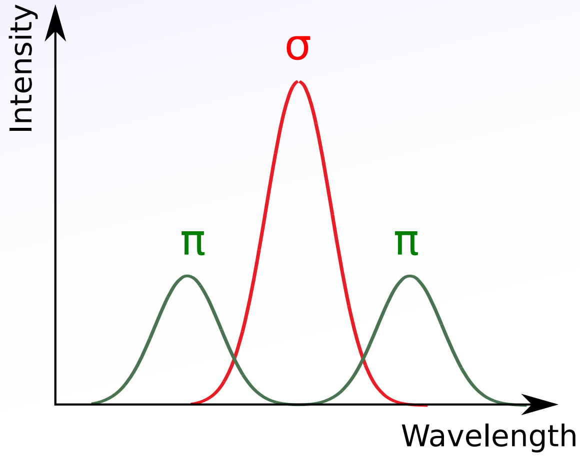


Spectral Coherence

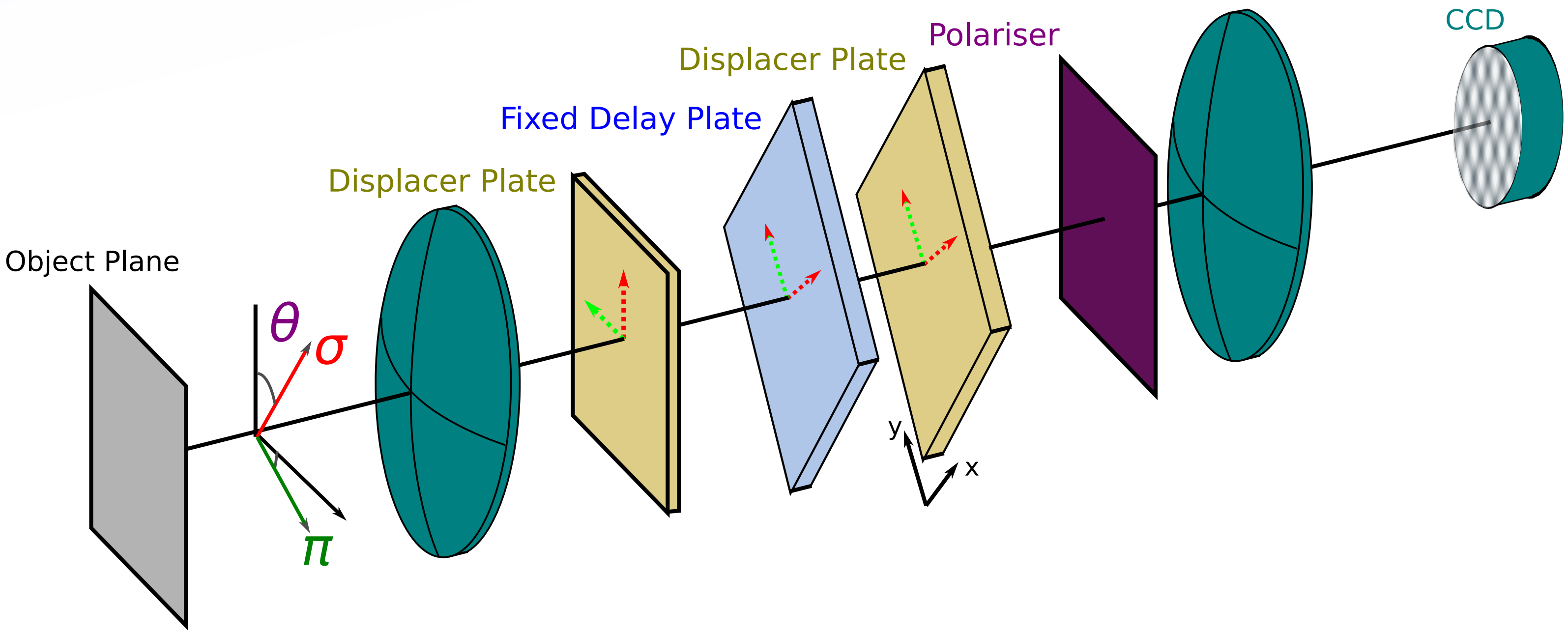
Add a delay plate to add spectral discrimination, but amplitude now also dependent on contrast:

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

Need to separate spectral contrast ζ from θ



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



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

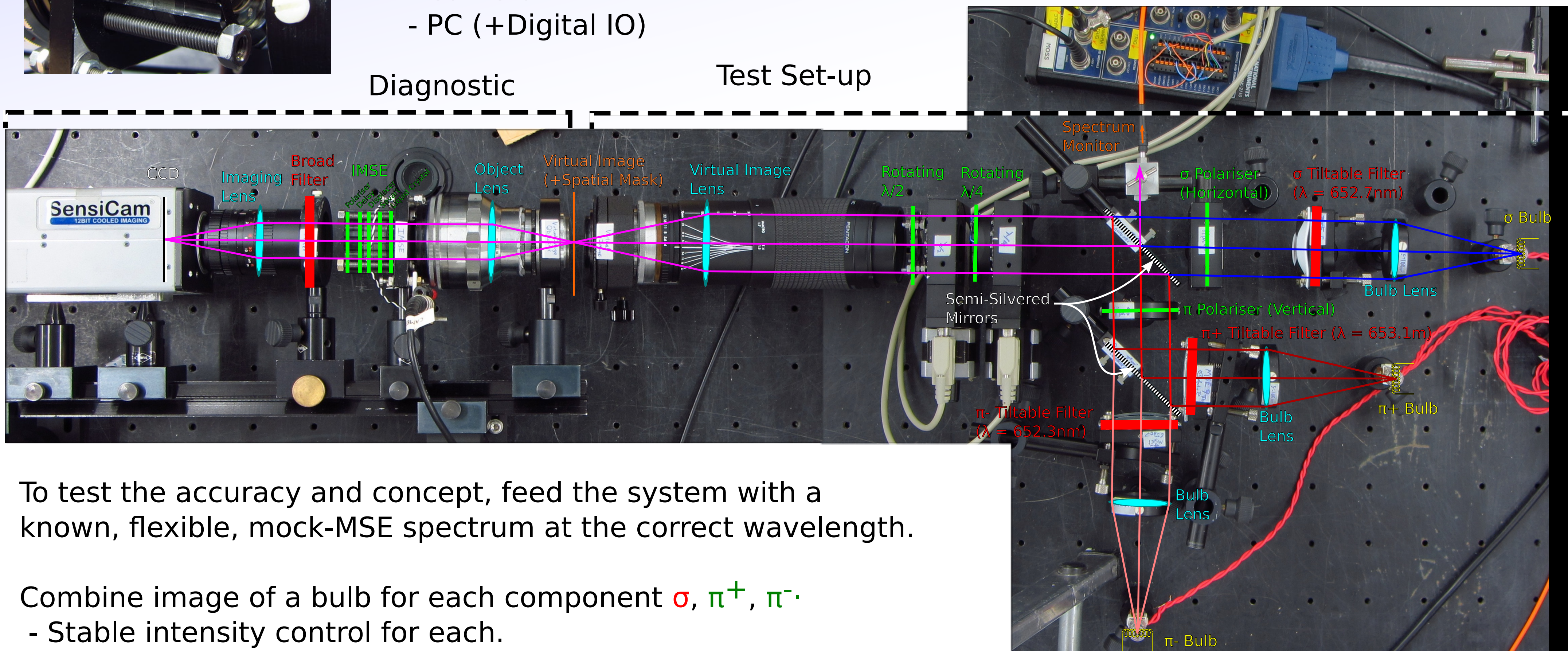
Test Setup

The IMSE hardware is very simple:

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

Optional:

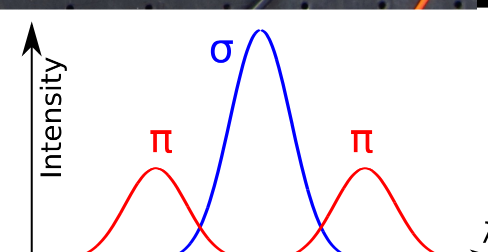
- Ferroelectric Liquid Crystal (FLC) for flexibility
- Temperature Cell (for temperature stability)



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

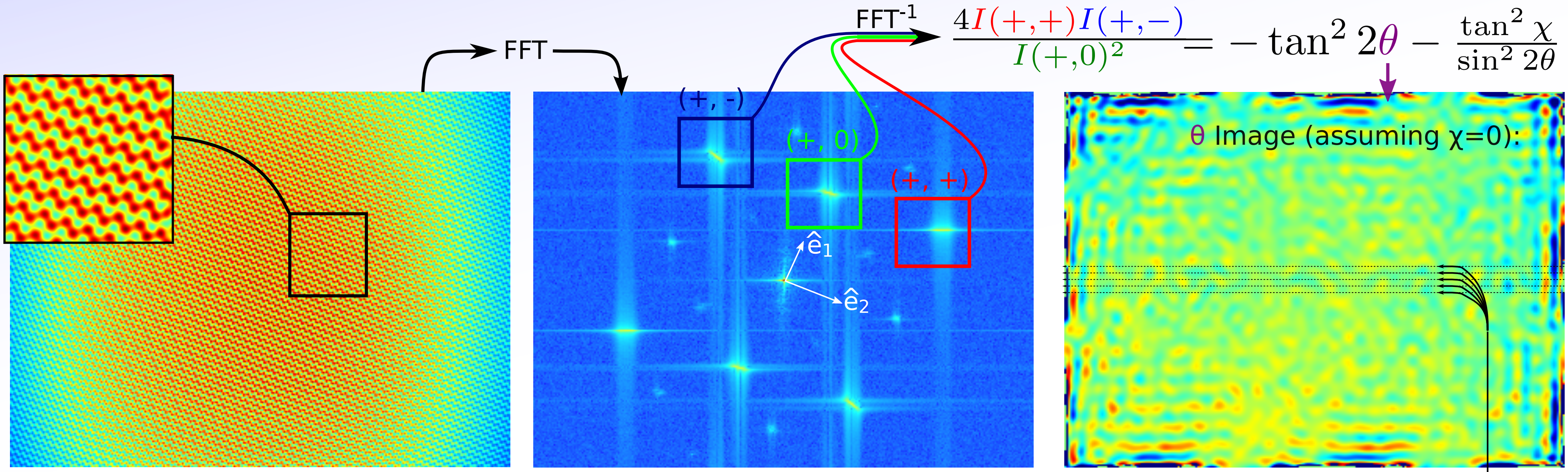
Combine image of a bulb for each component σ, π^+, π^-.

- 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.



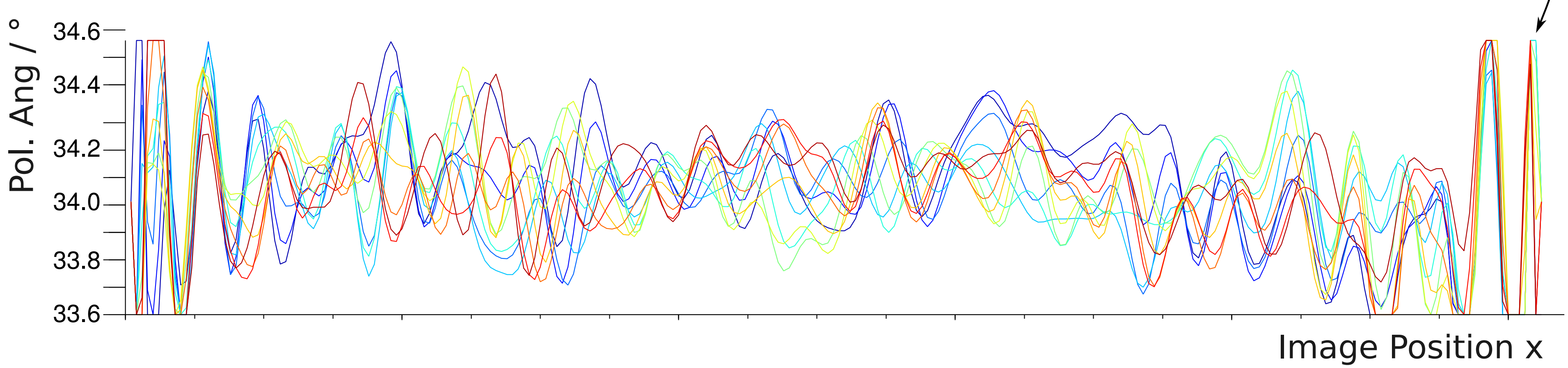
Full Fringes and Demodulation

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

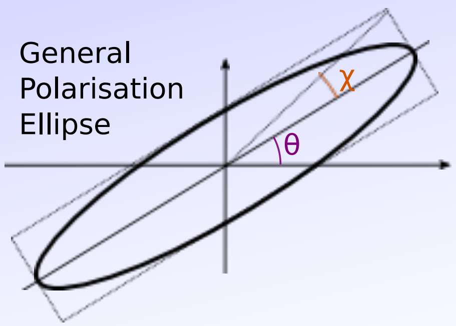


$$\frac{4I(+,+)I(+,-)}{I(+,0)^2} = -\tan^2 2\theta - \frac{\tan^2\chi}{\sin^2 2\theta}$$

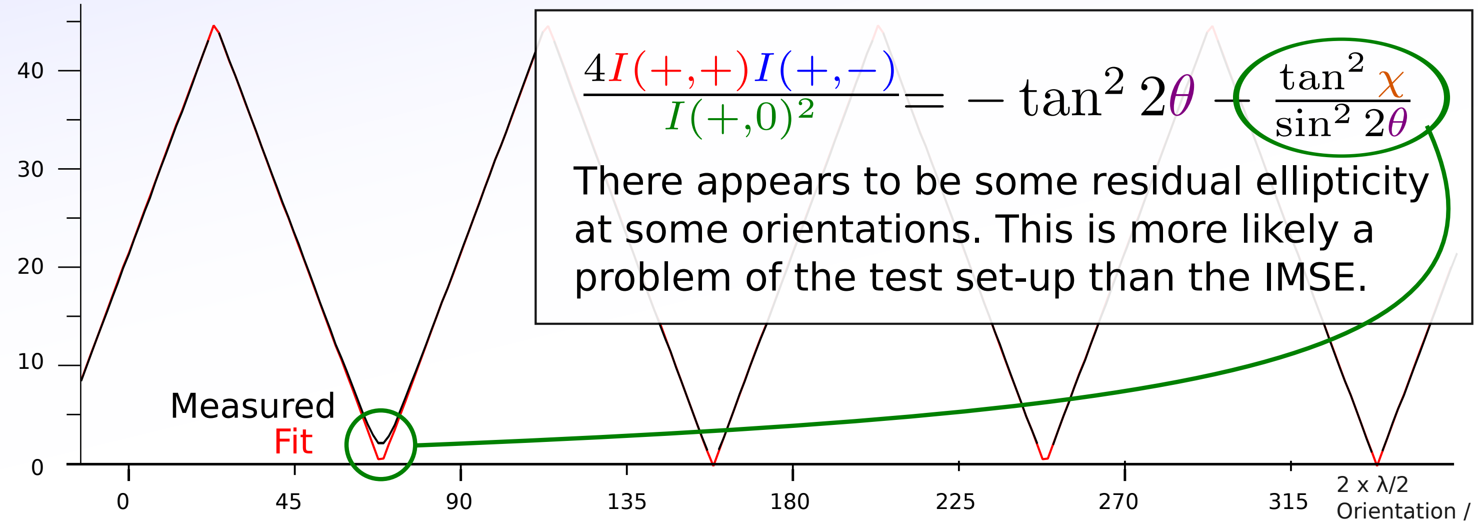
Pixel accuracy is degraded by edge effects etc. It might be possible to reduce this by improving the demodulation procedure later, but for now averaging 3-4 fringes works.



Calibration Sweep

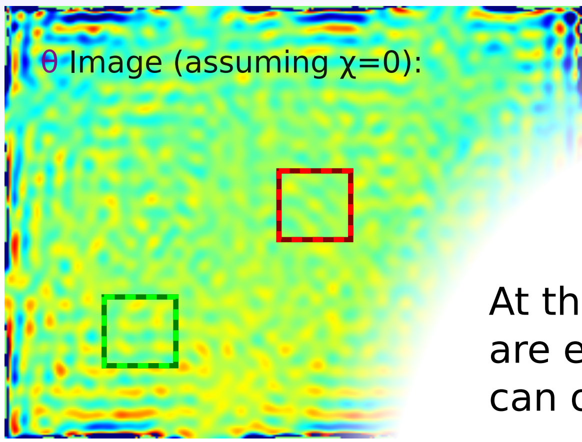


Check linearity and systematic error by averaging a small area and scanning the λ/2 plate to rotate the polarisation.

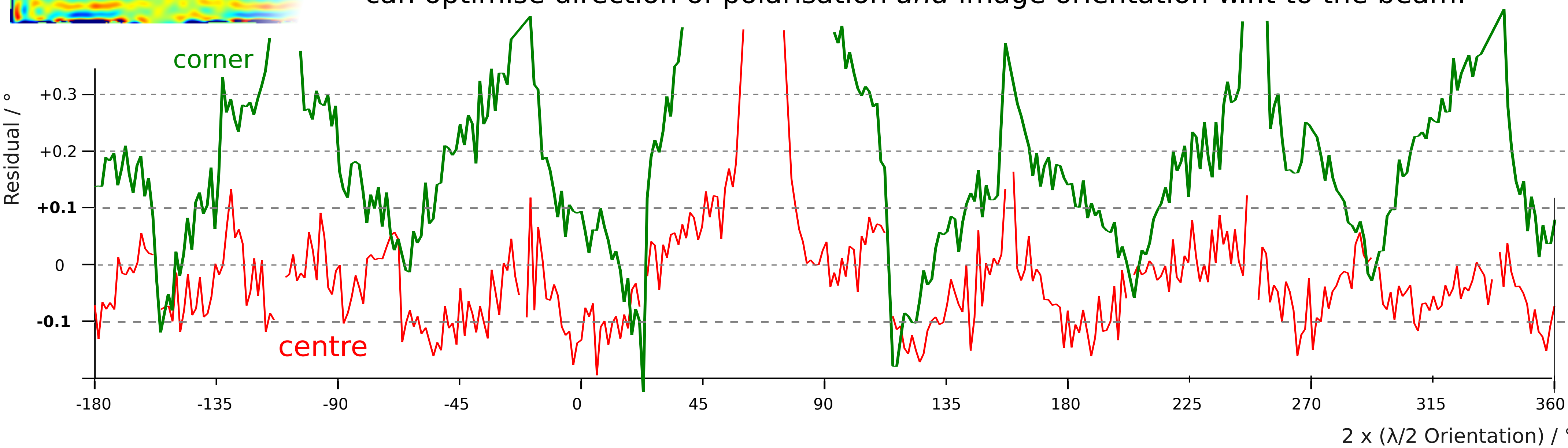


$$\frac{4I(+,+)I(+,-)}{I(+,0)^2} = -\tan^2 2\theta - \frac{\tan^2 \chi}{\sin^2 2\theta}$$

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



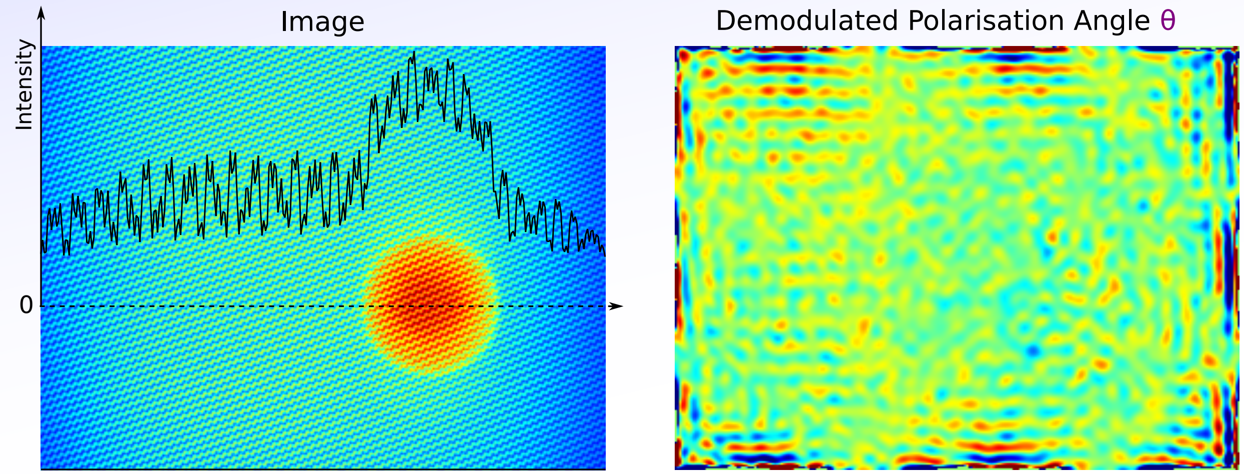
At the centre of the image, the residual is at the desired ±0.1°. Two corners are equally good but the other two corners show stronger ellipticity. We can optimise direction of polarisation *and* image orientation w.r.t to the beam.



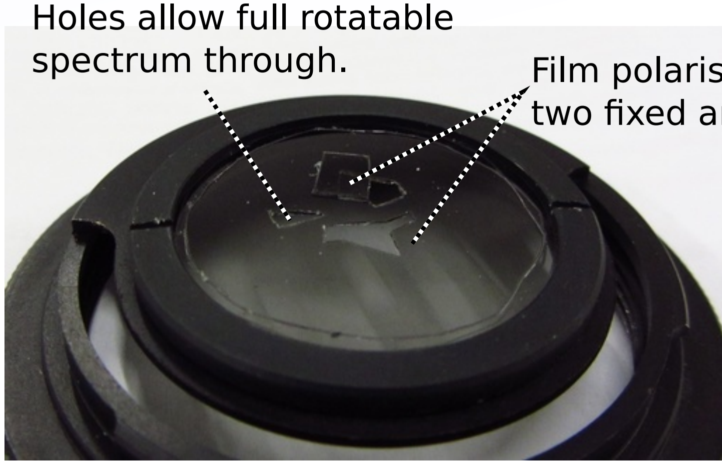
Background and spatial Variation.

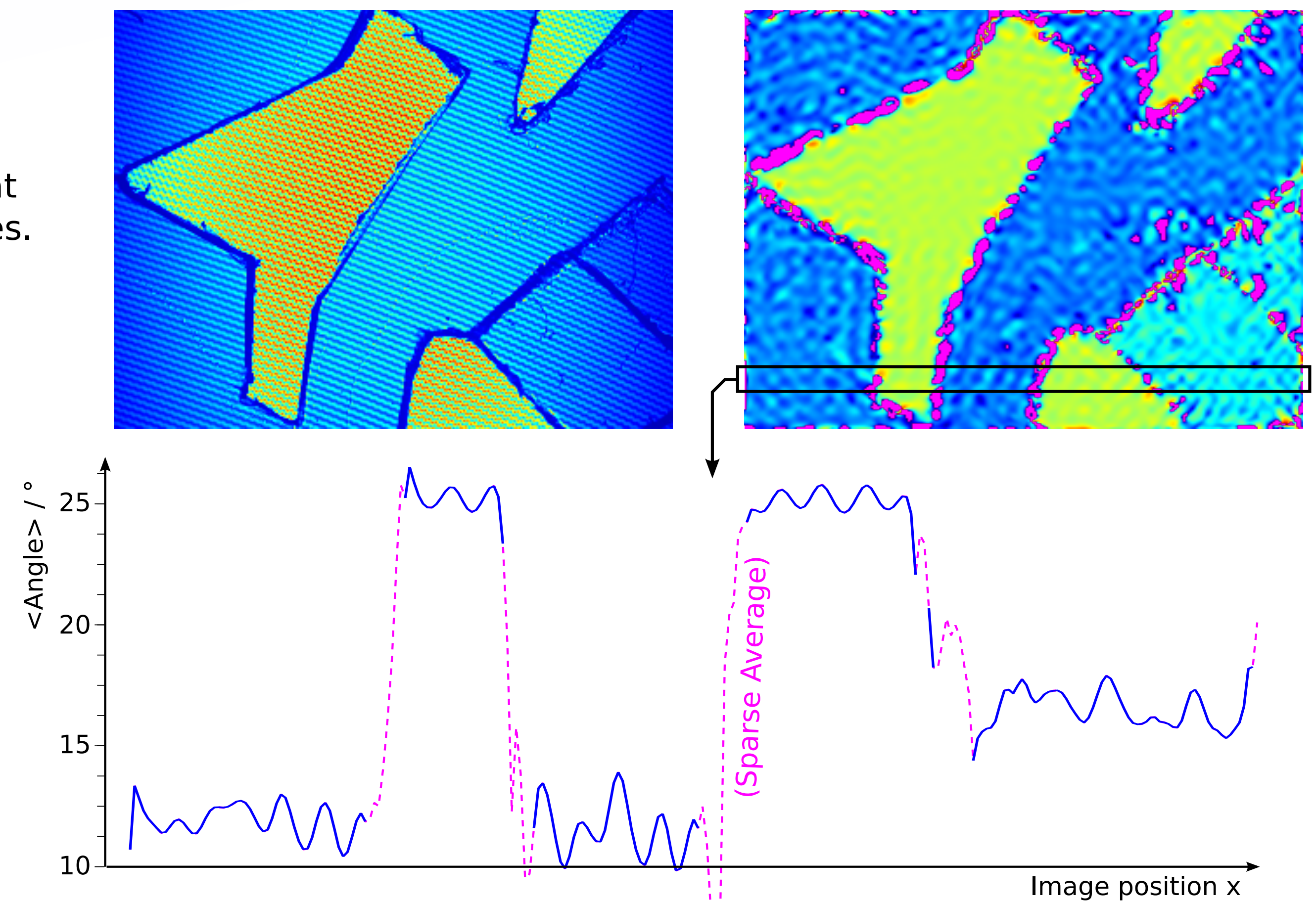
The measurement should be impervious to unpolarised *or* broadband background. To test, introduce bright light after filters and polarisers (backlight spectral monitor):

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:



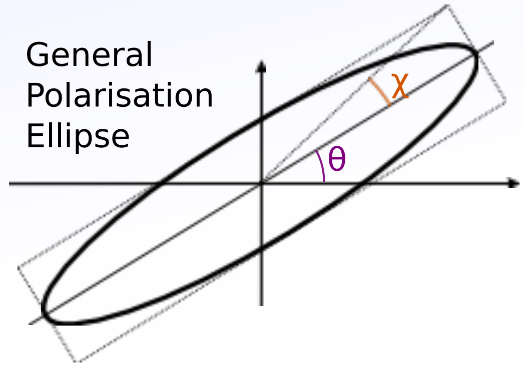


Spatial resolution is down to about 4x the fringe period. Sharp transition errors usually gives imaginary θ results.

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

Ellipticity

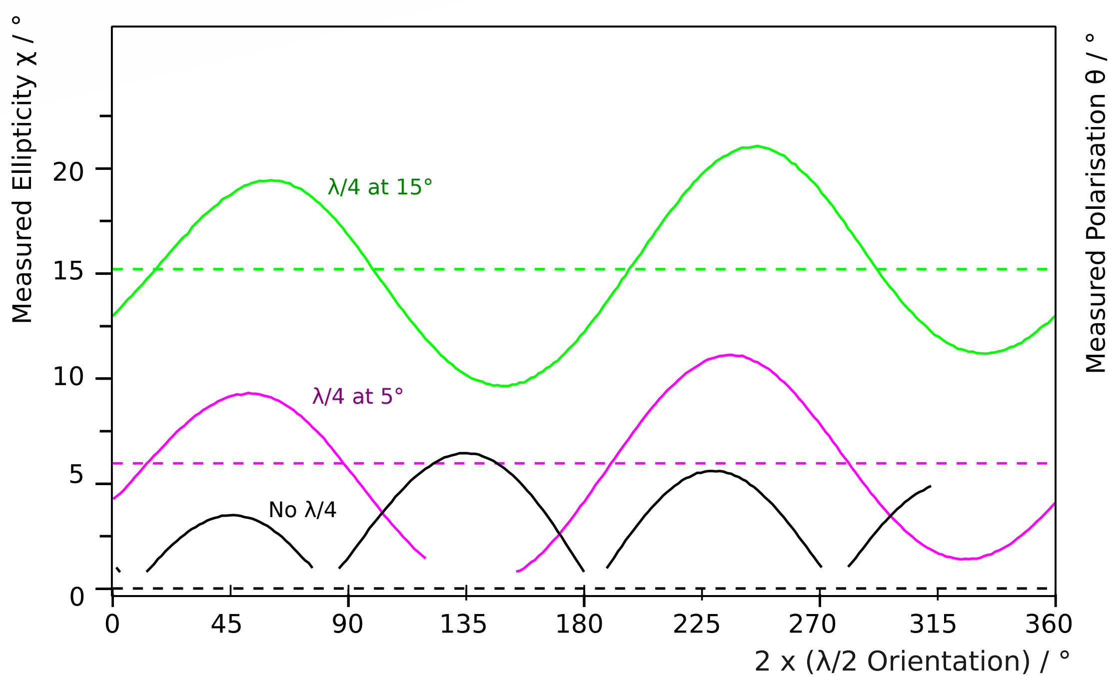
The λ/4 Ferroelectric-Liquid Crystal (FLC) gives a different operating mode of the system. When on, the amplitude demodulation gives the ellipticity angle: *tan χ*.



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.

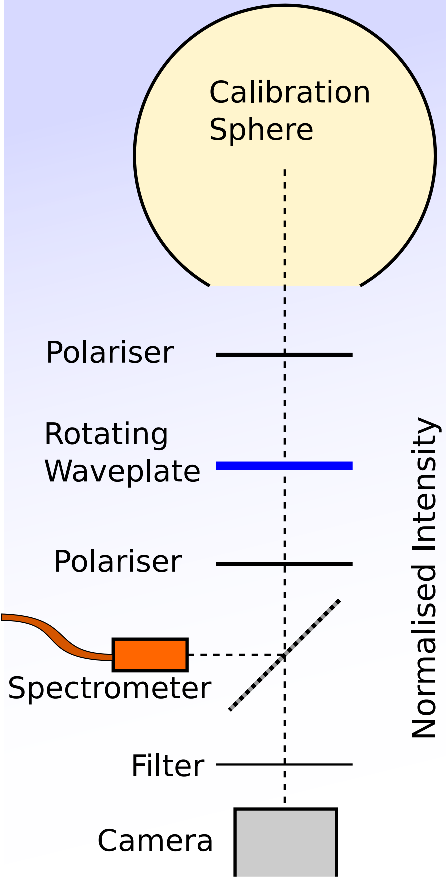
Tested using a λ/4 plate to create ellipticity and rotating the λ/2 plate to change angle.

Unfortunately, it didn't work....



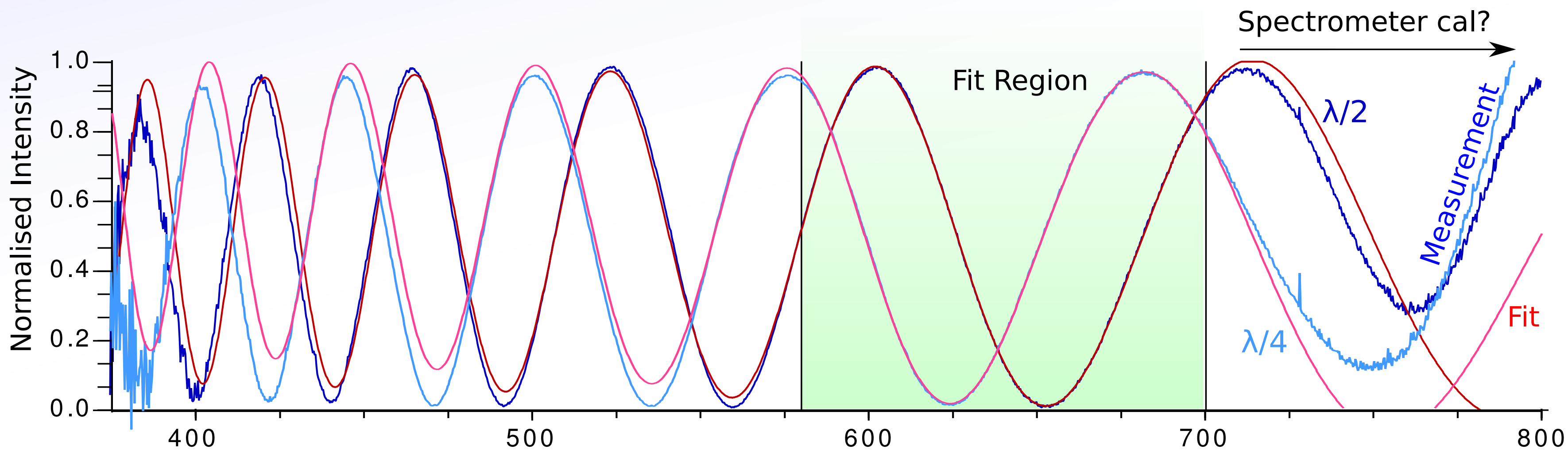
Waveplate Tests

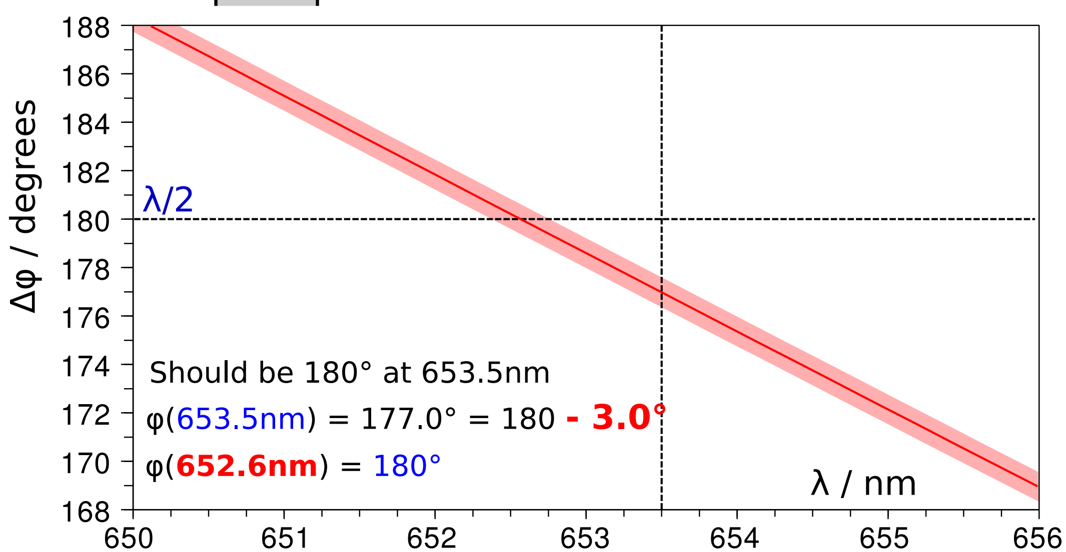
Oliver Ford
IPP Greifswald

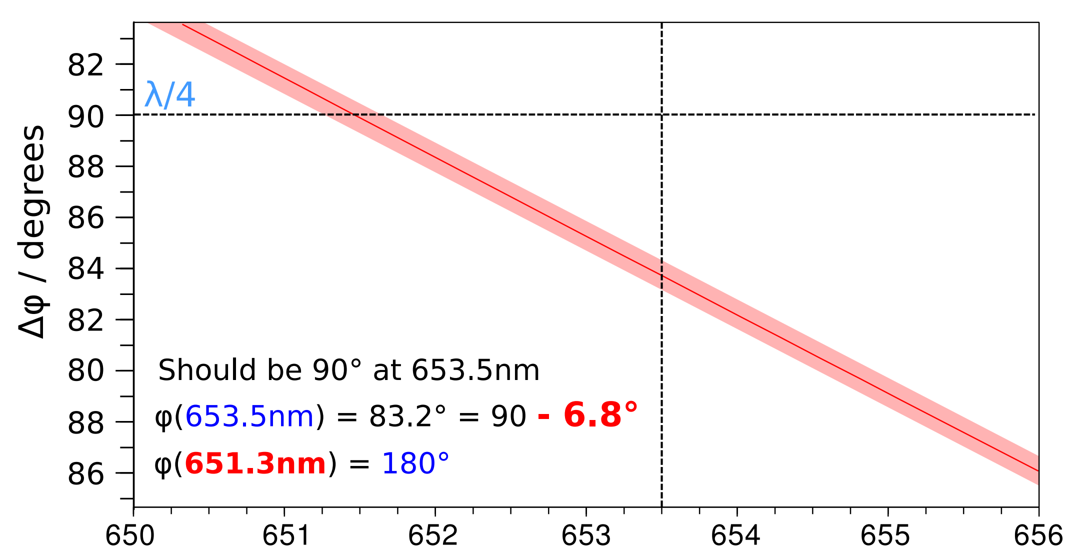


Tested the λ/2 and λ/4 plates to see if they are accurate enough.
Cross 2 polarisers, view spectrum of plate at 45° normalised to plate at 0°.

$$I \propto \frac{1}{2} - \frac{1}{2} cos(\phi) \qquad \phi(\lambda) = \frac{\lambda_0}{\lambda} \frac{\Delta N(\lambda)}{\Delta N(\lambda_0)} \phi(\lambda_0)$$





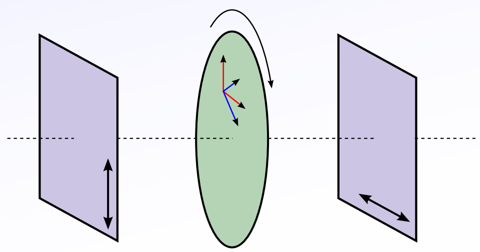


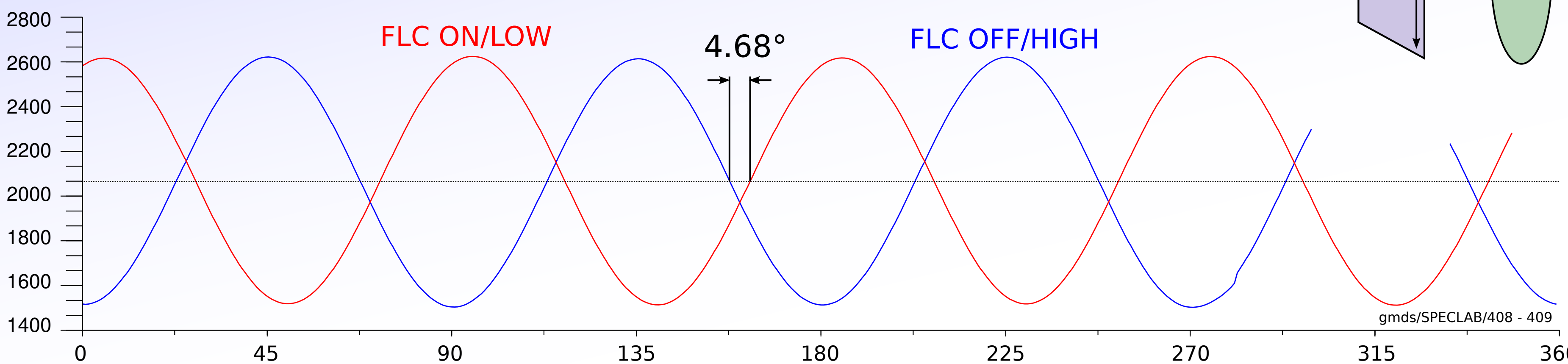
I'll buy some real zero-order precise plates later on, but for now just avoid using them.

Waveplate Tests - FLC

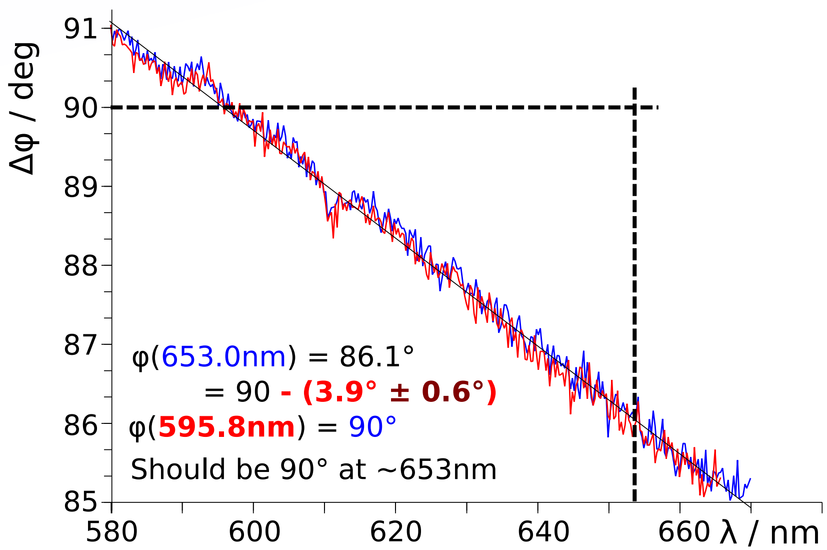
Oliver Ford
IPP Greifswald
gmds/SPECLAB/408,409

The FLC should be a λ/4 plate when on or off and the axis should rotate through 45°.
Put between crossed polarisers and rotate to find axes in both ON and OFF states:

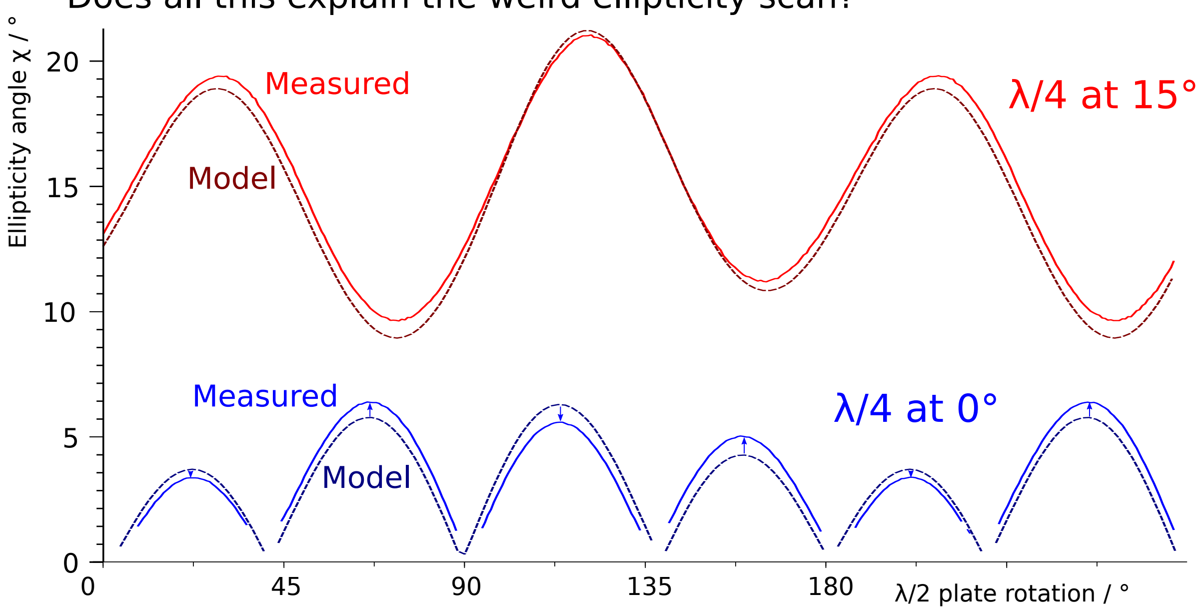




ON axis should be 45° from OFF, but is ***4.68°*** ±0.05° less.
The phase shift in both positions should be 90°:



Does all this explain the weird ellipticity scan?



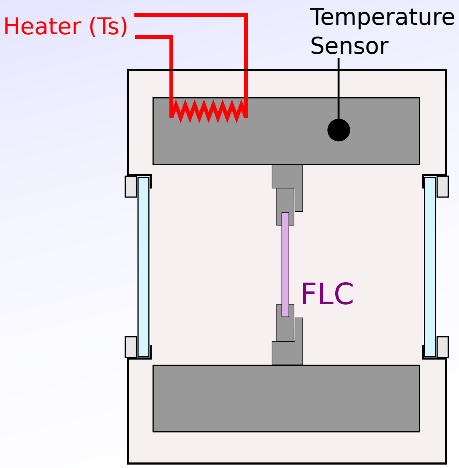
Basically, yes, it explains most of it, though there is a small remaining unknown.
- Avoid using λ/2 and λ/4 plates for now - last minute change to mechanical design.

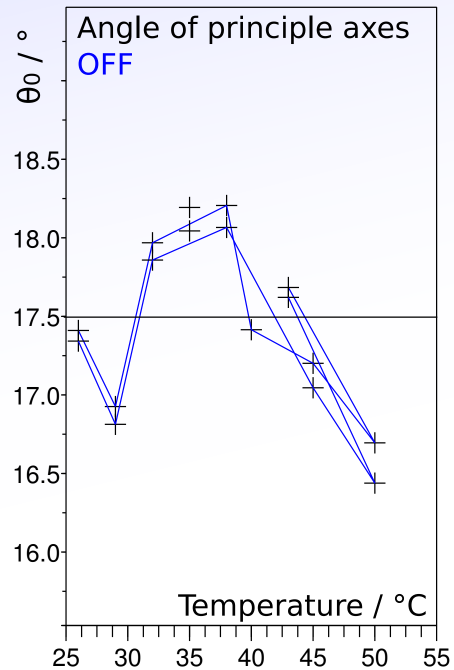
FLC is required for ellipticity measurement/compensation. For January experiments, can try cooking it...

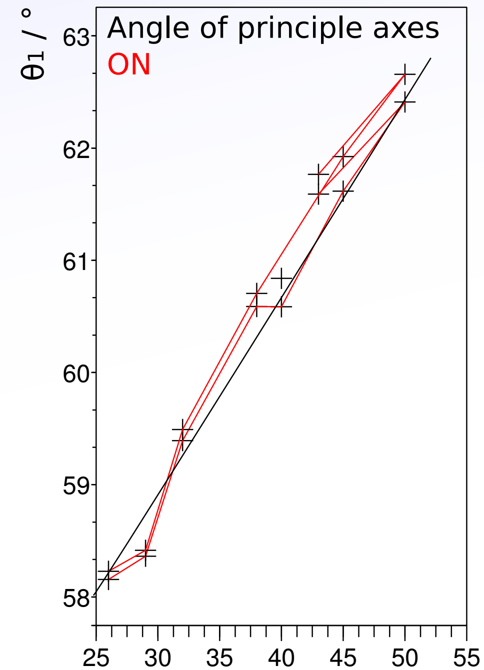
Waveplate Tests - Temperature Effect on FLC

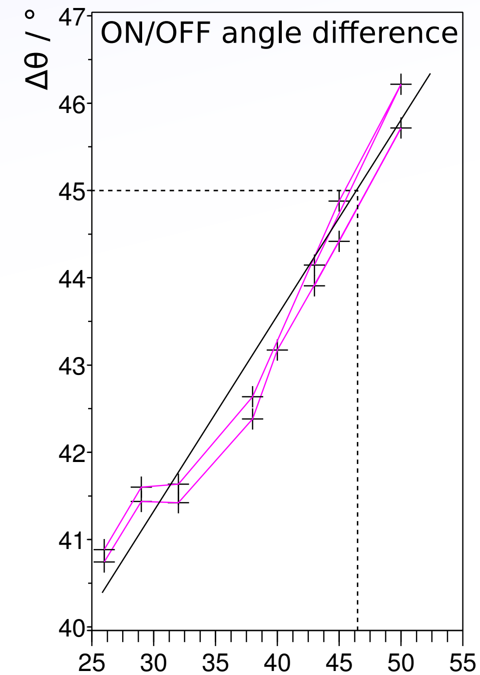
Oliver Ford
IPP Greifswald
gmds/SPECLAB/408,409

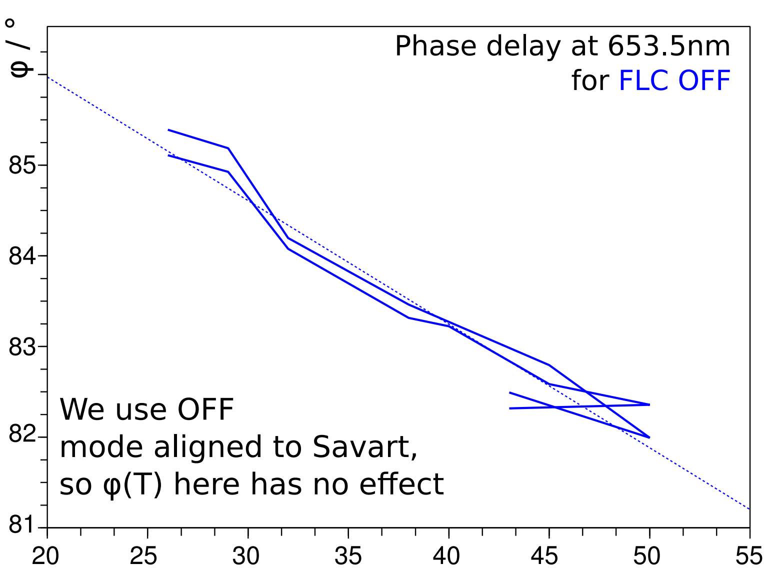
Loaded FLC into centre of heating cell and measured axis angles and phase shift vs temperature:

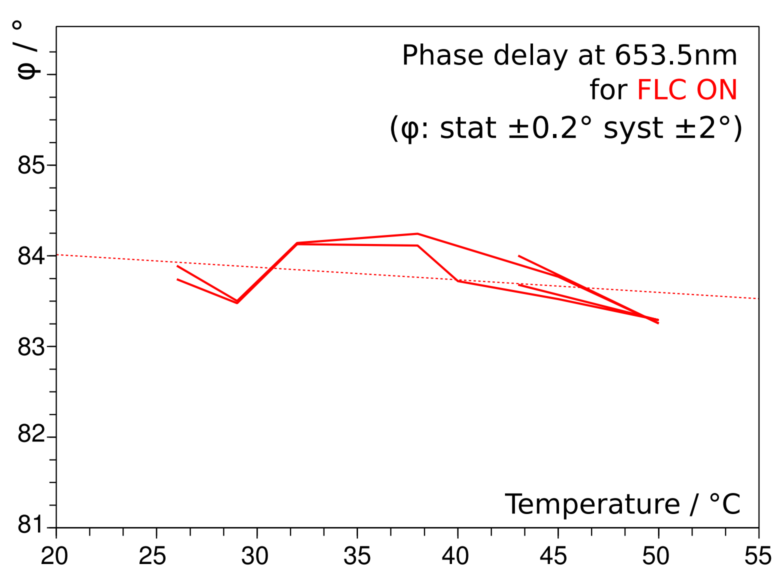










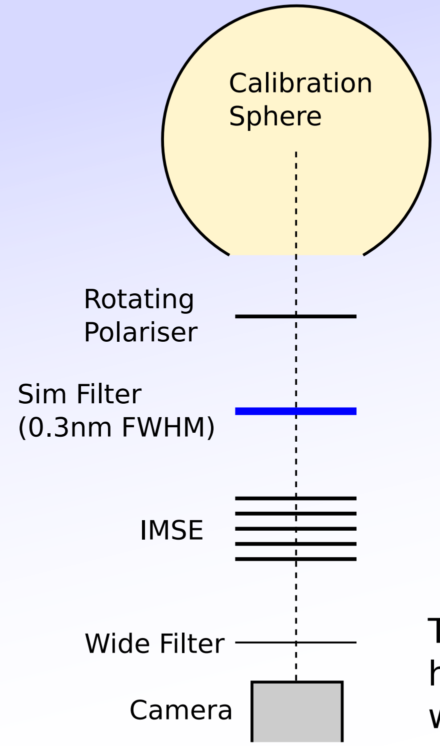


Temperature seems to effect only θ when on, and only φ when off.

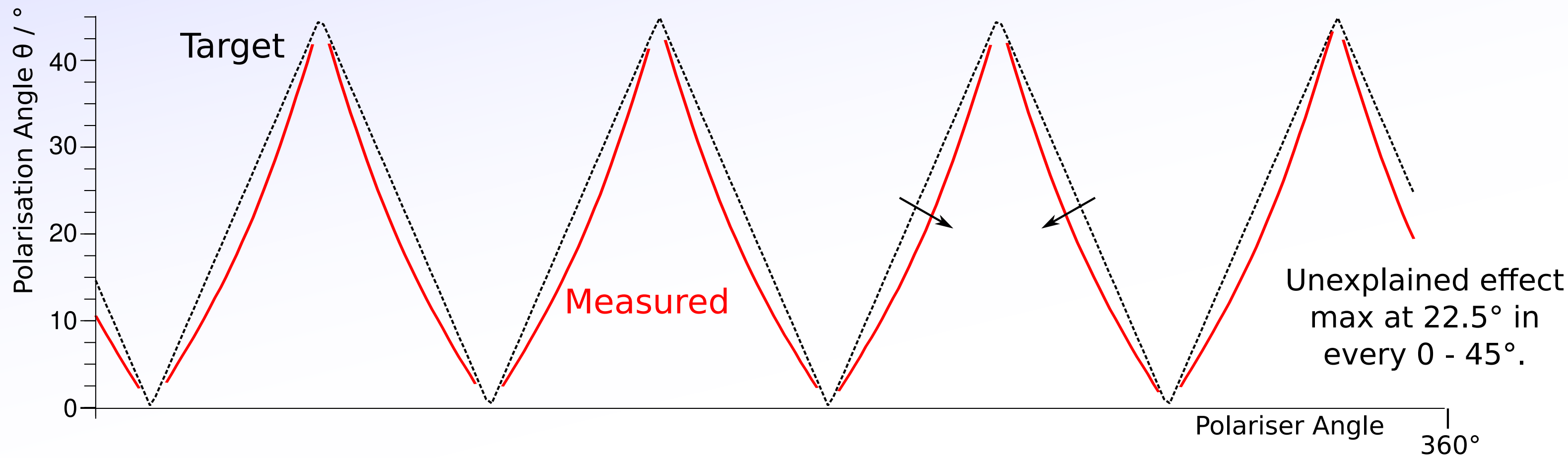
Running at 47°C gives 45°±0.5° switch and Δφ = 84°. Knowing the Δφ, I can in principle correct for the 84° phase effect.

The Mysterious Magic Number...

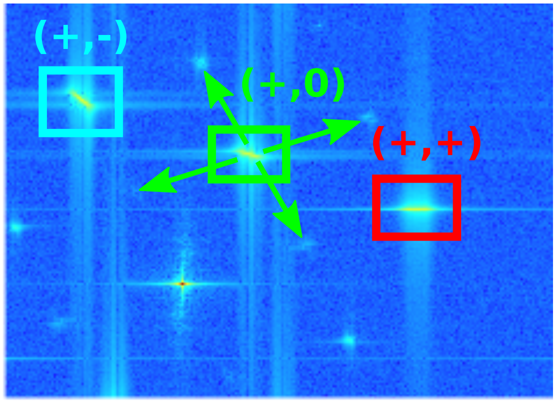
Oliver Ford
IPP Greifswald



The simplest possible setup, does not give the expected result (and never did):



This also happened a bit with the MSE test setup. At the time, I hypothesised it was due to ±0.5° misalignments of the plates which scatter one FFT component outside the evaluated region.

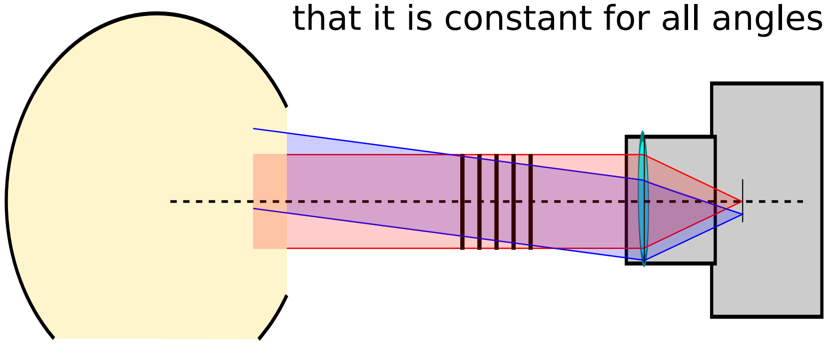


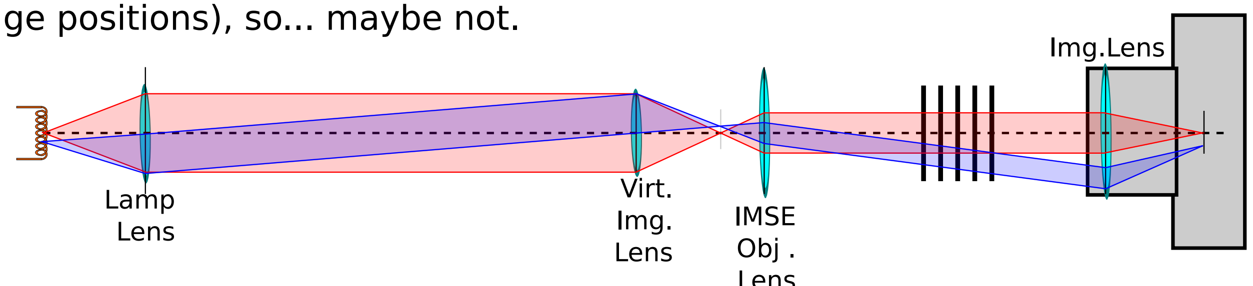
90% of the (+,0) component FFT power was outside, so I multiplied it by 110% and it fixed the problem - one single number fixes the whole image at all angles.

- the magic number was best at 89% and seemed to be fixed regardless of spectrum, rotation, ellipticity, plate angles etc.

However, for the calibration sphere, the magic number is 56%.

I think I've ruled absolutely everything else out, and the only thing left is that it has something to do with the light delivery. Something *seems* to vary with the area of the plates used. It is still very odd that it is constant for all angles (image positions), so... maybe not.





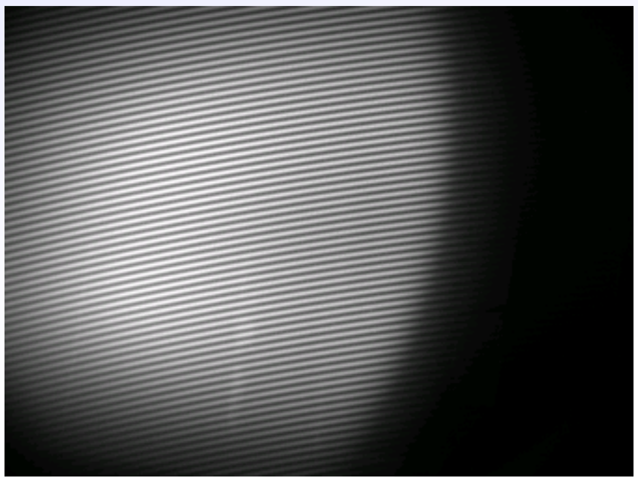
Any thoughts?

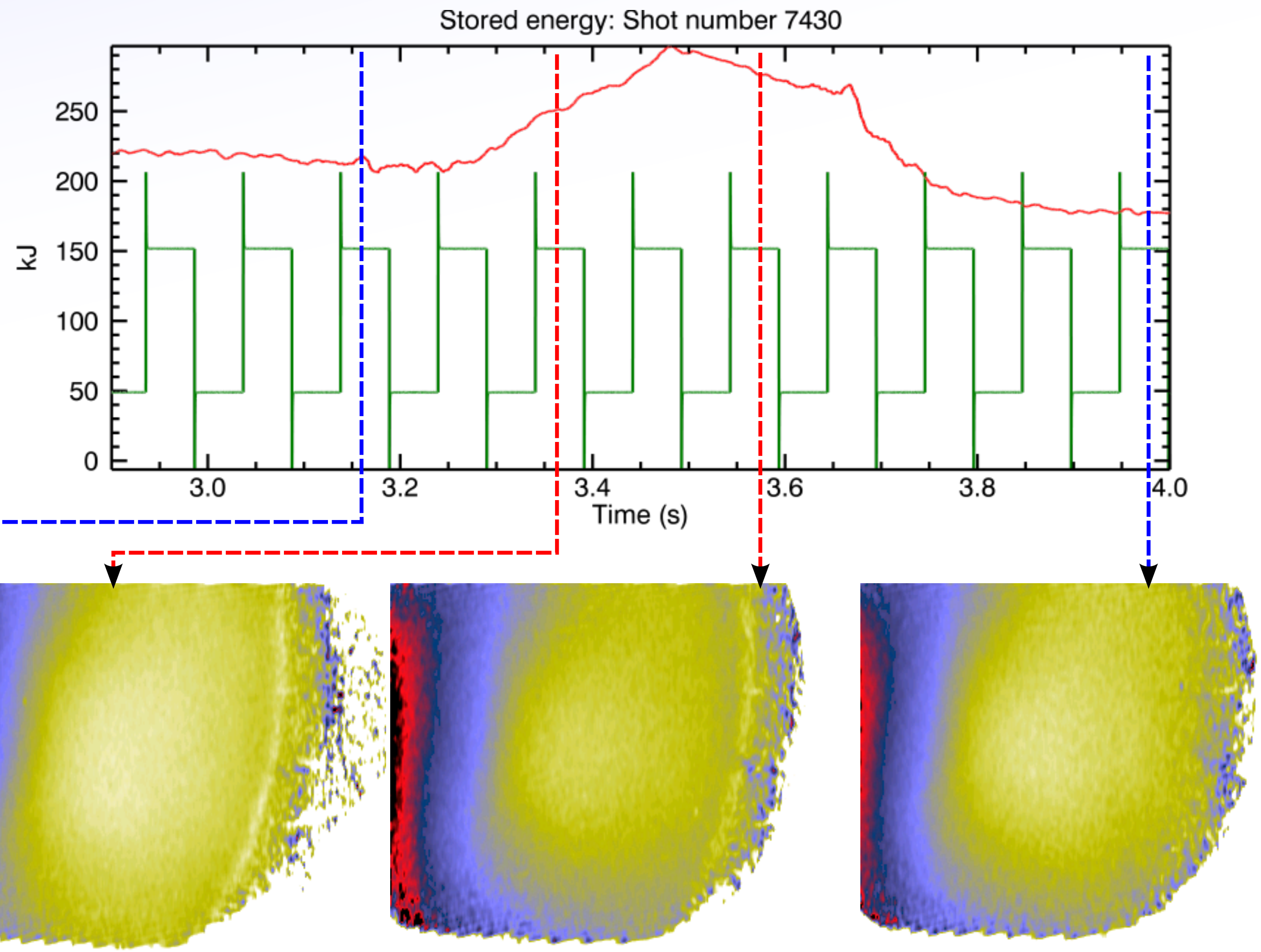
Diagrams are not to scale and are completely made up.

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.

IMSE Design - Status Dec 2012

Oliver Ford
IPP Greifswald

2011

- ✔ 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.

2012

- ✔ Asses lens options for optics coupling.
- ✔ Calculate and order required crystals (for middle range of lenses)
- ✔ Calculate and order filter (approximate done, ••• order the optimal one)
- ✔ Investigate non-orthogonal fringes idea (works great)
- ✔ Build polarisation test setup (simulated spectrum, OK, getting better filters).
- ✔ Measurement principal test (Zeeman splitting).
- ✔ Assess realistic polarisation accuracy.
- ✔ Develop experiment software (Camera, ADC, spectrometer, Calib. Stepper etc)
- ✔ Software/Methods for exact alignment of plates.
- ✔ Assess neutron damage probability to camera (not much info, but looks OK)
- ✔ Design support structure.
- ✔ Lighting of background polarisers for absolute calibration.
- ~✔ Get support structure built.

Next...

- ••• Test camera under magnetic field (in-place)
- ••• 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 .
- ••• 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.
- ••• **Figure out the source of the 'magic number' and/or a way to find it in place at AUG.**
- ••• **Collect some data at AUG!**

Much later...

- ✔ Modelling and image generation for W7X.
- ✔ Ability to infer polarisation angle for W7X images.
- ✔ Ability to infer parallel current for W7X.
- ••• W7X assessment based on AUG results.