Motional Stark Effect Imaging for ASDEX Upgrade:

Performance Tests and Expected Capabilities

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2: Plasma Research Laboratory, Australian National University, Canberra

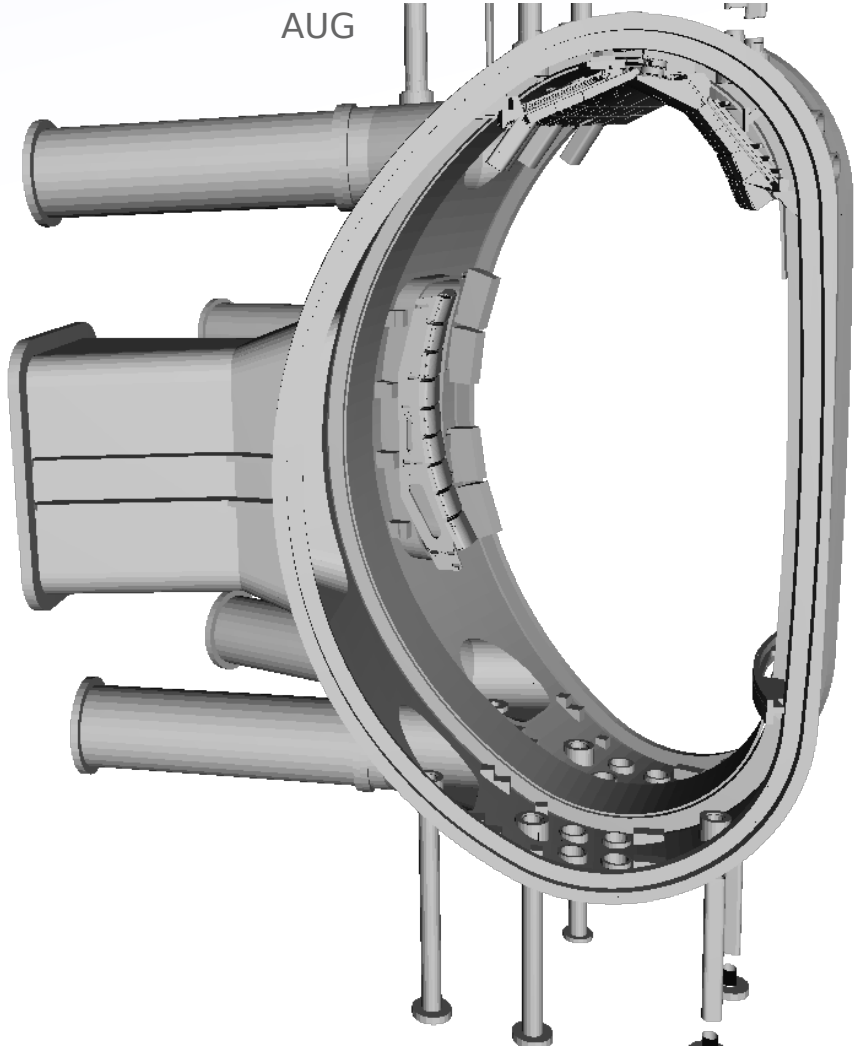
- Basic Principle
- Concept and Accuracy Tests
  - Test Spectrum
  - Polarisation angle measurement
  - Spatial variation
  - Unpolarised background
  - Ellipticity

  [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.

Rendering of beams + background



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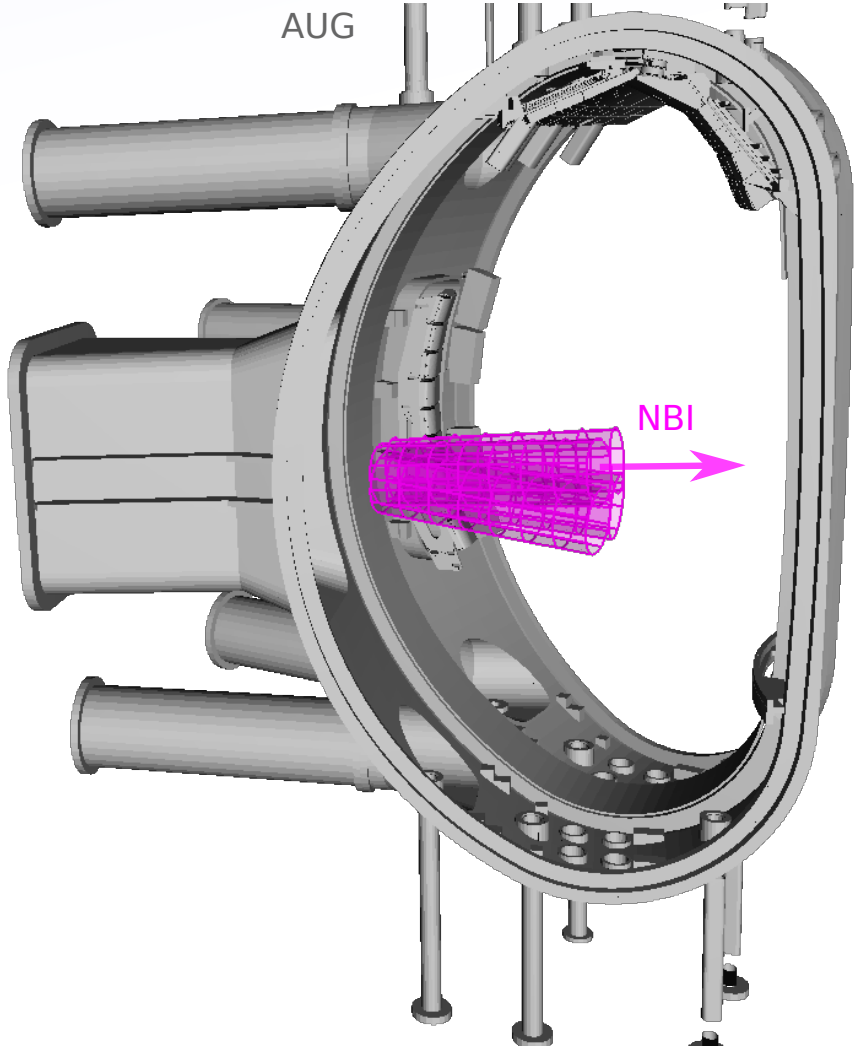

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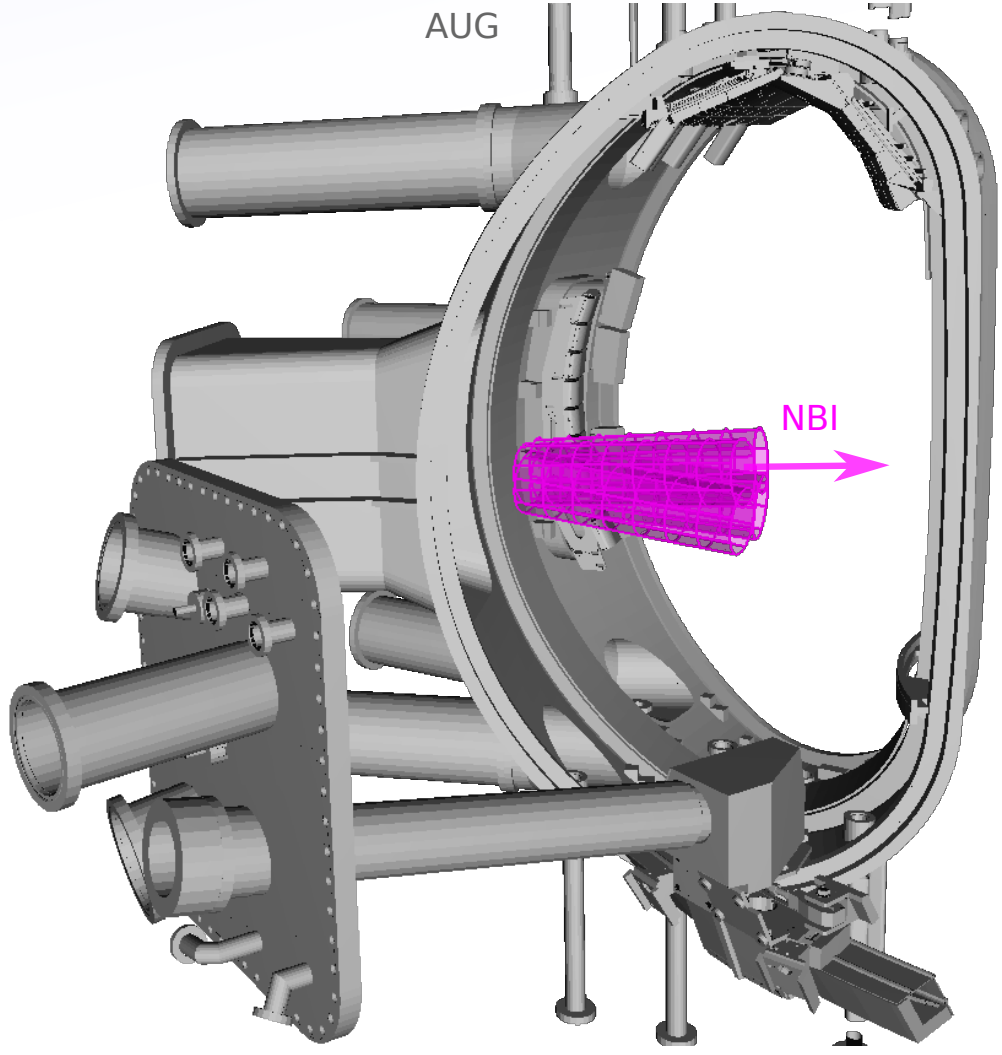

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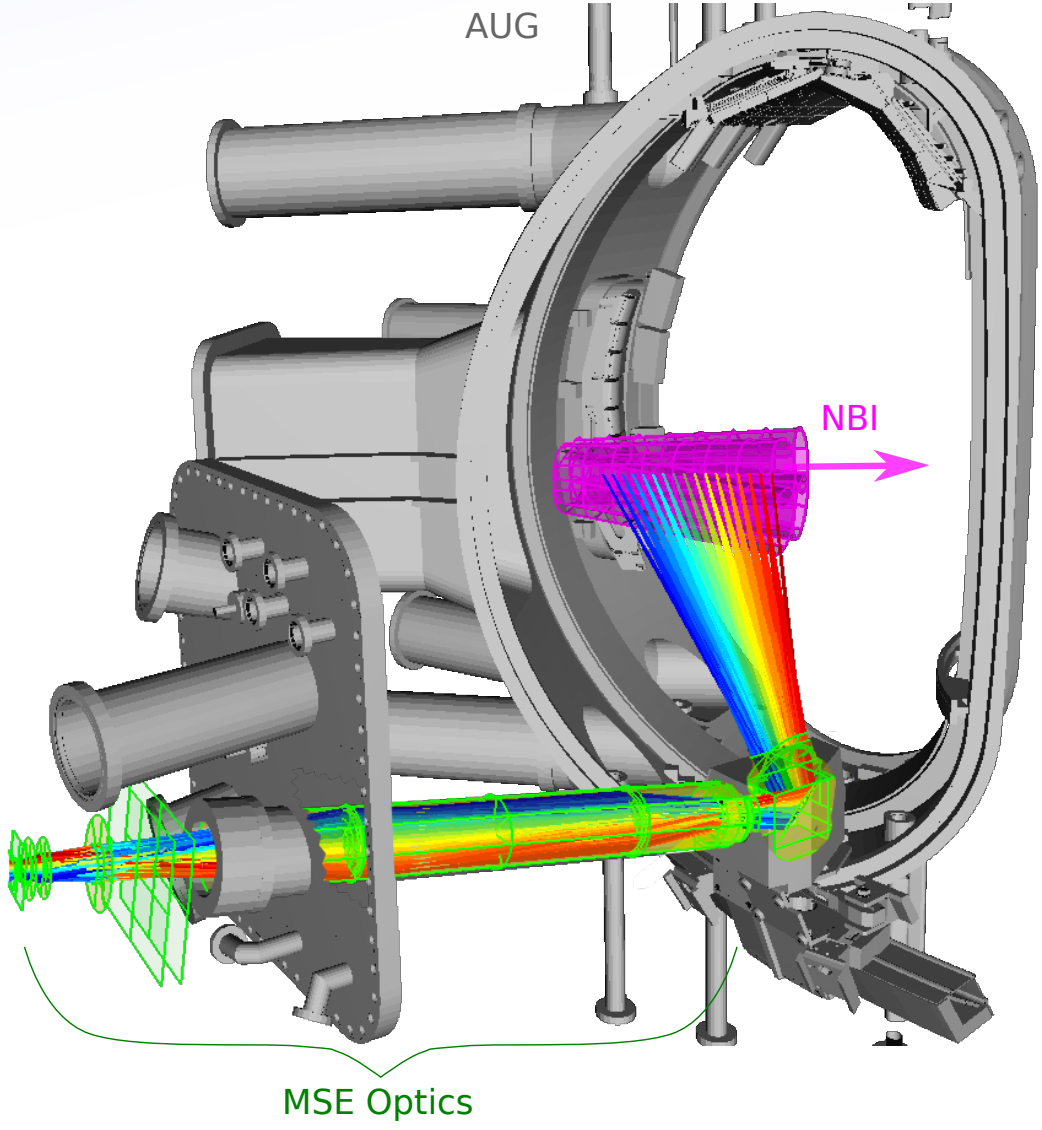

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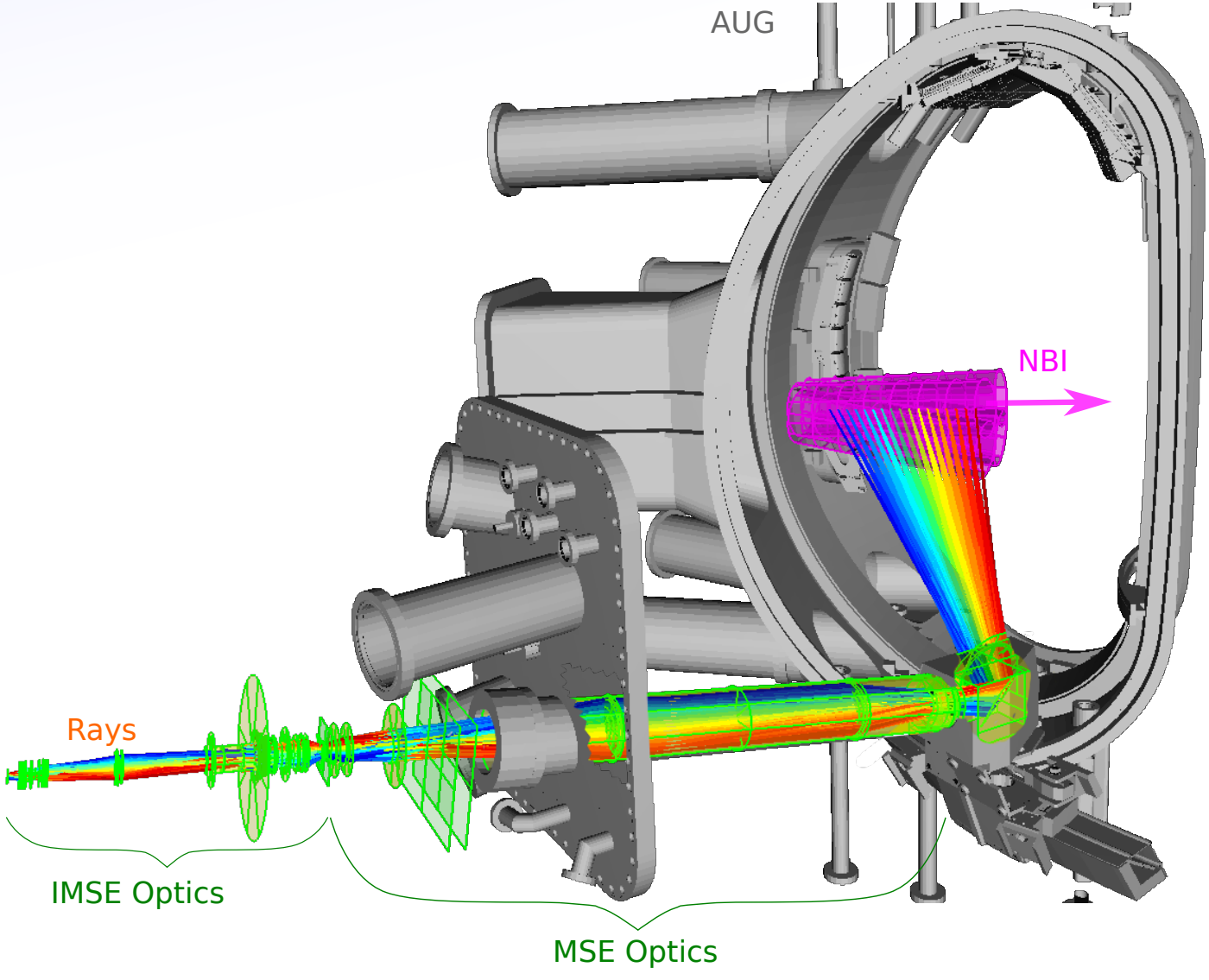

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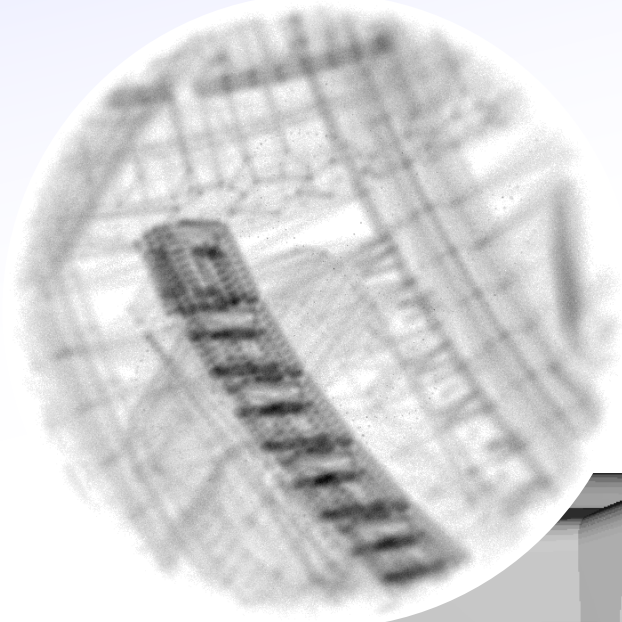

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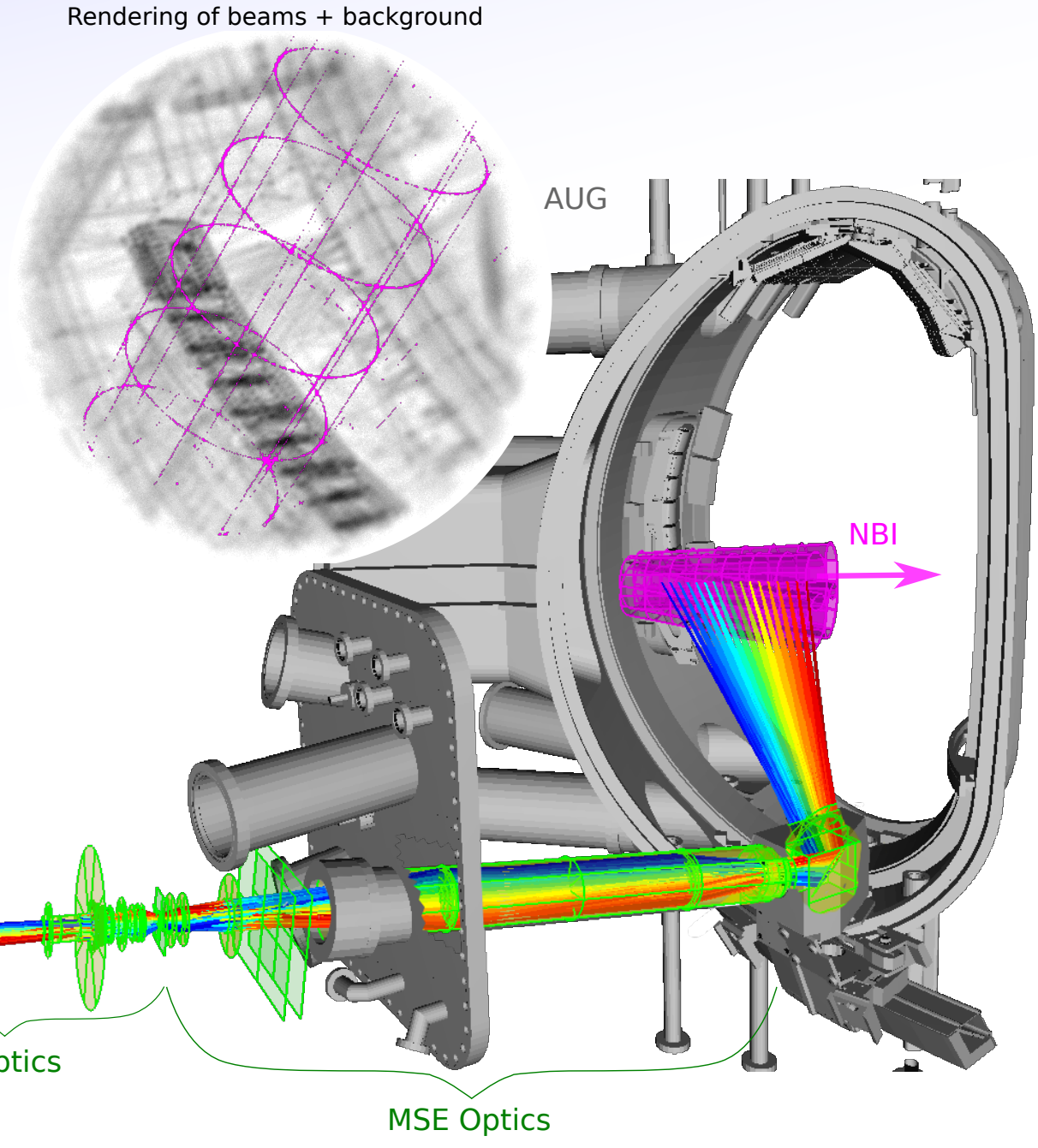

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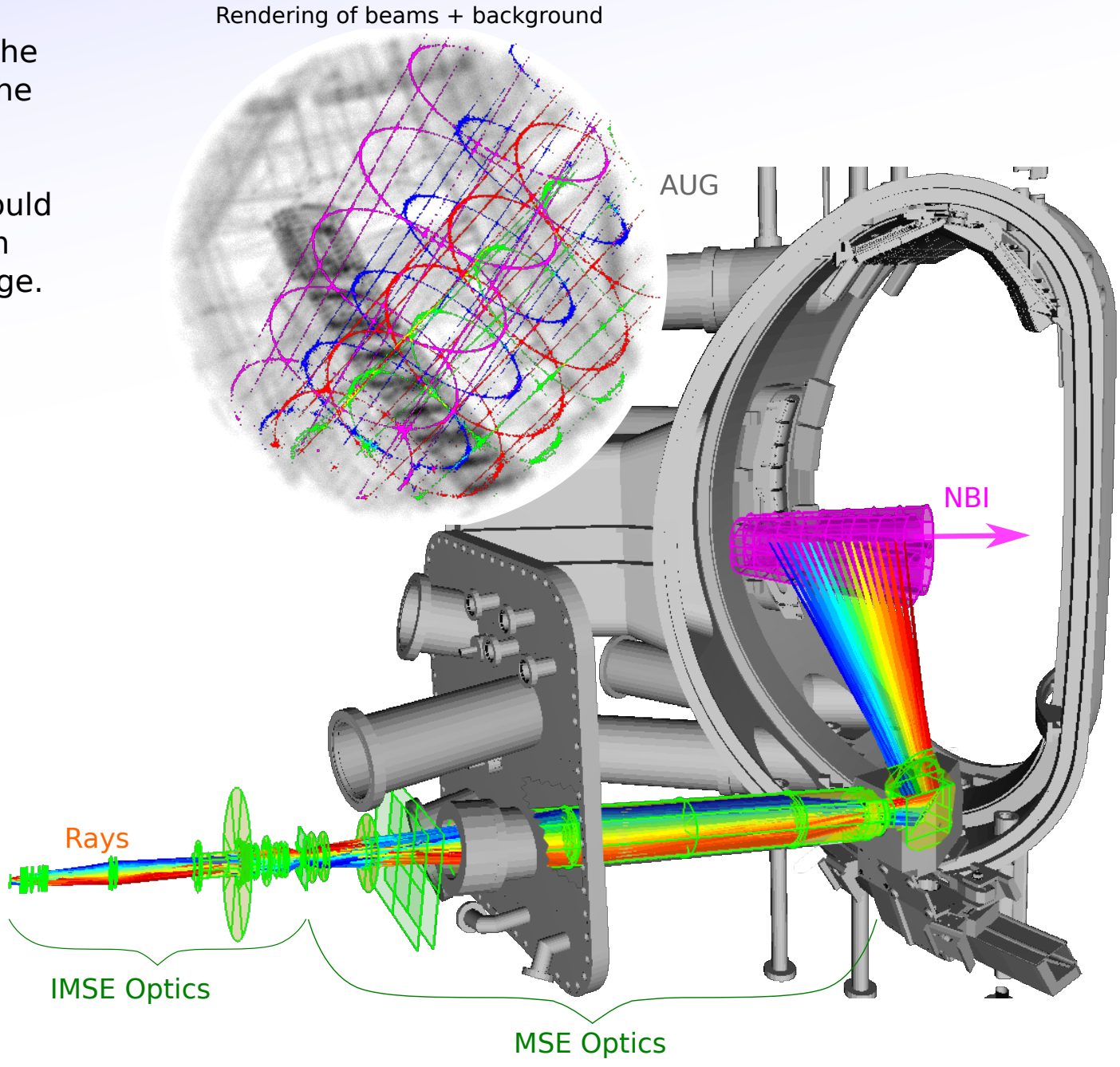

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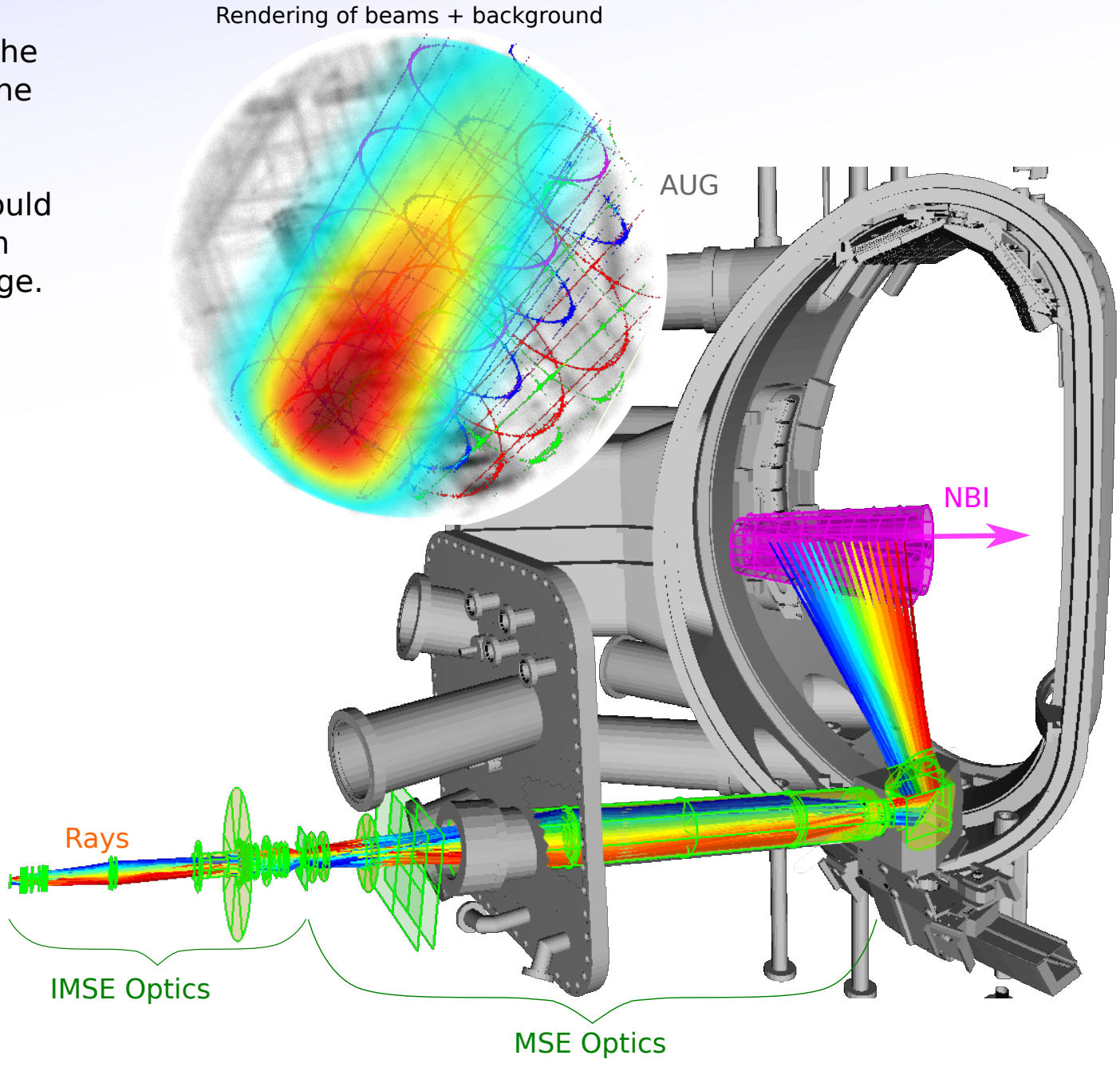

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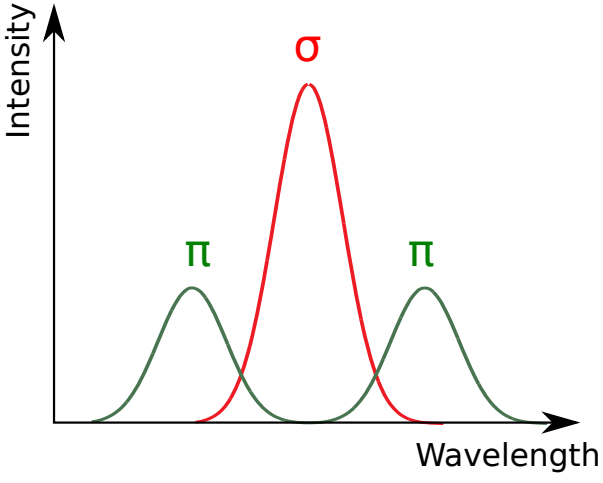
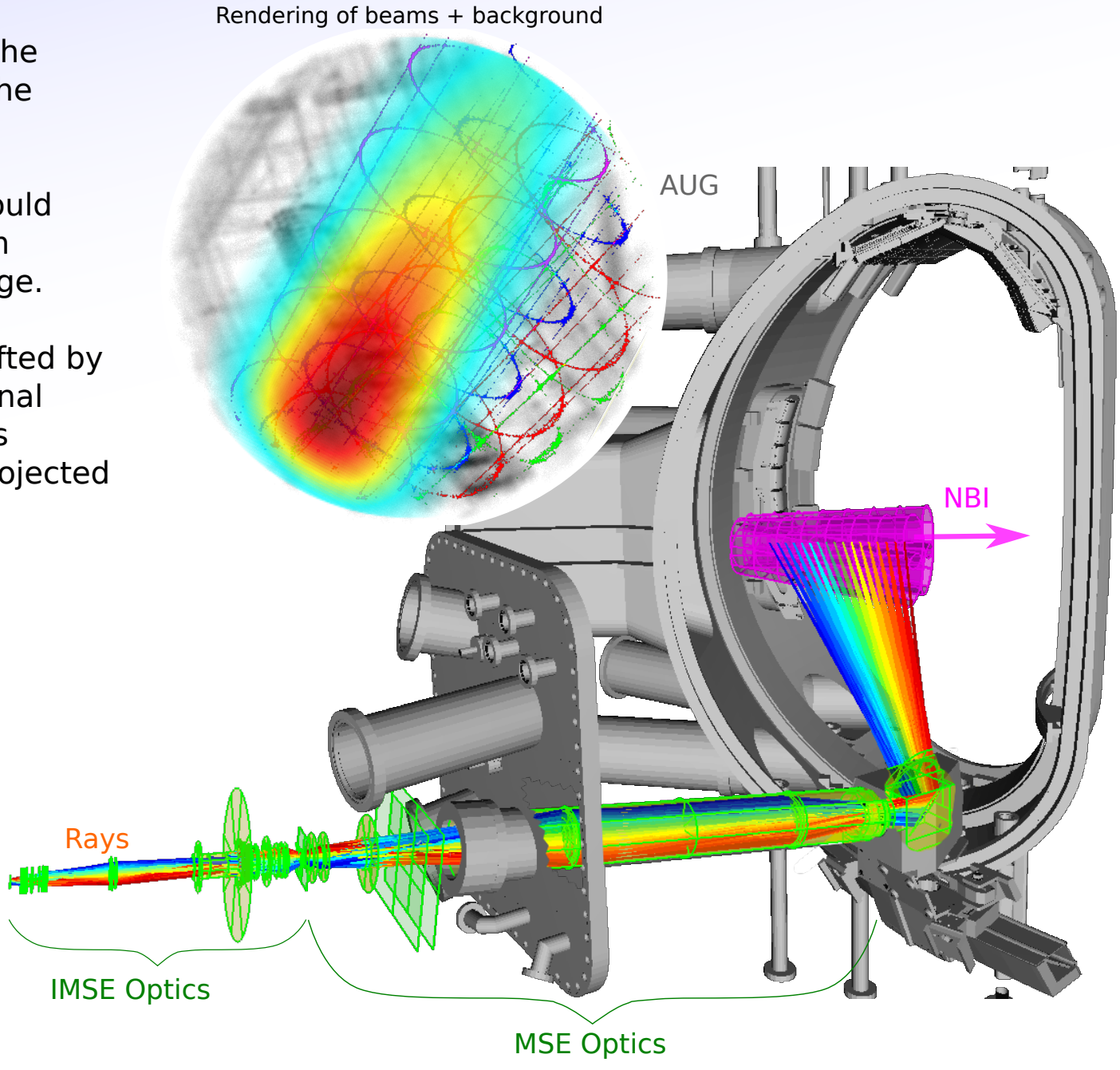
Hα/Dα beam emission is Doppler shifted by beam velocity and split by the Motional Stark Effect into π and σ components which is polarised perp/parallel to projected ***v*** *x* ***B*** direction.





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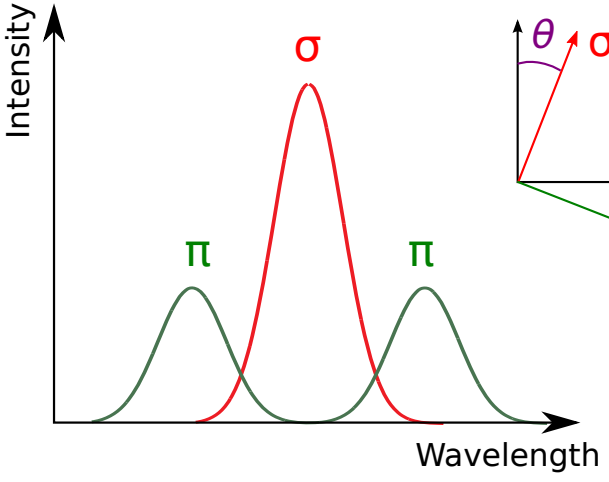
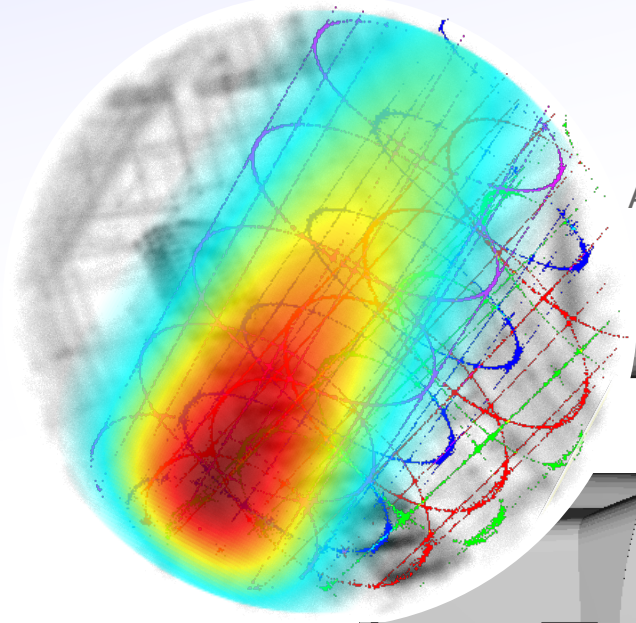
The polarised component of σ is always almost exactly perpendicular to π, so net polarisation of entire spectrum is always 0.



We want to measure θ

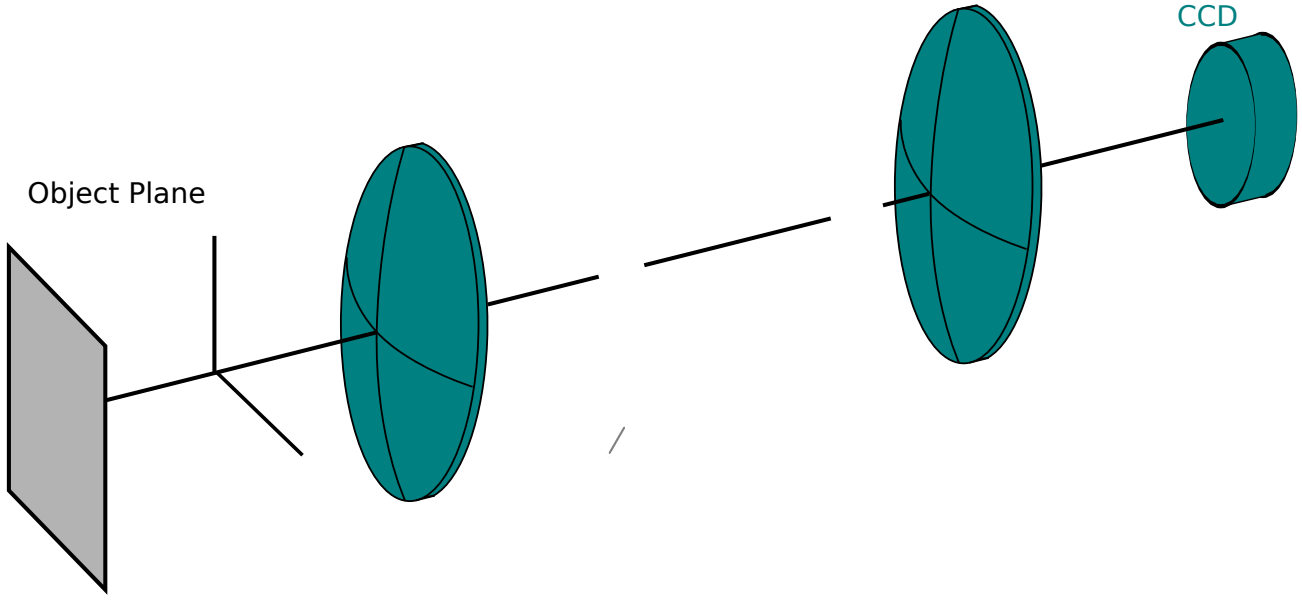
Rendering of beams + background



Coherence Imaging with Displacer Plates

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





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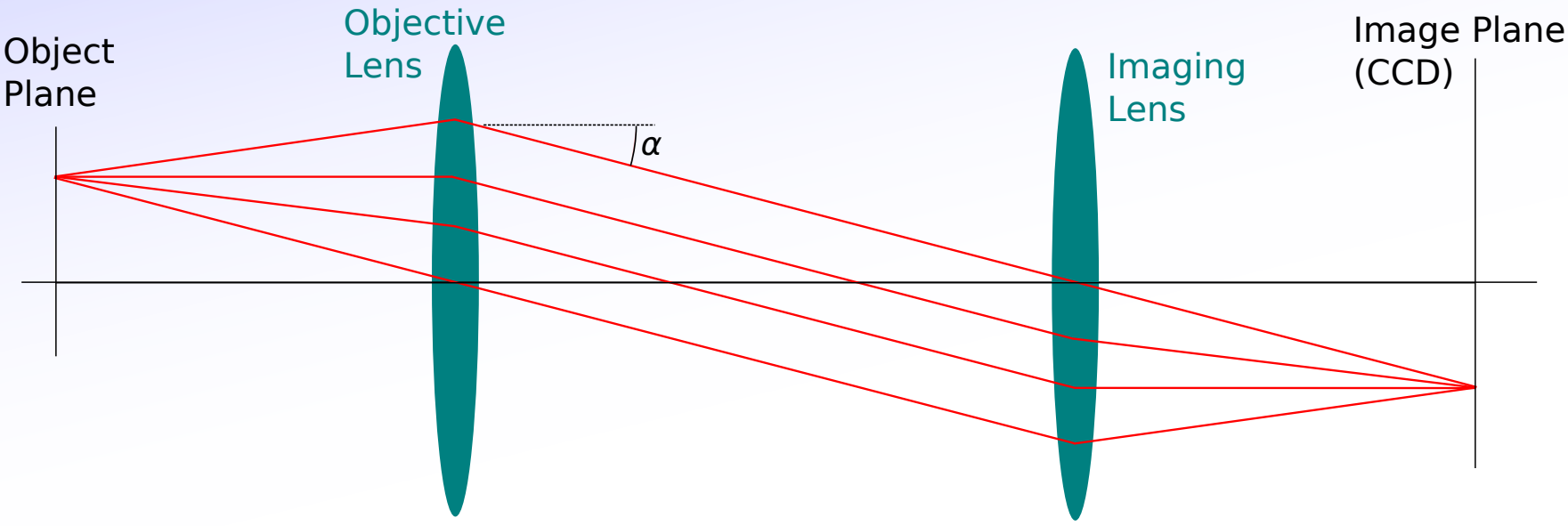

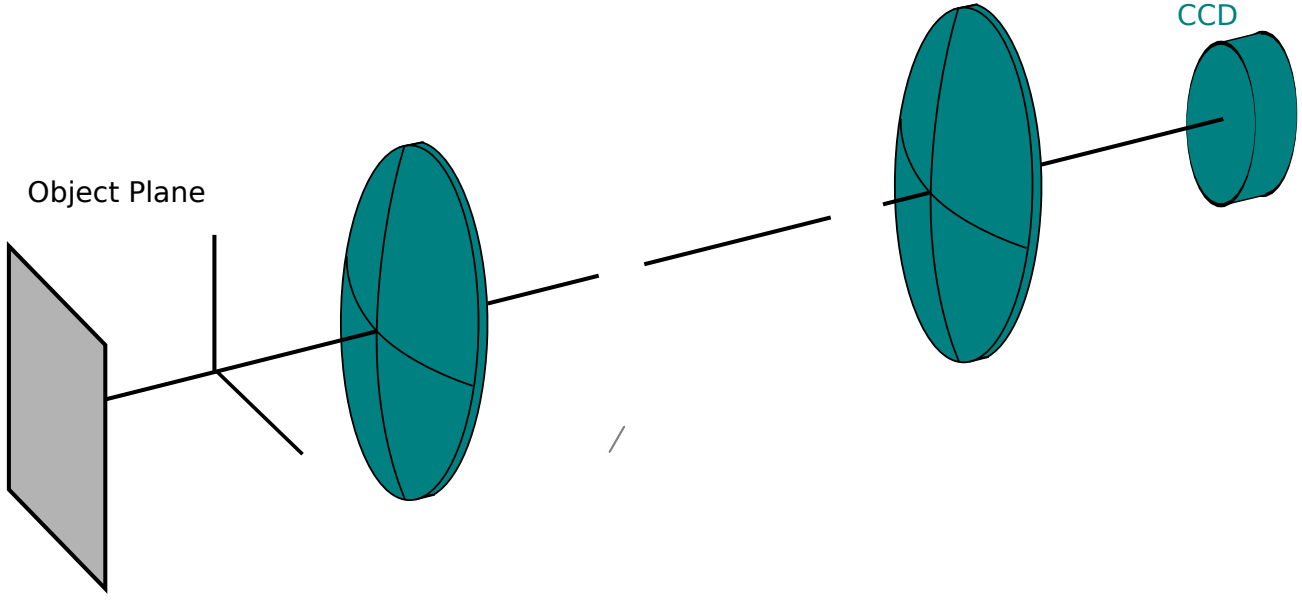

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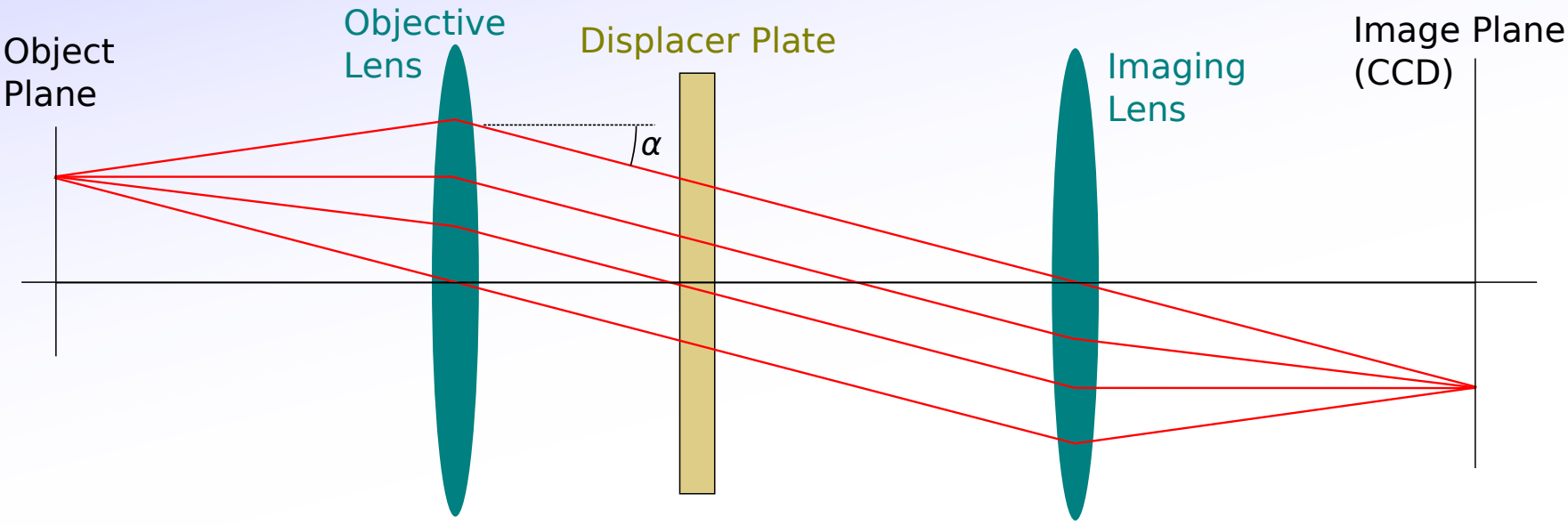

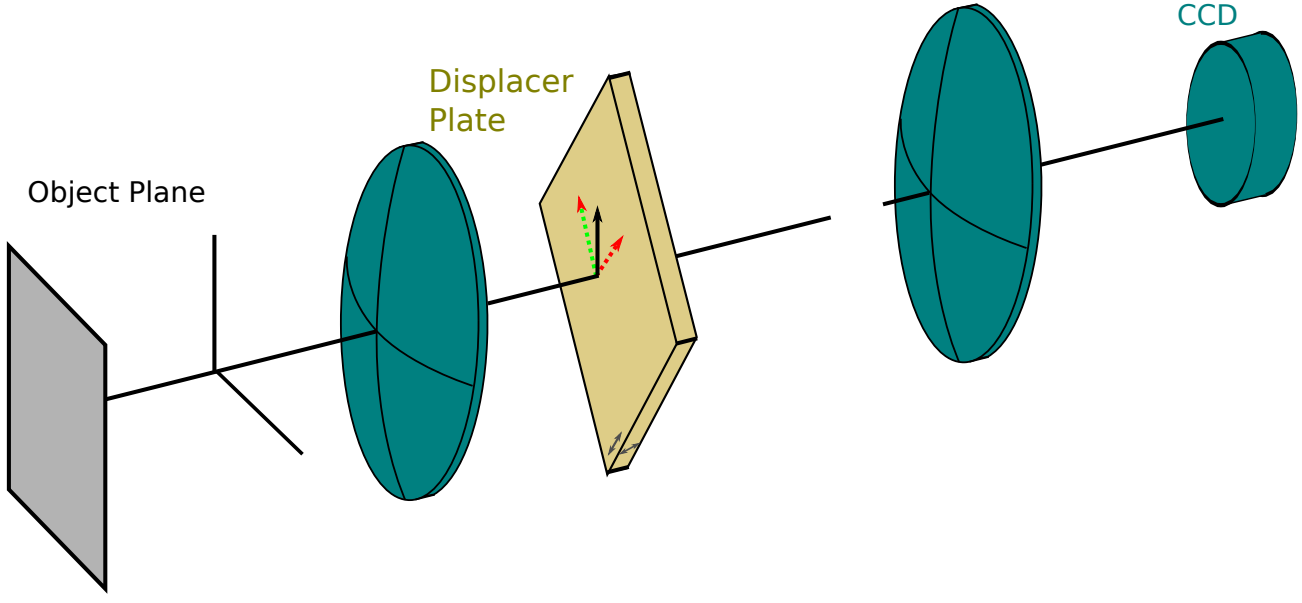

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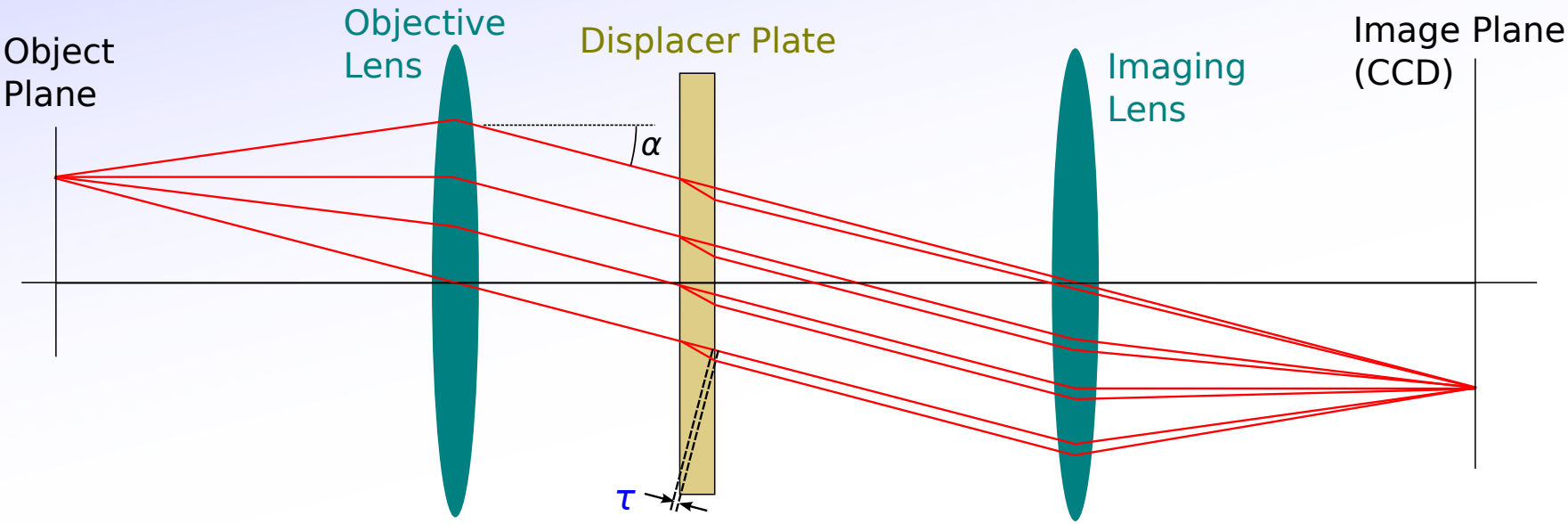

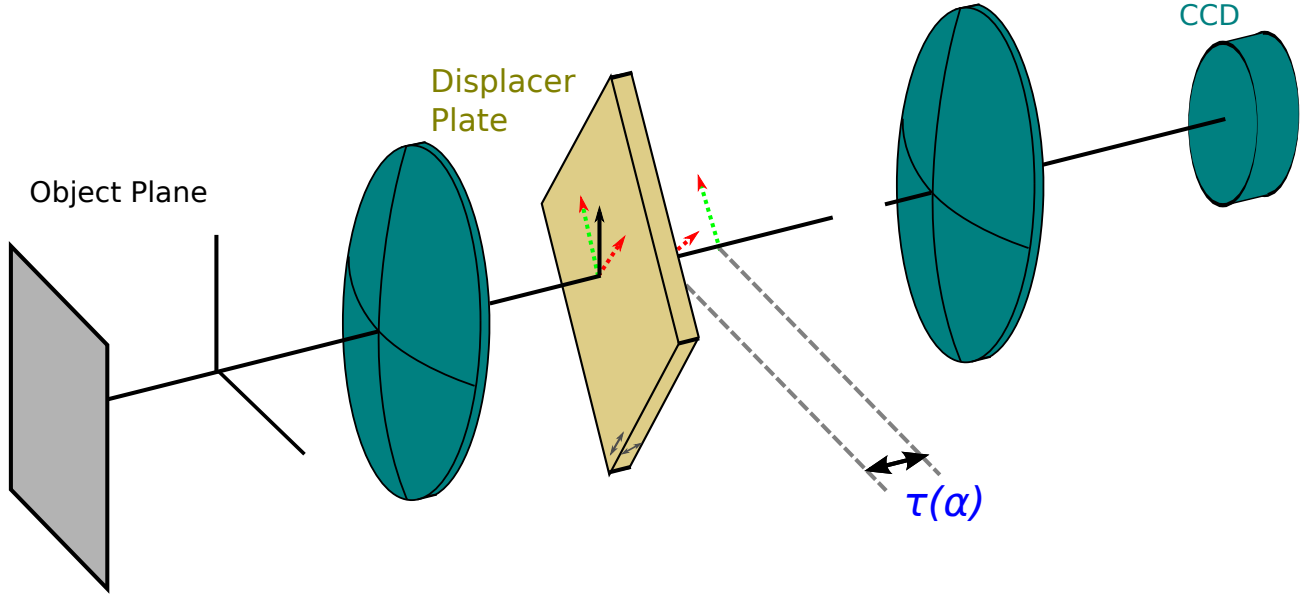

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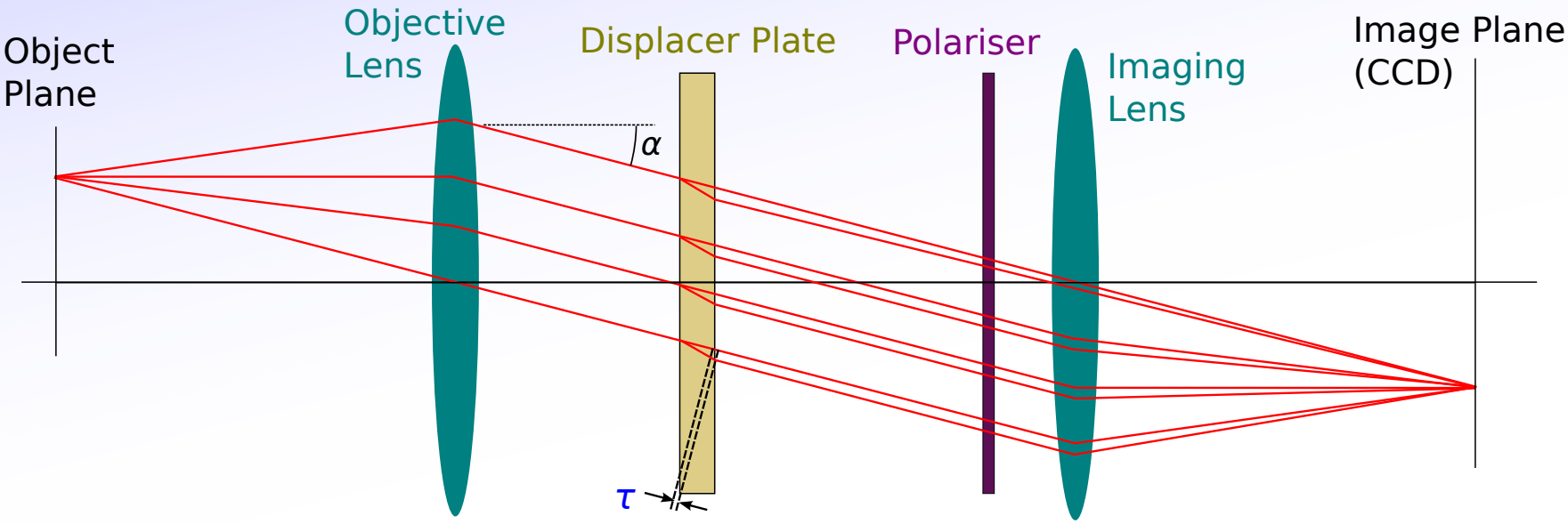

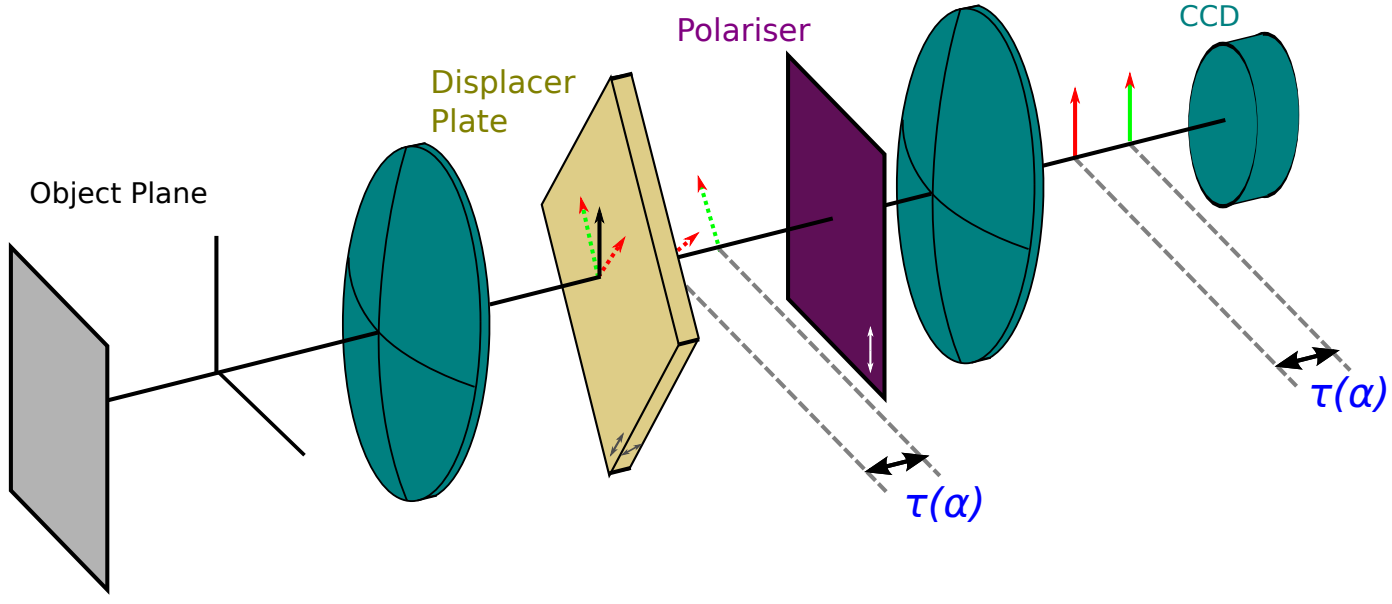

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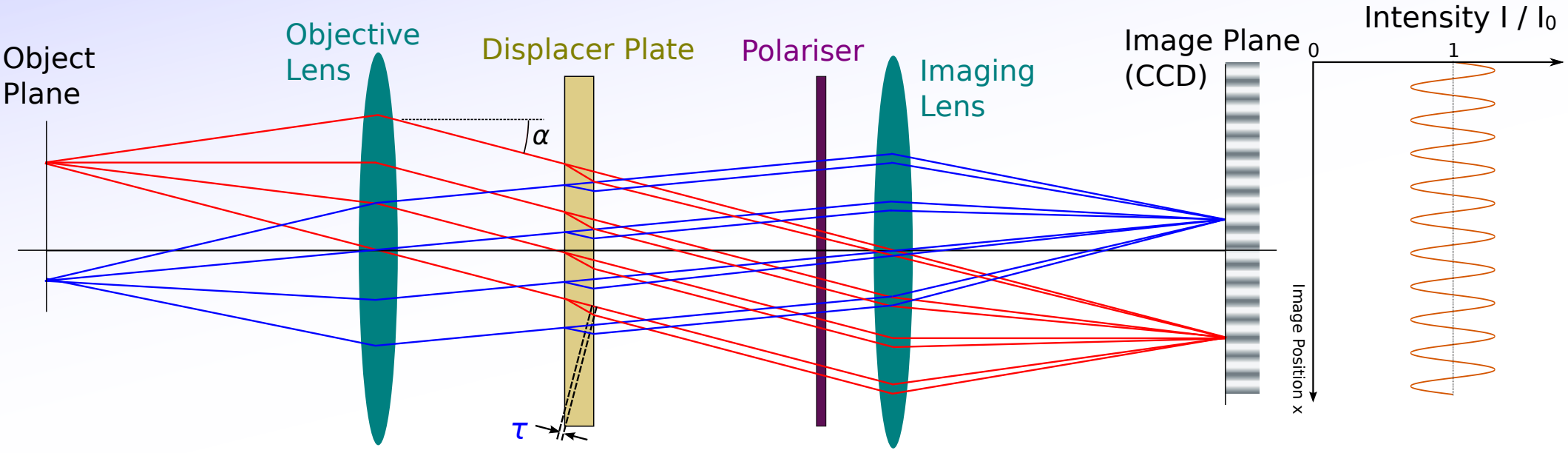

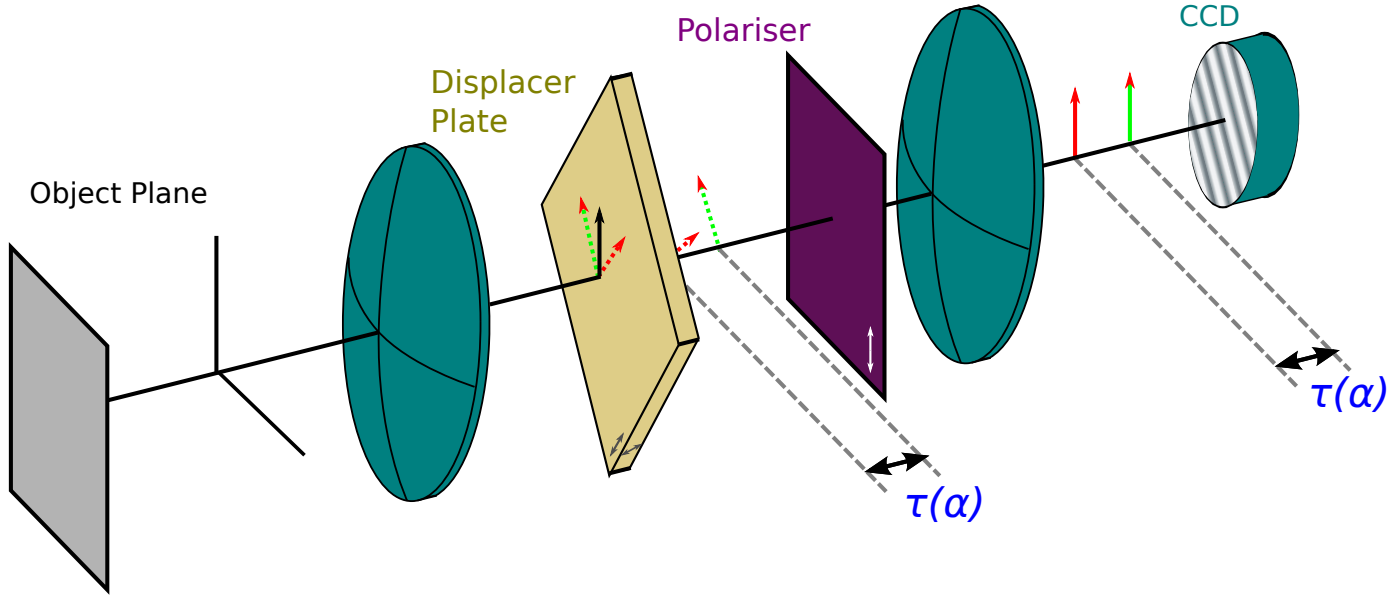

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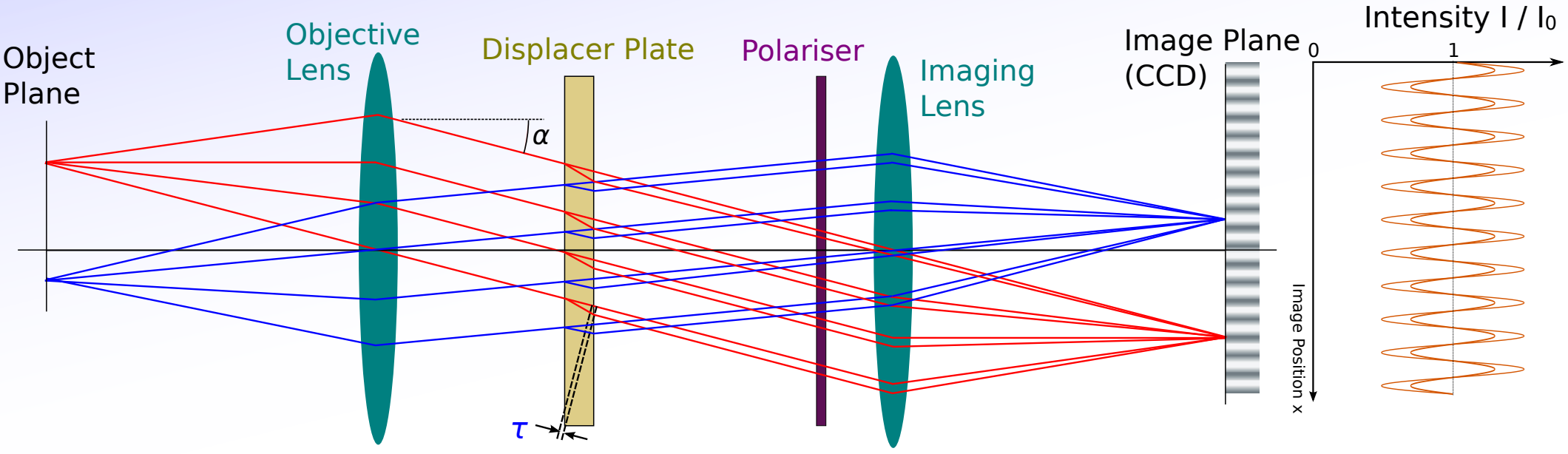
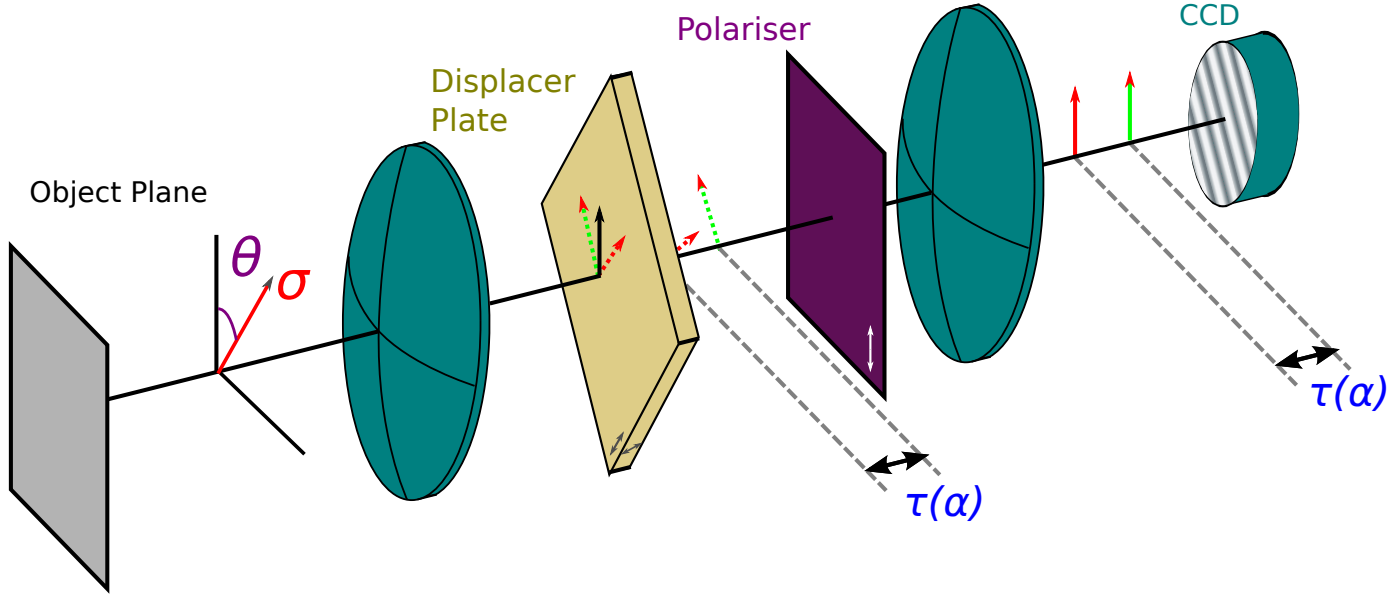


Oscillation amplitude proportional to polarisation angle.

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



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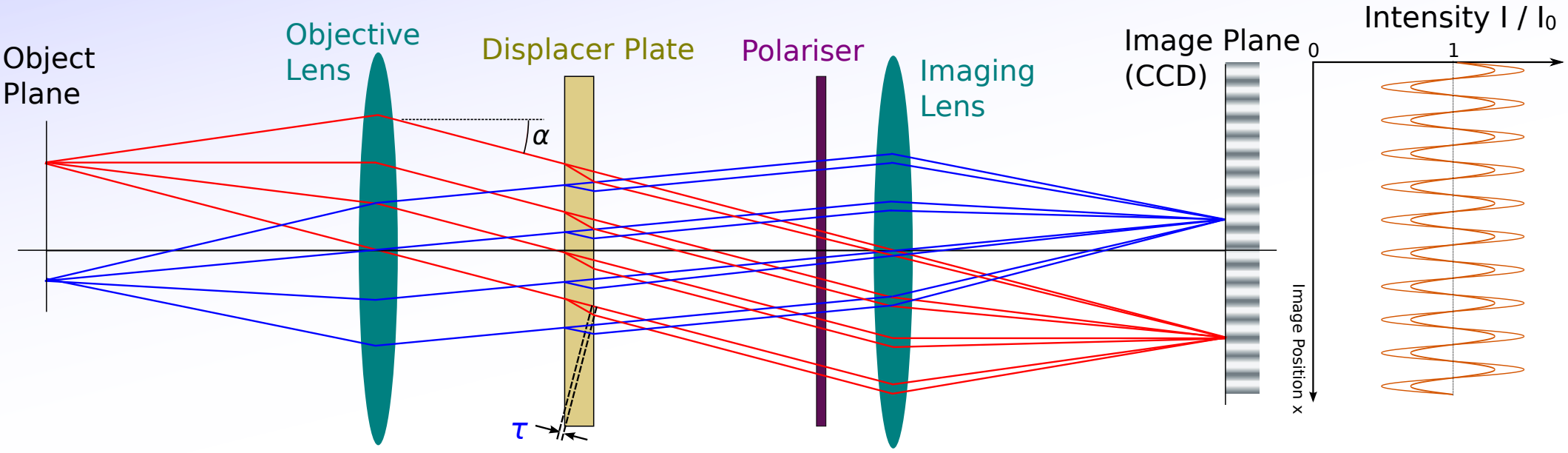
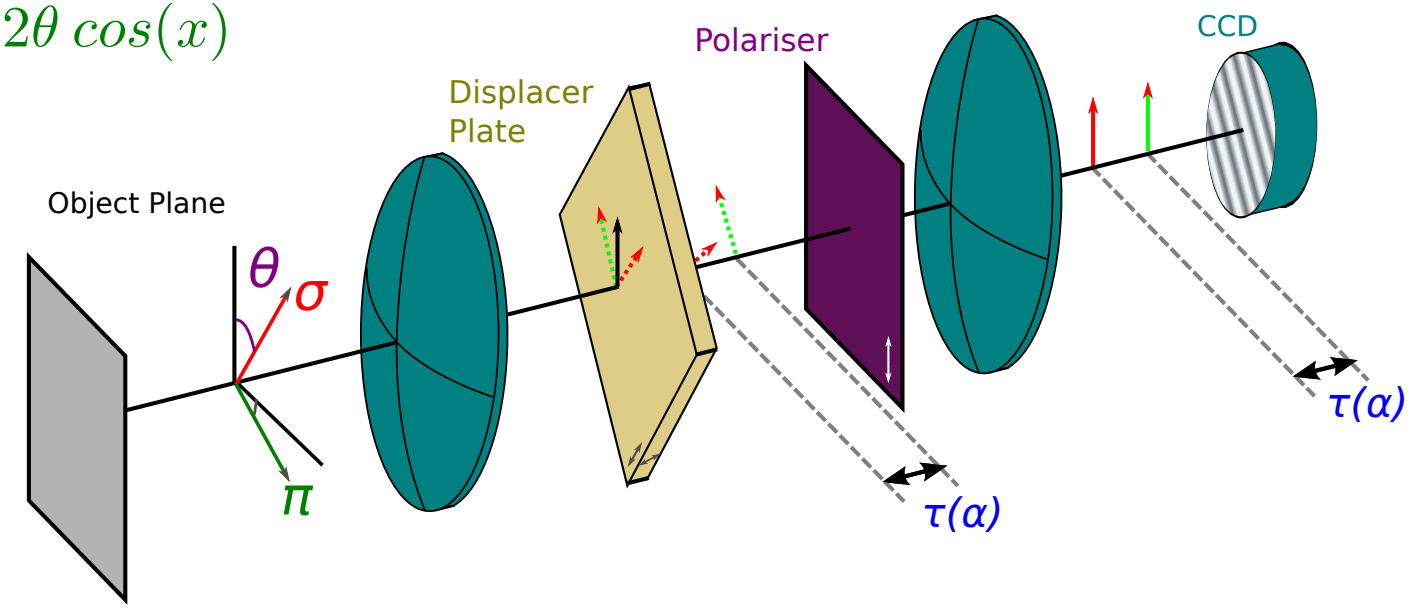


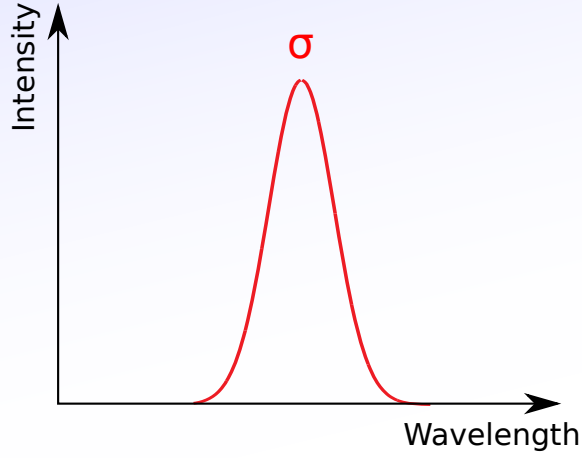
Oscillation amplitude proportional to polarisation angle.

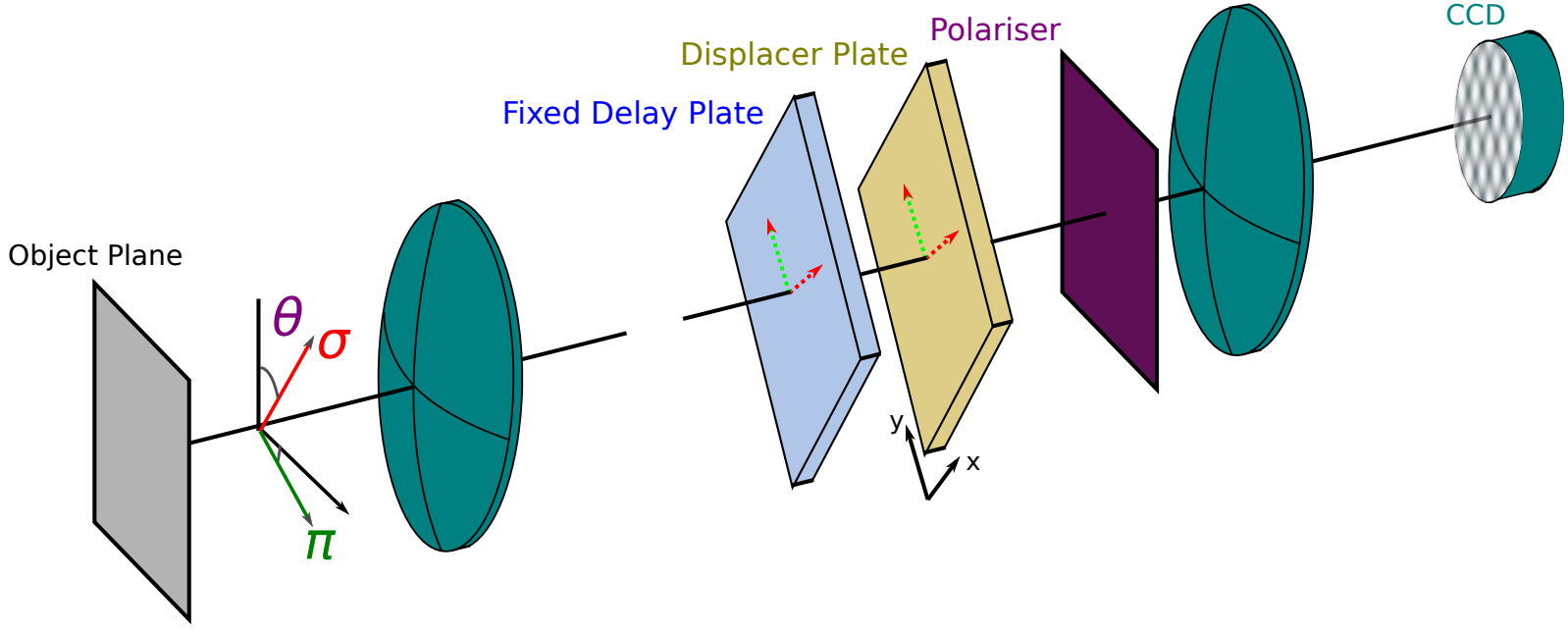
$$I \propto 1 + cos2\theta\, cos(x) - cos2\theta\, cos(x)$$

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



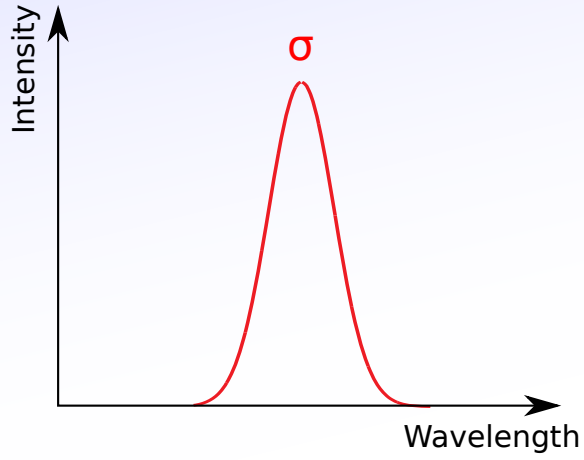
Spectral Coherence

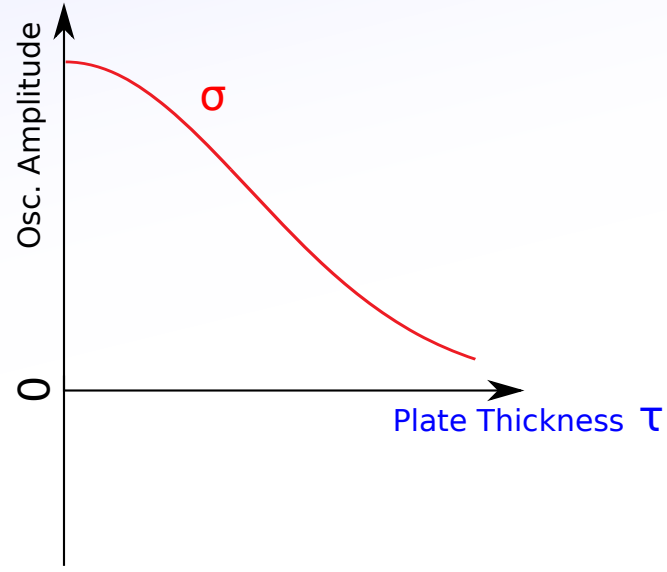


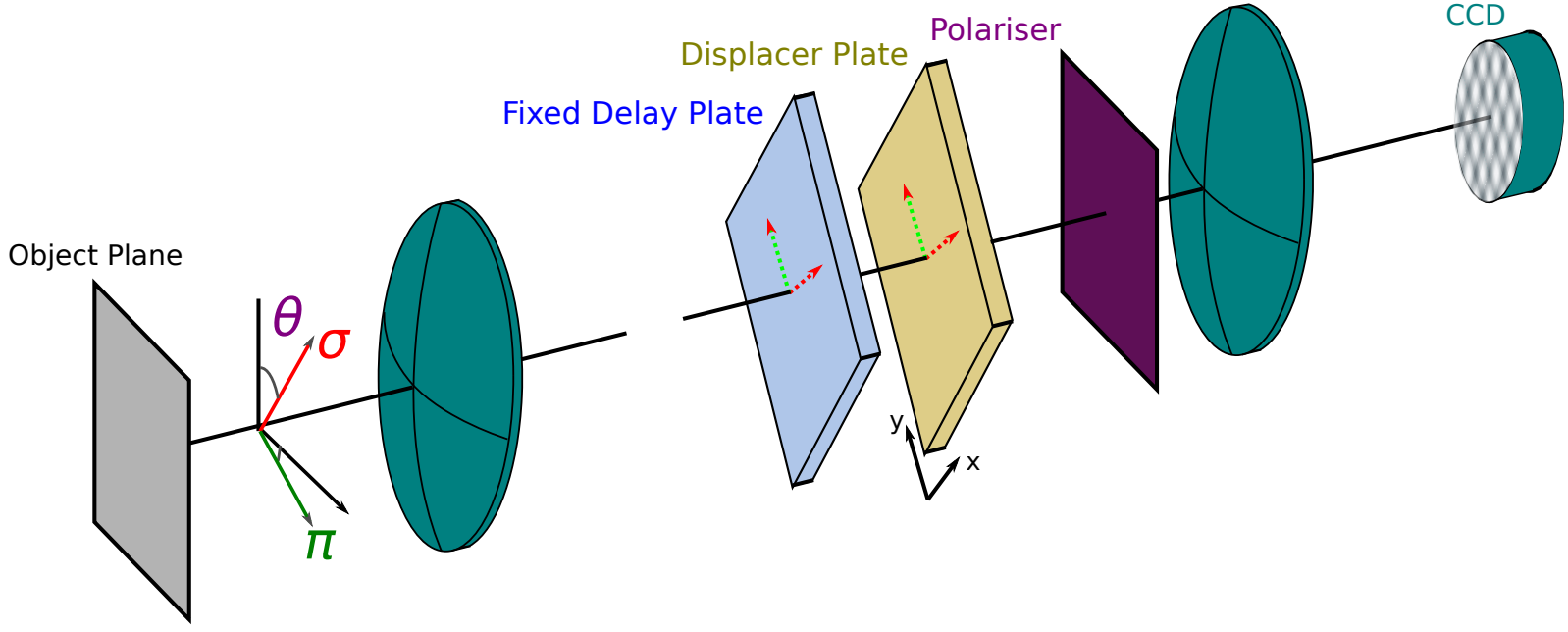


Spectral Coherence

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







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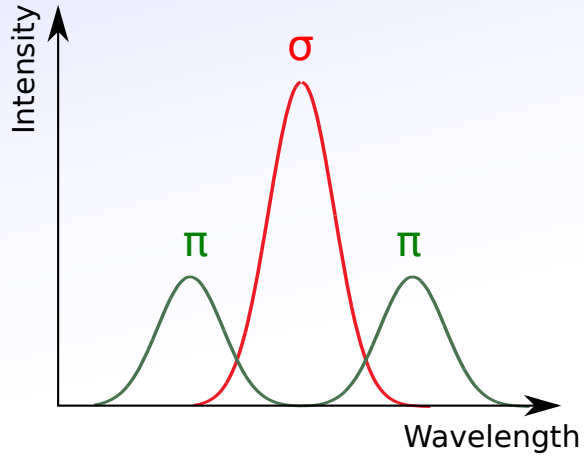
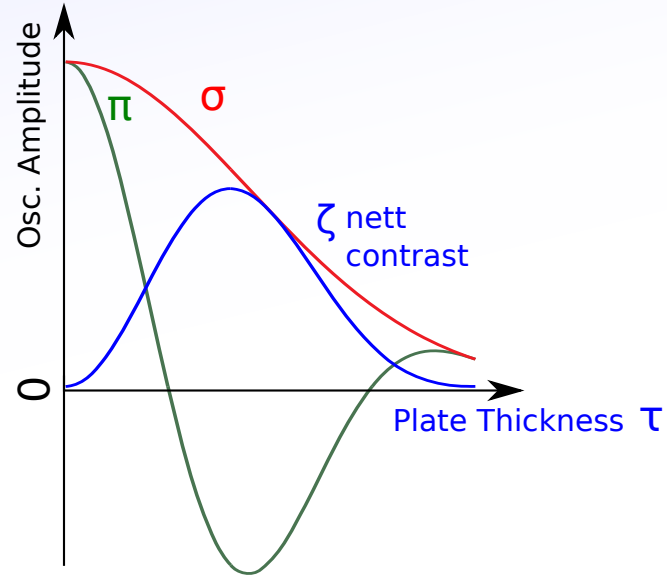
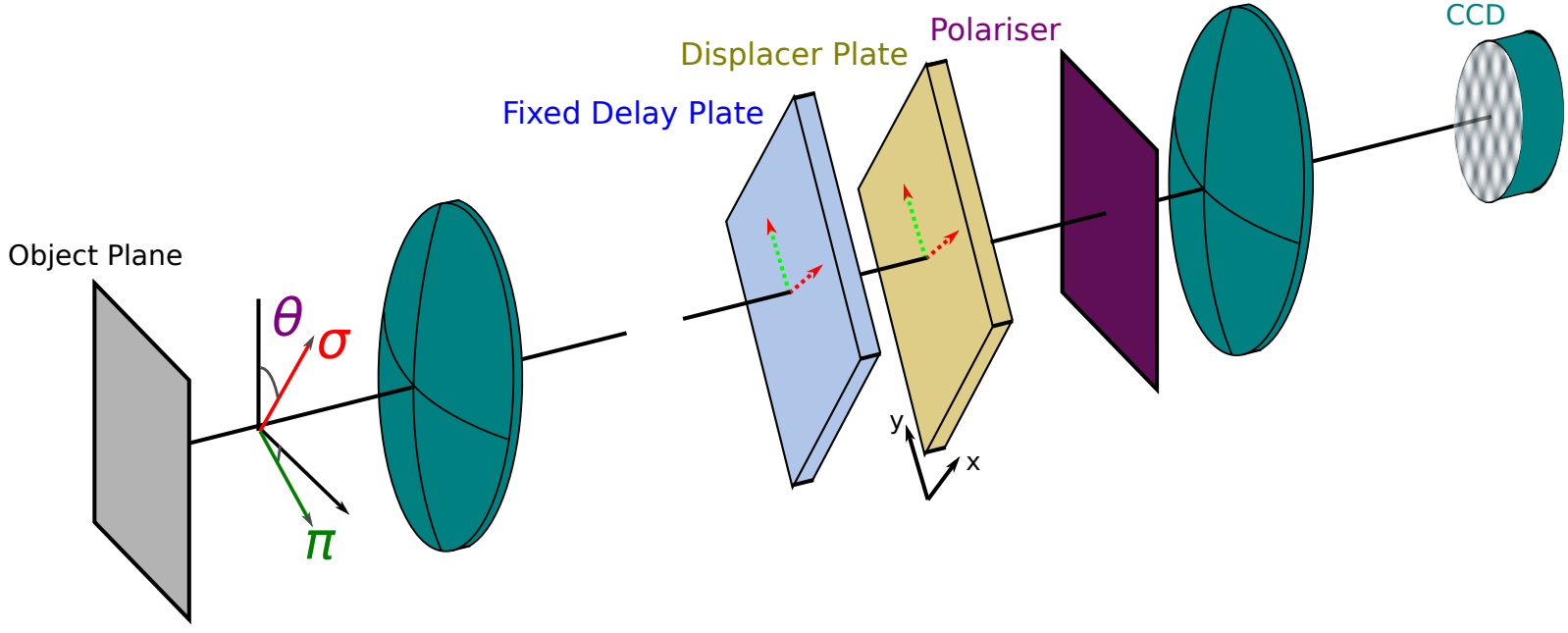
For a specific τ, the phase of the π wings is 180° from σ. This cancels the 180° from the opposite polarisation, and the patterns add.







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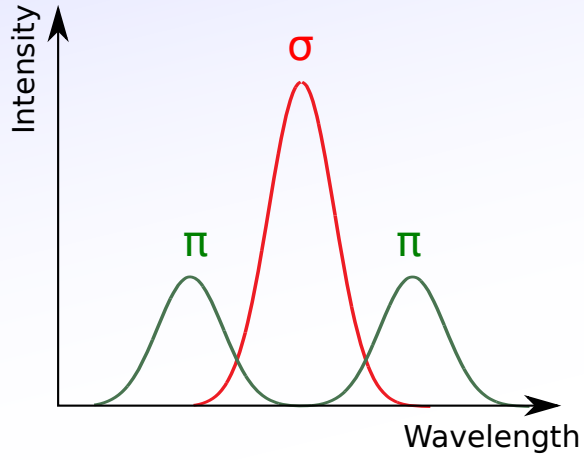

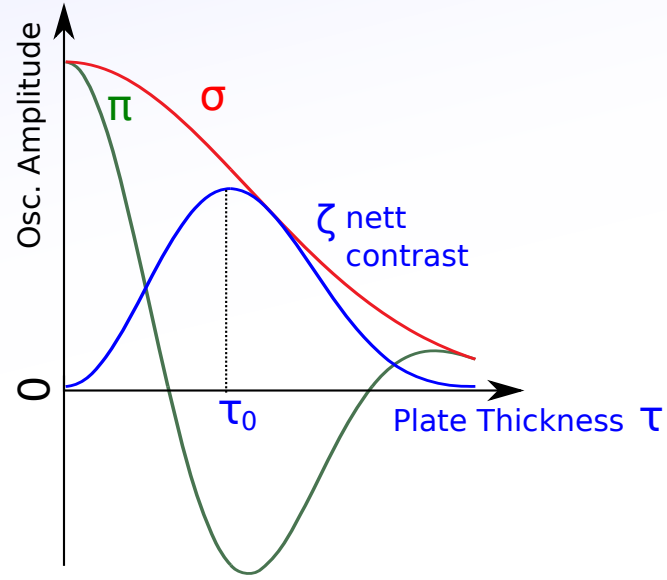

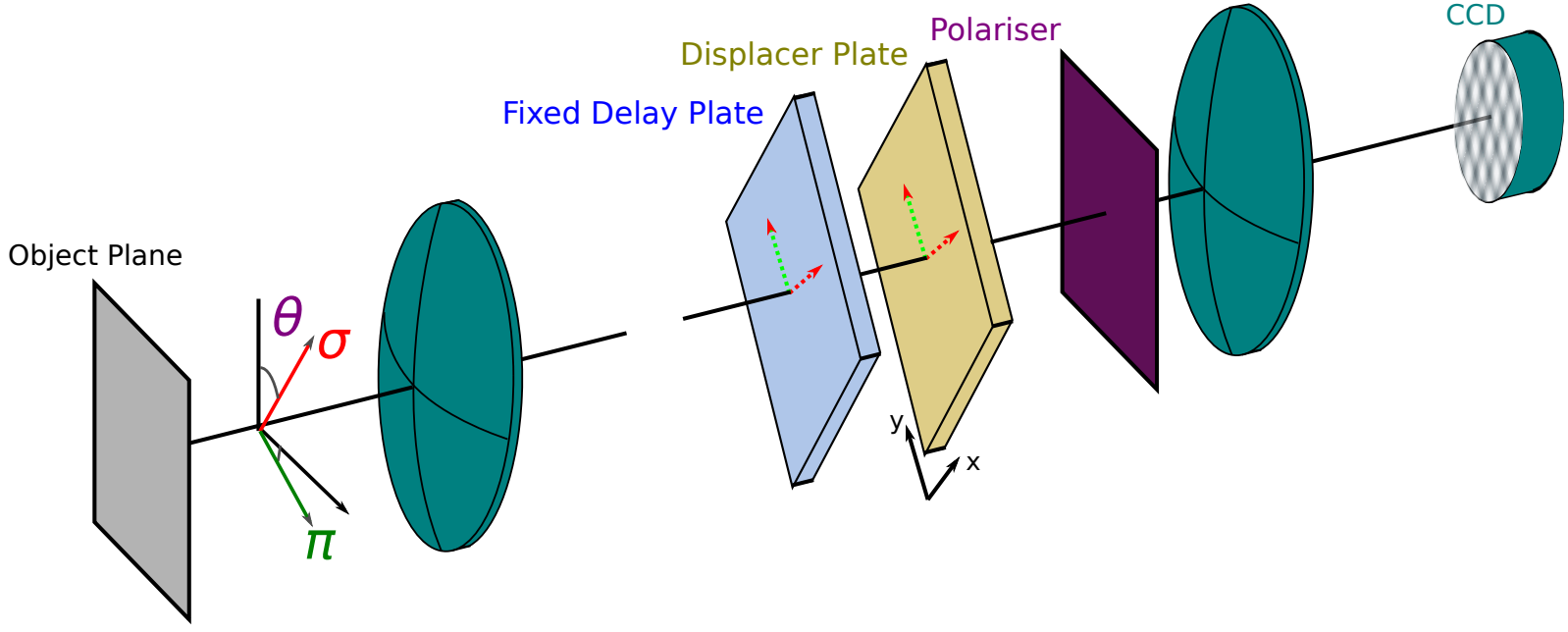

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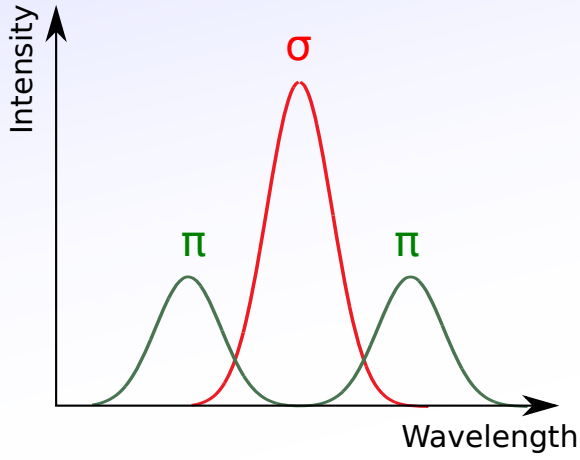

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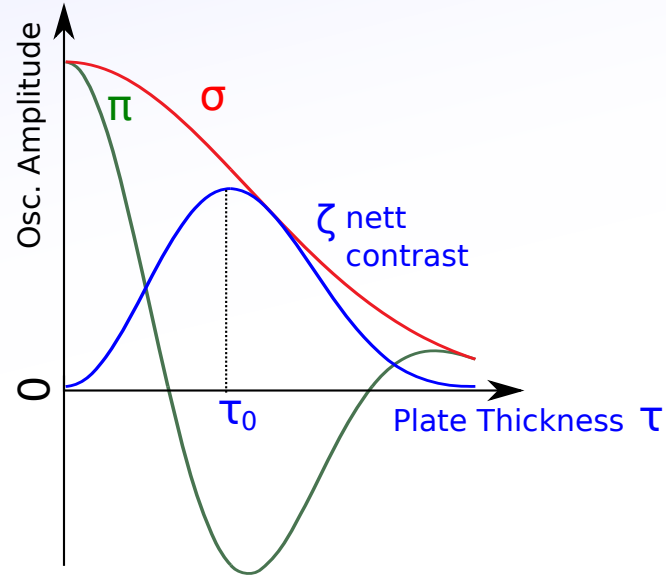

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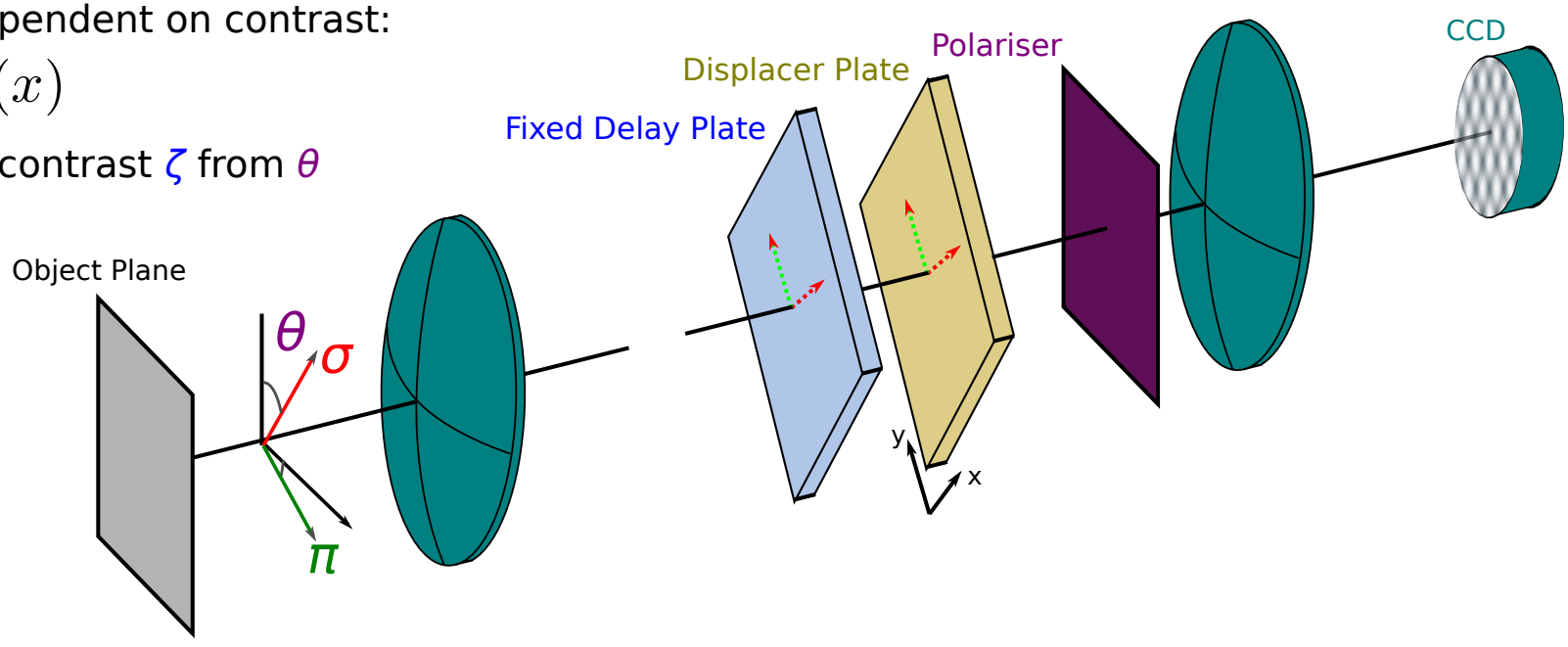
but amplitude now also dependent on contrast:

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

Need to separate spectral contrast ζ from θ



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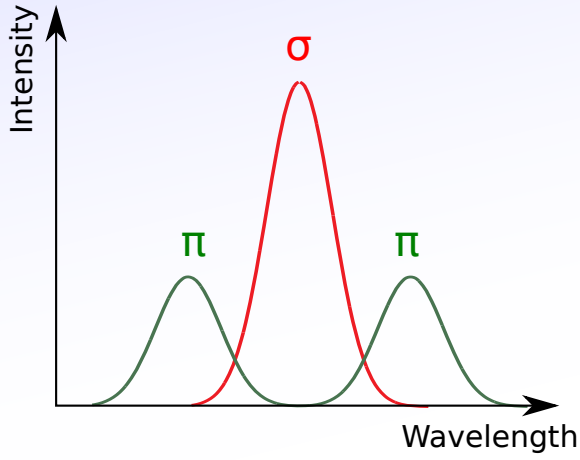

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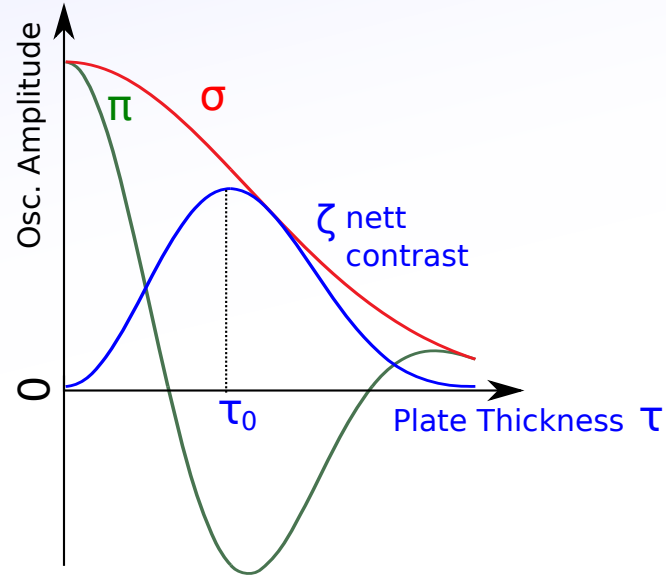

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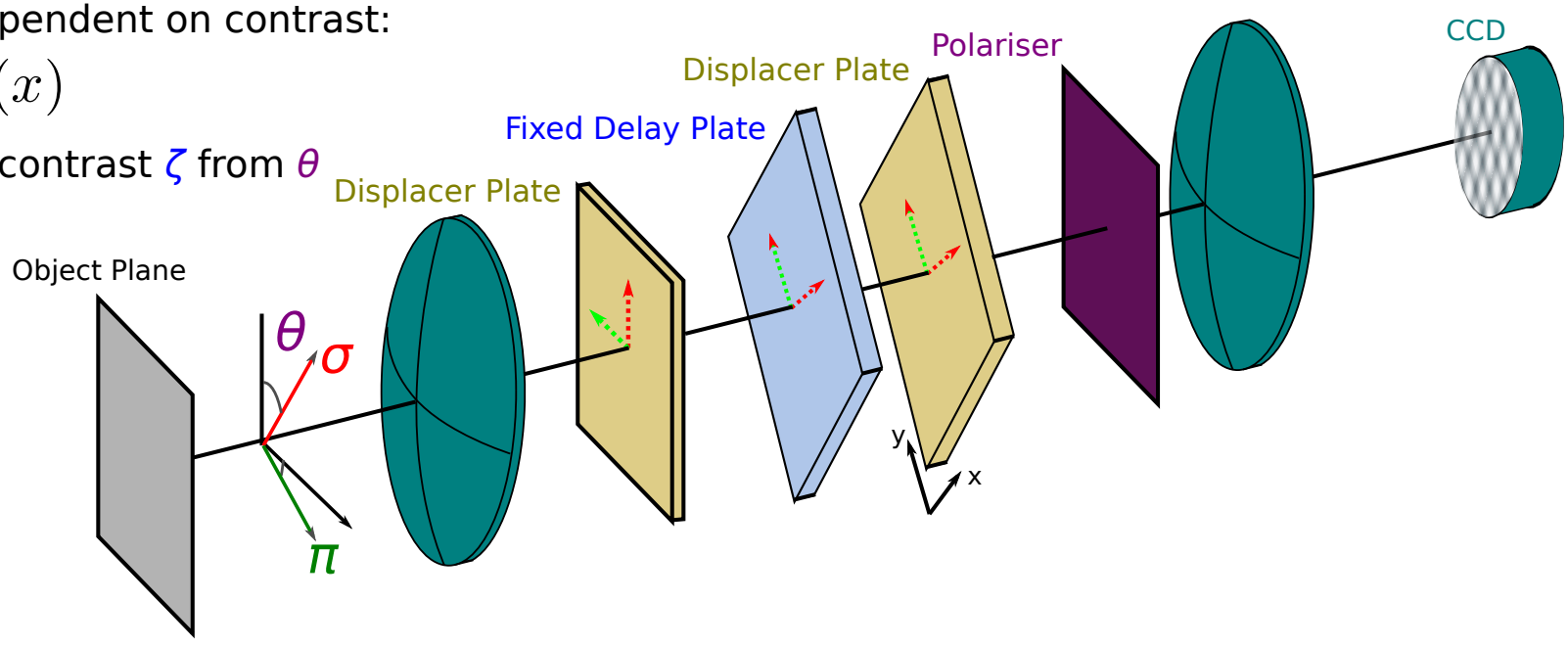

add another displacer at 45°.

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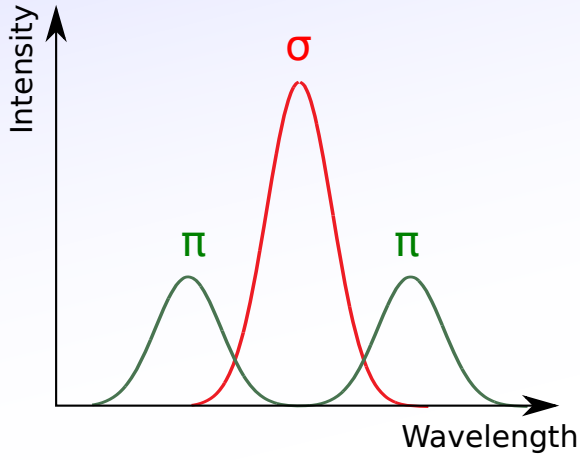
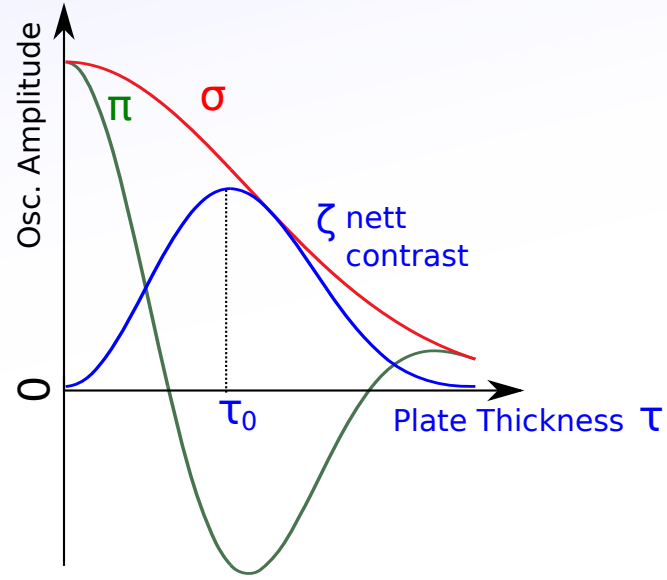
Phase delay of a plate depends on wavelength. For large τ and finite spectral width, amplitude is reduced by decoherence.





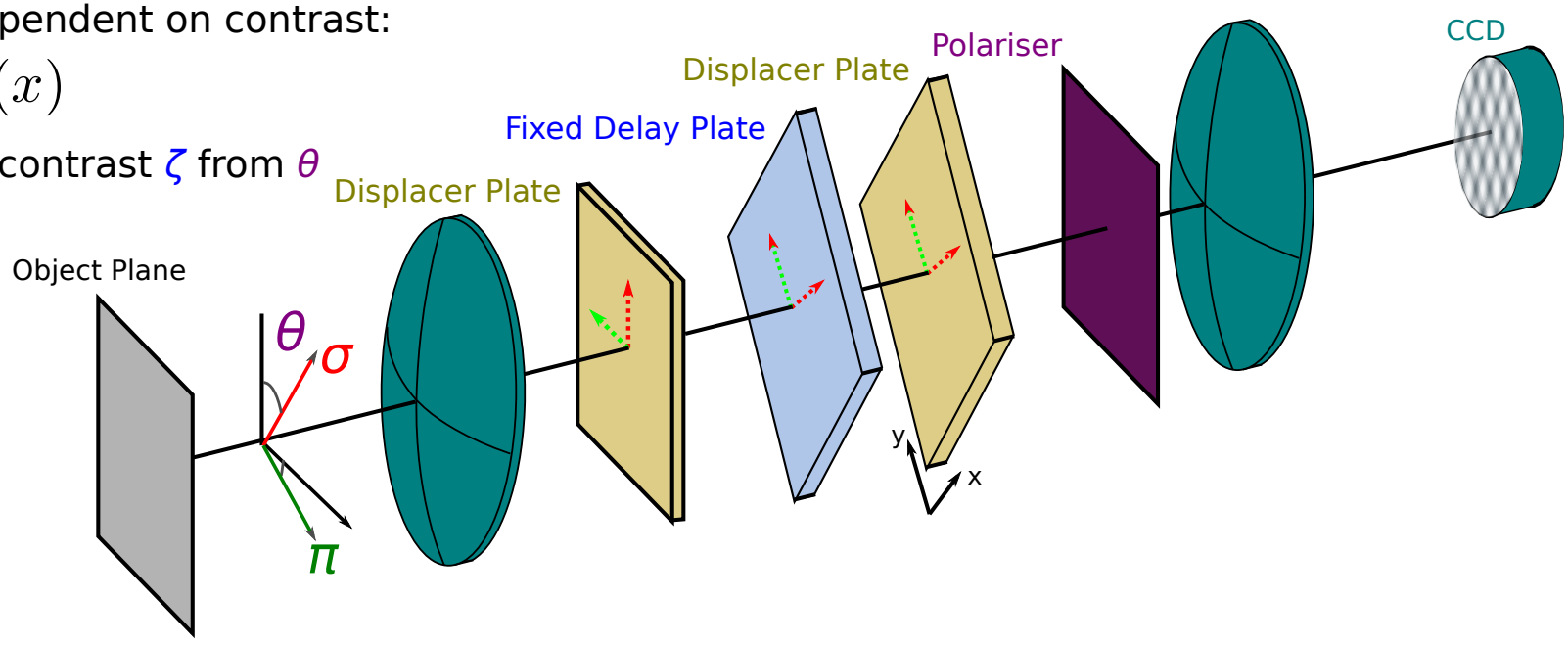
For a specific τ, the phase of the π wings is 180° from σ. This cancels the 180° from the opposite polarisation, and the patterns add.

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

but amplitude now also dependent on contrast:

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

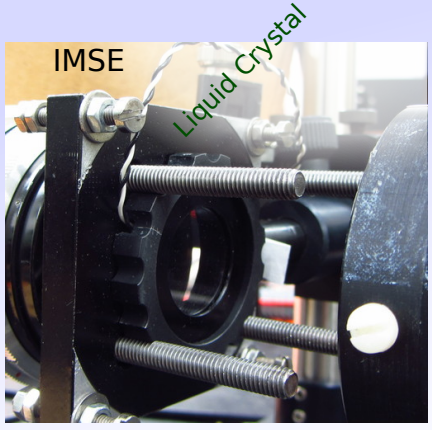
Need to separate spectral contrast ζ from θ



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)

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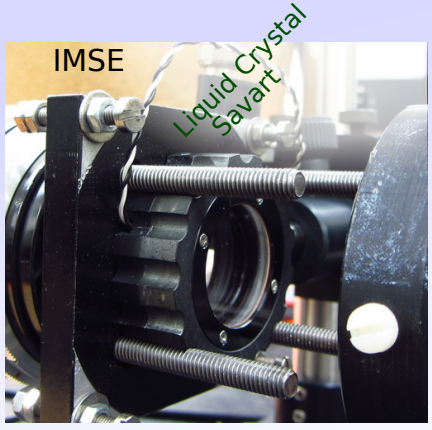

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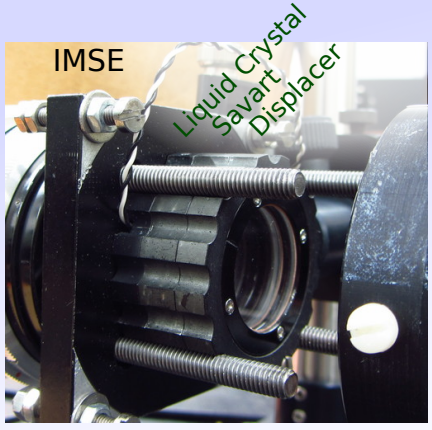

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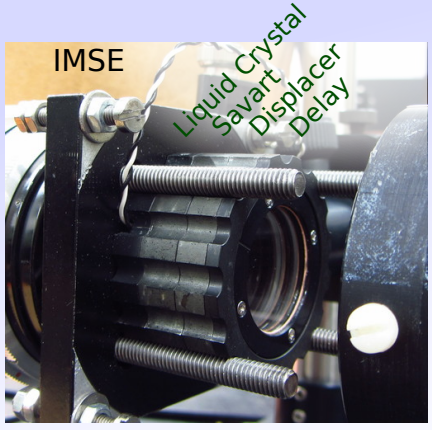

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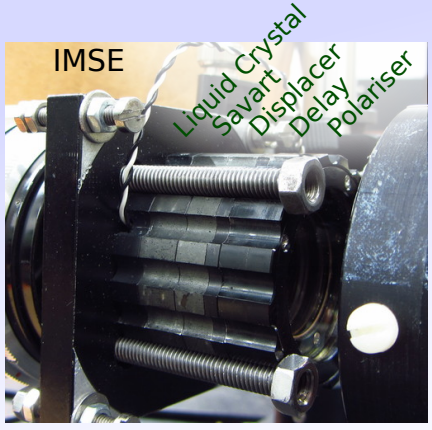

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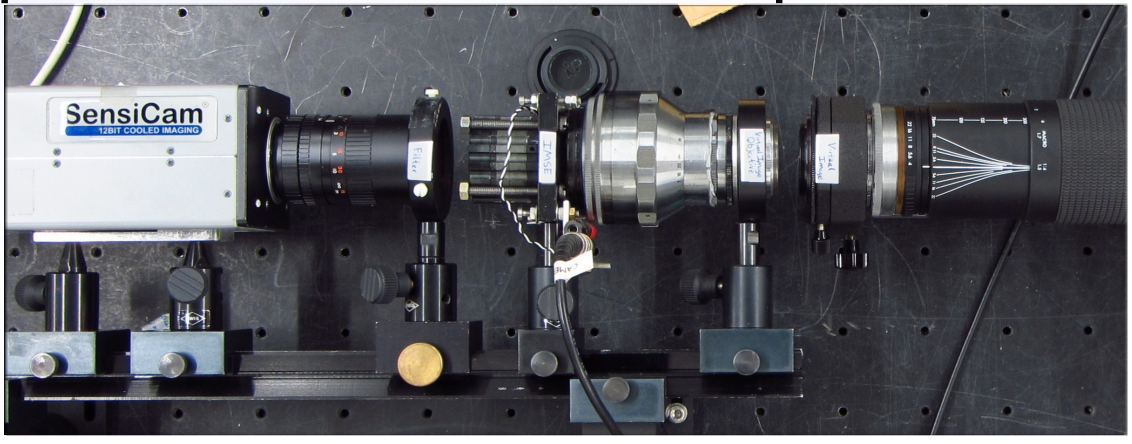

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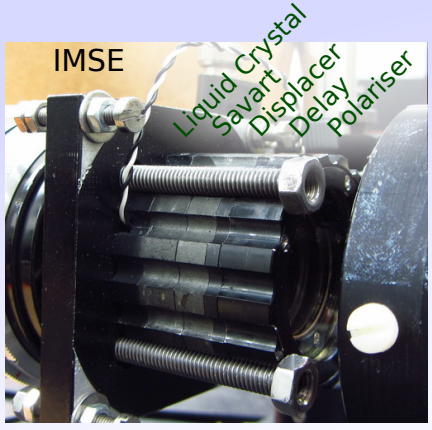

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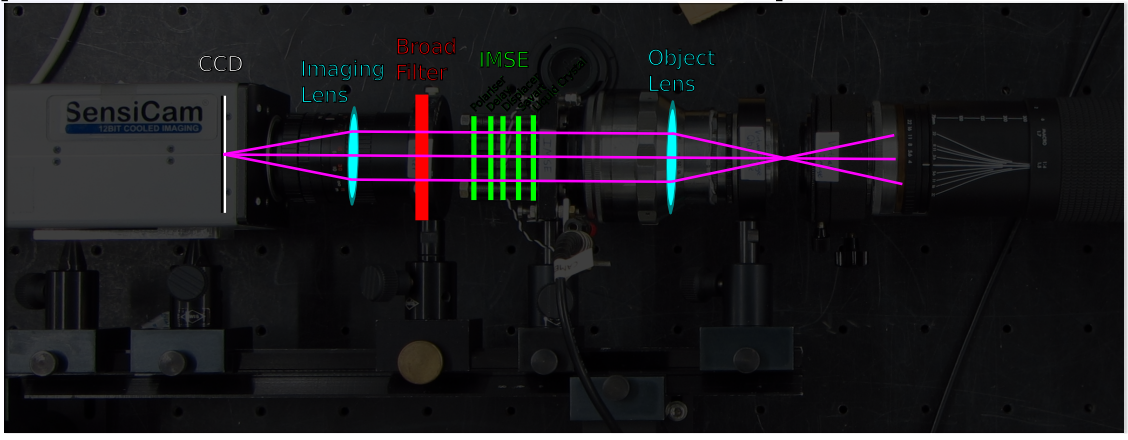

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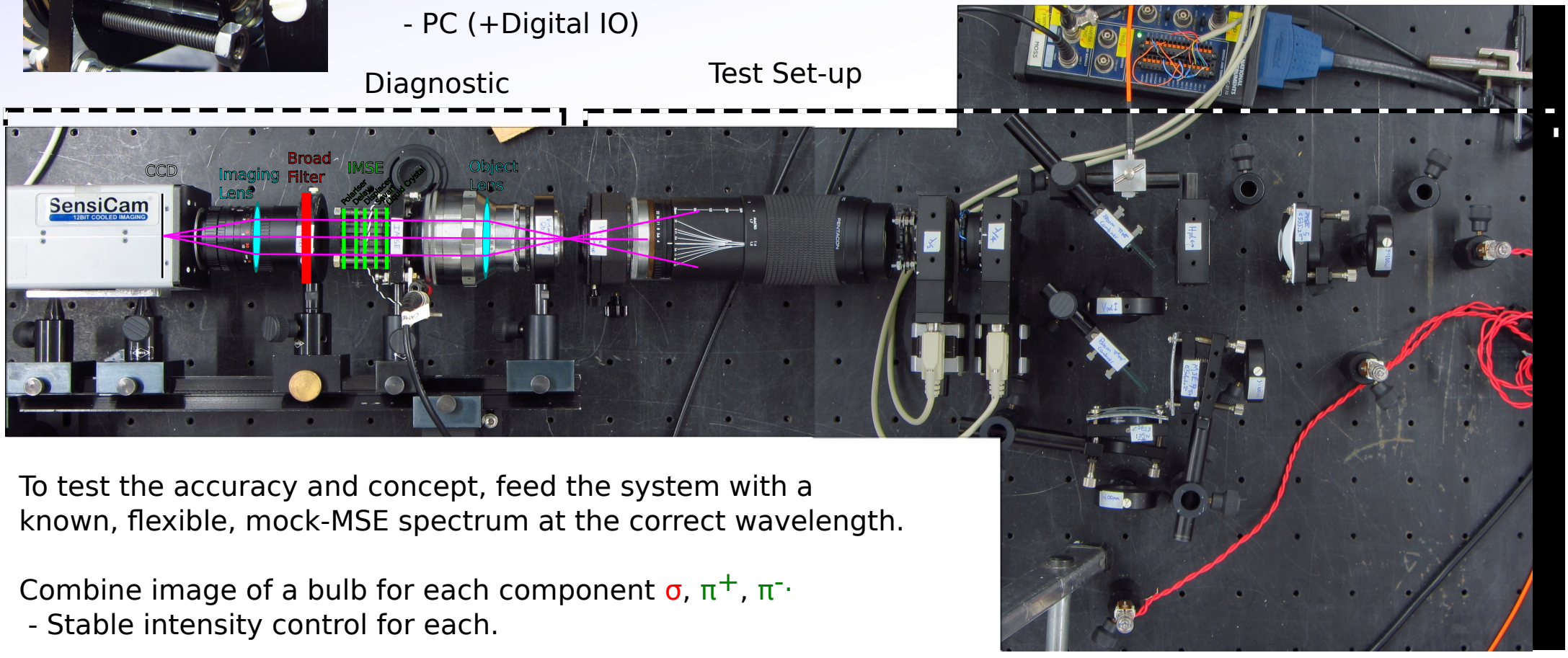

To test the accuracy and concept, feed the system with a known, flexible, mock-MSE spectrum at the correct wavelength.

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

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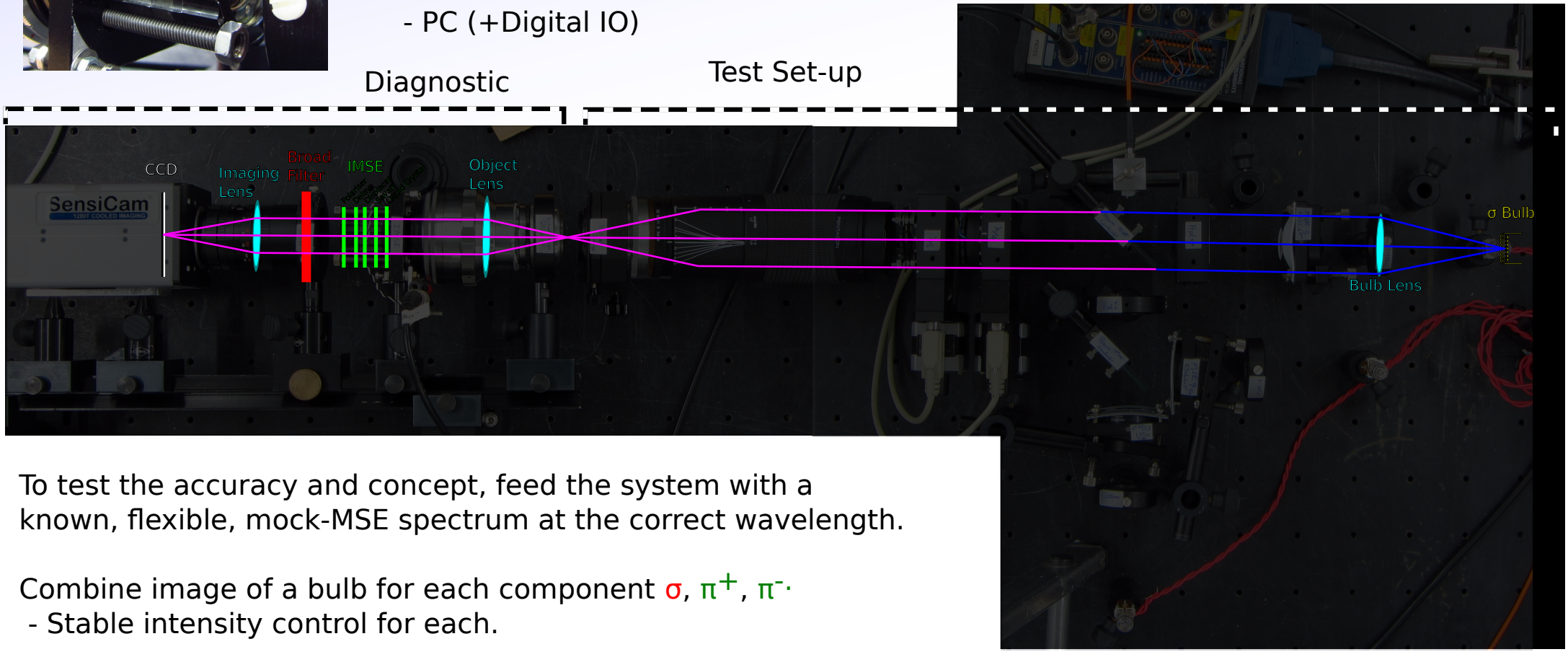

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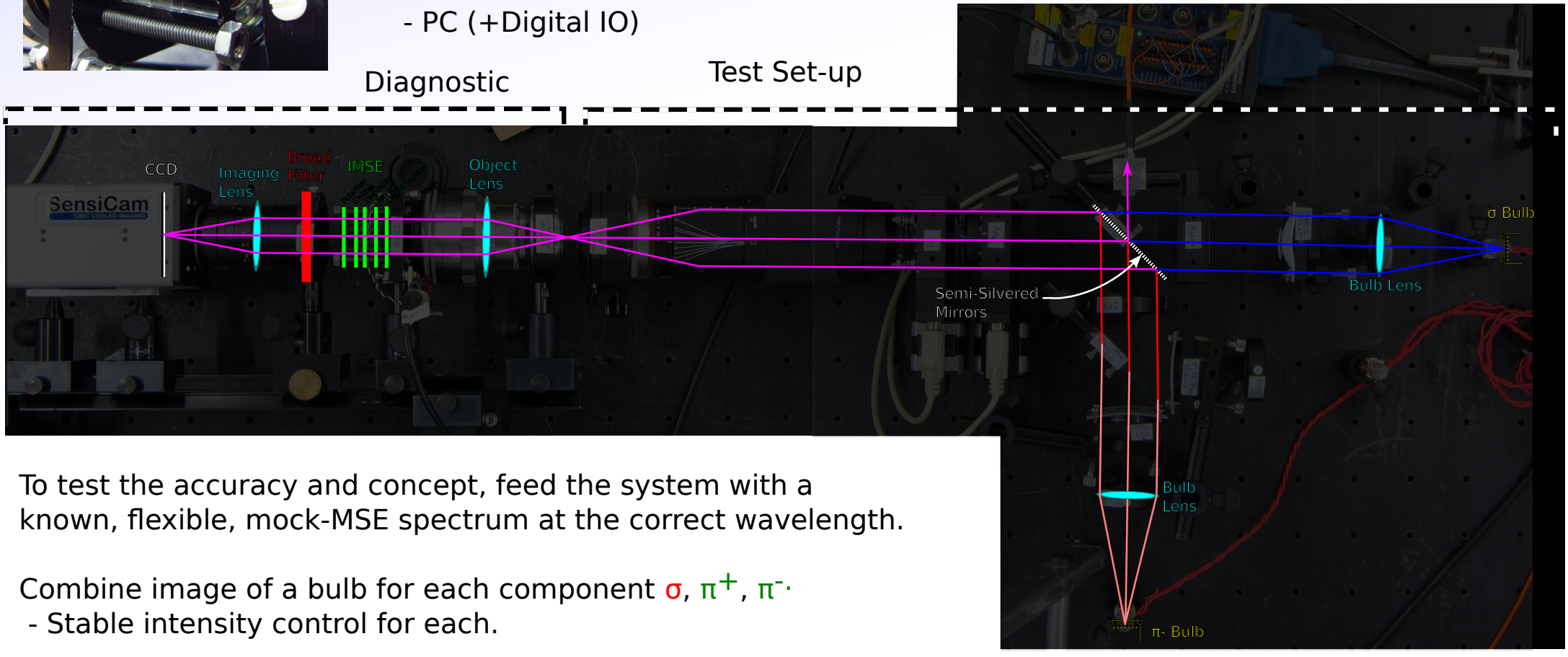

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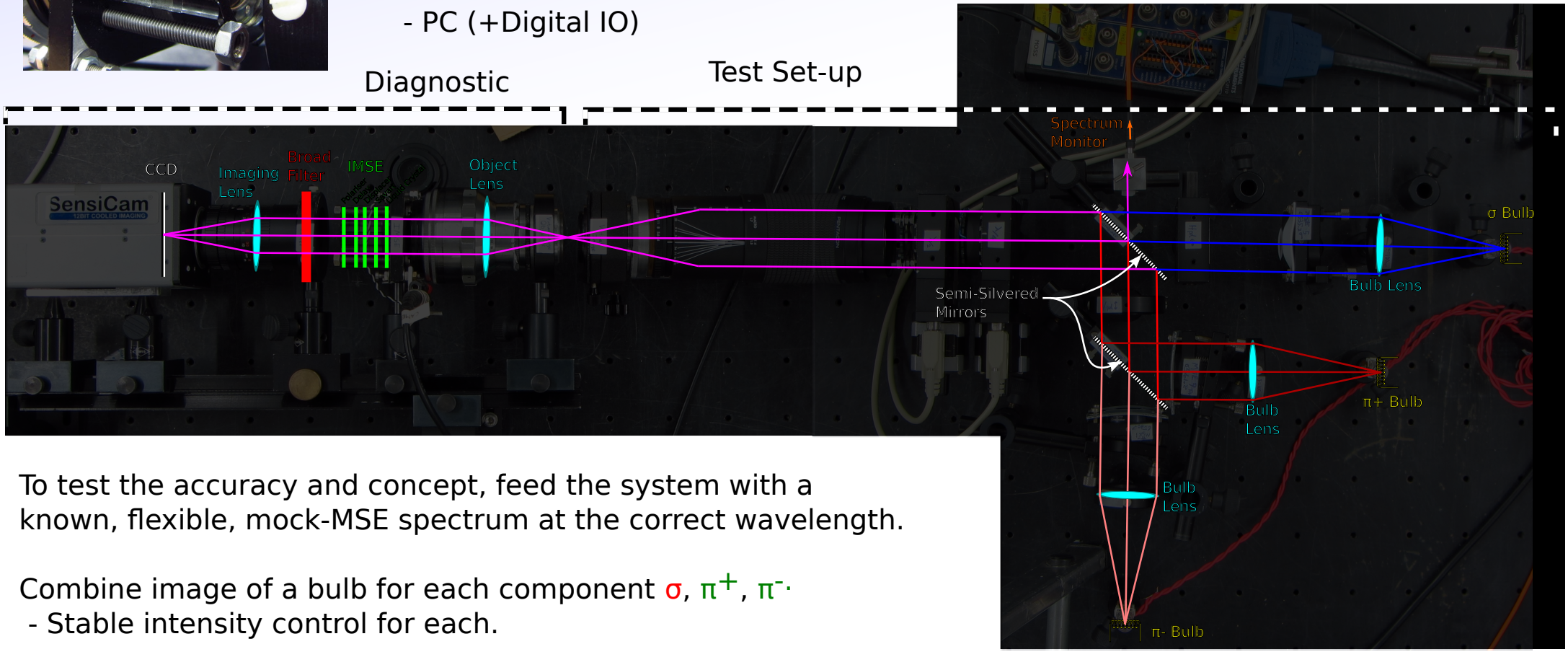

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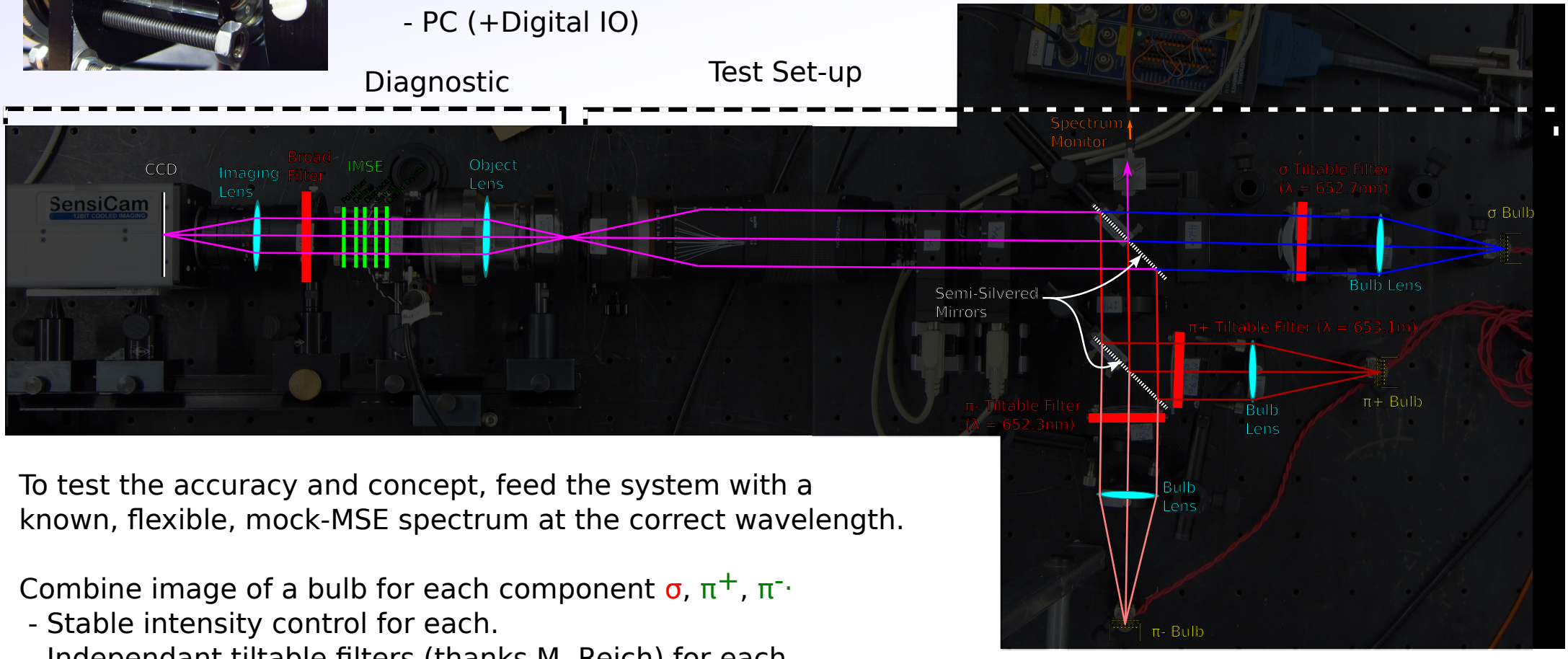

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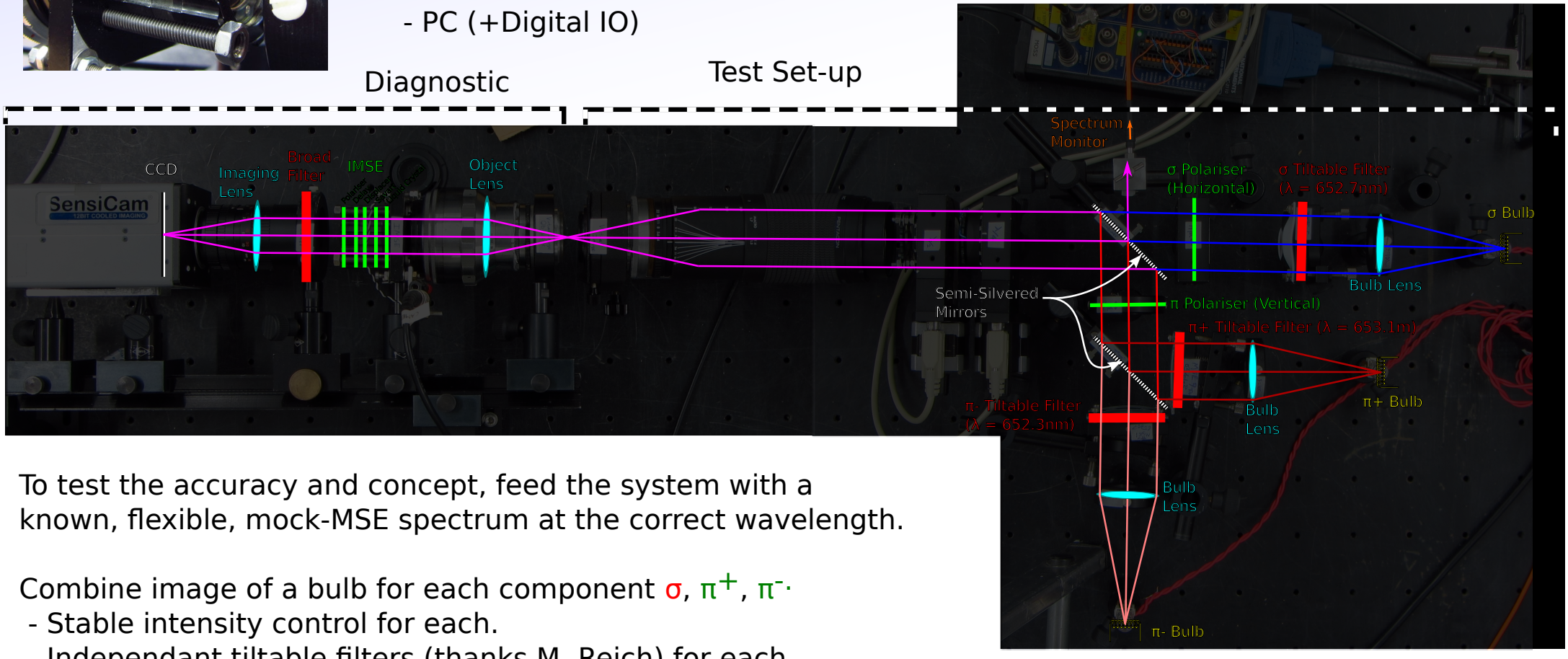

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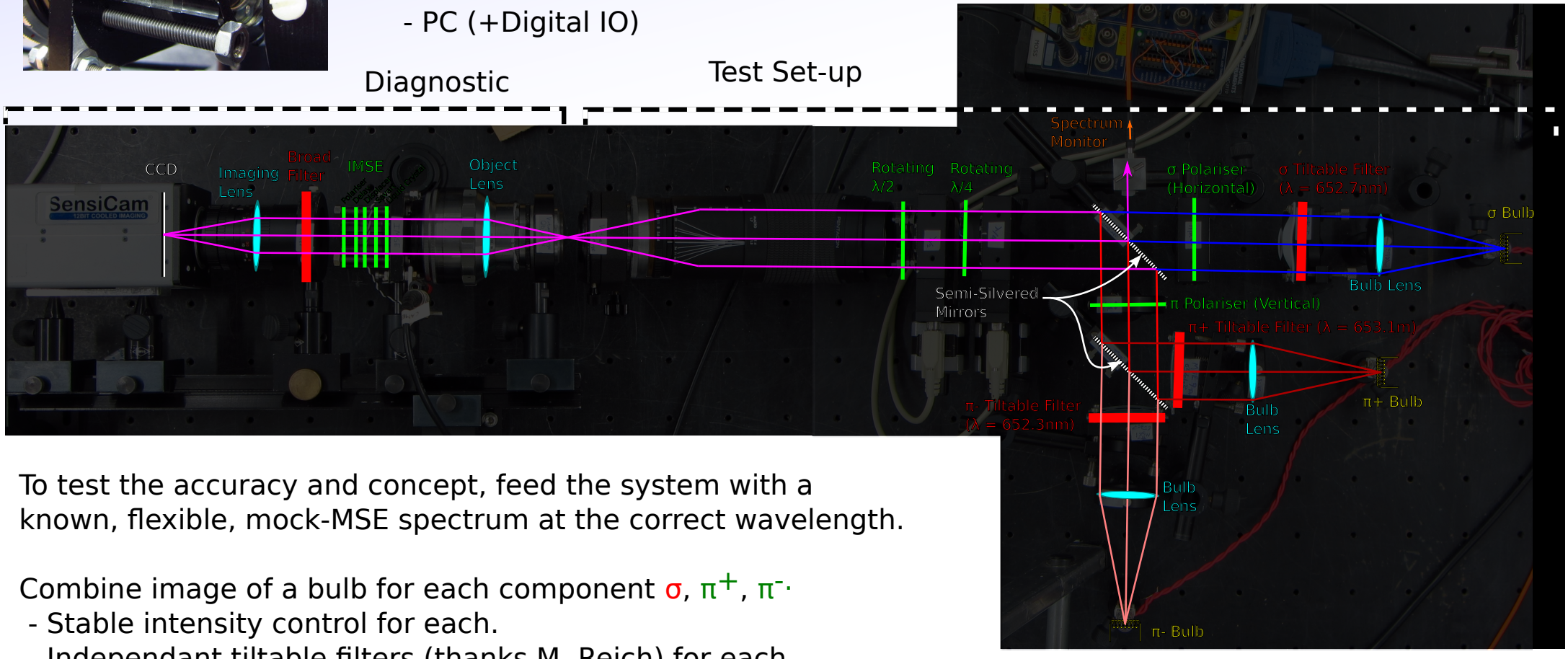

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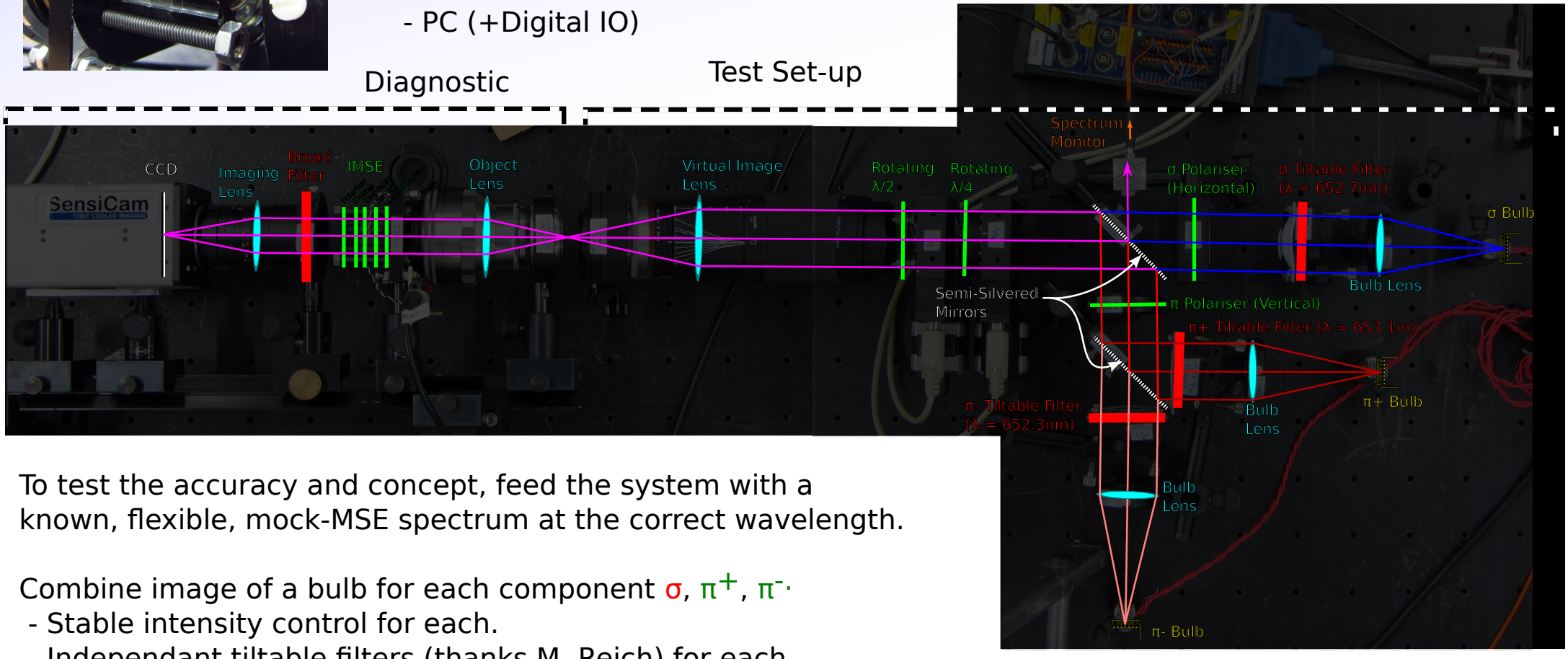

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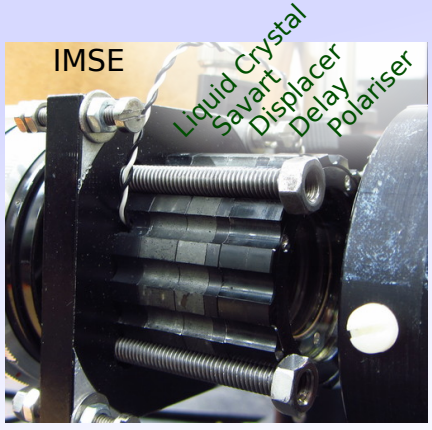

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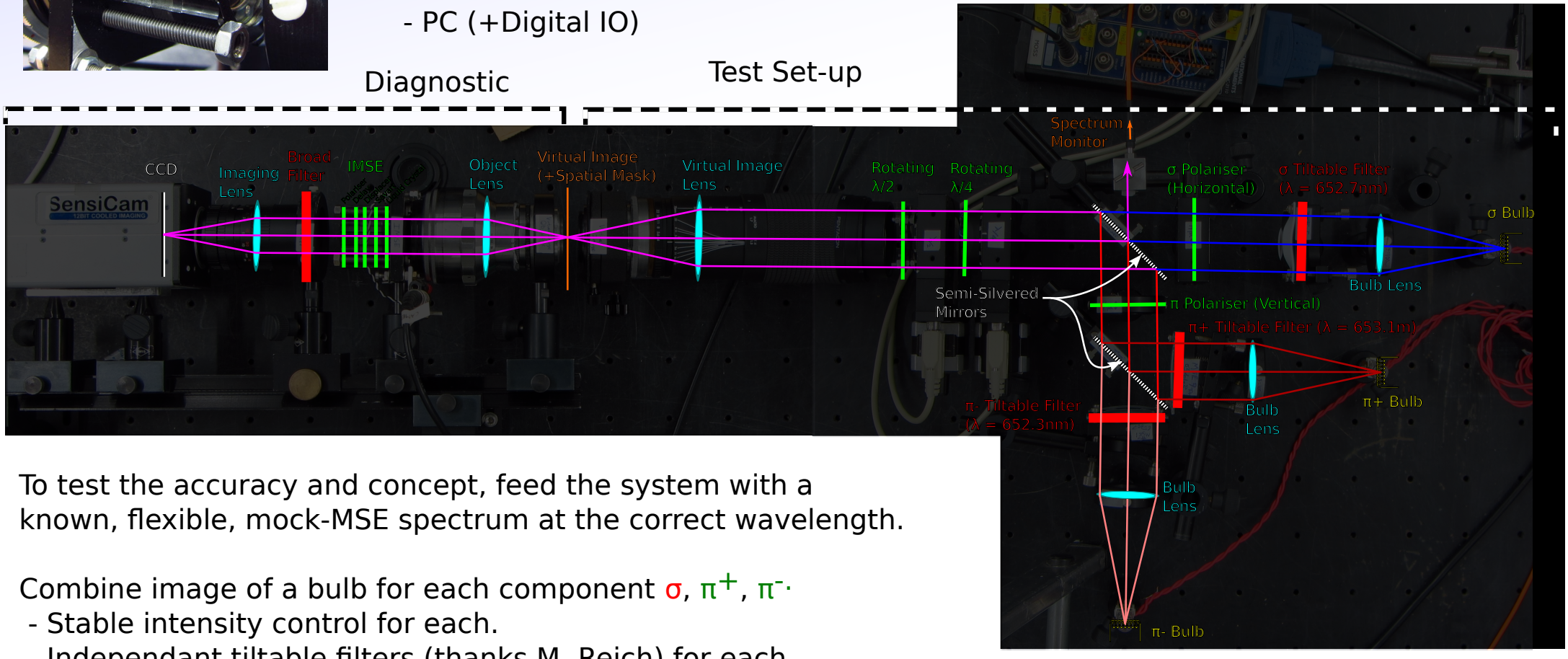

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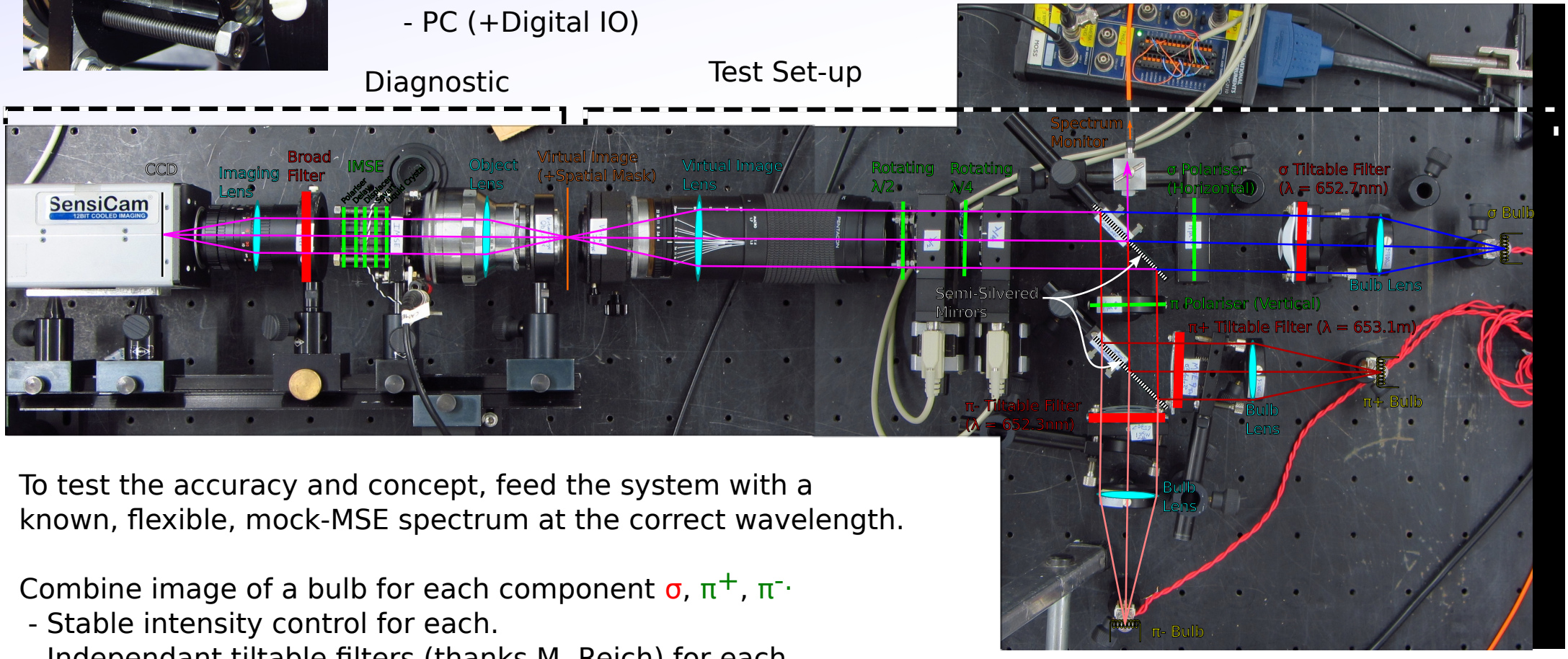

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Spectrum is set up to roughly mimic AUG MSE spectrum.

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

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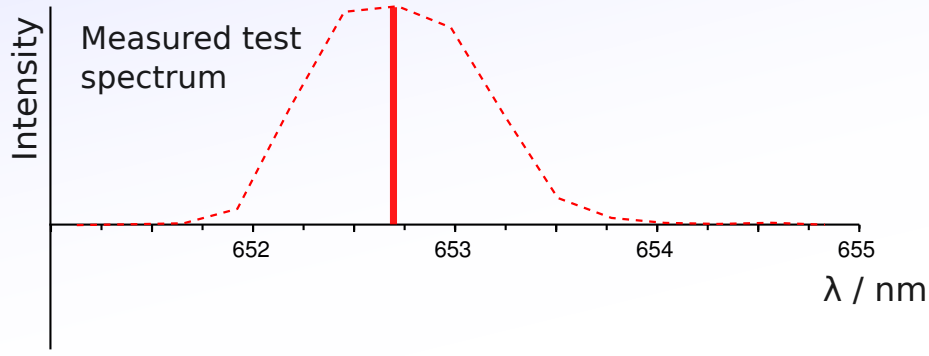

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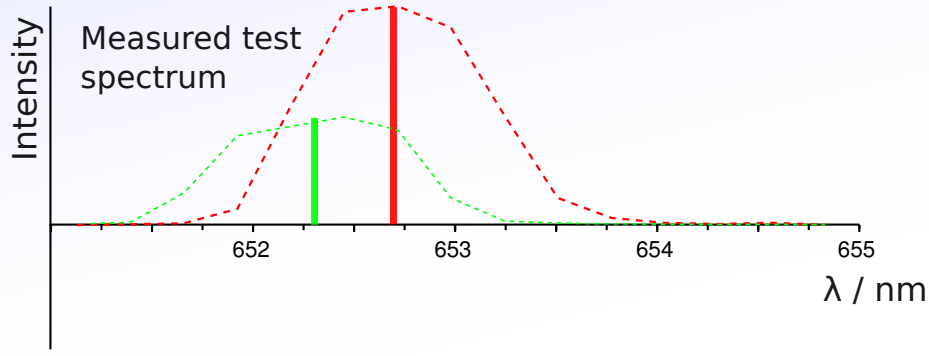

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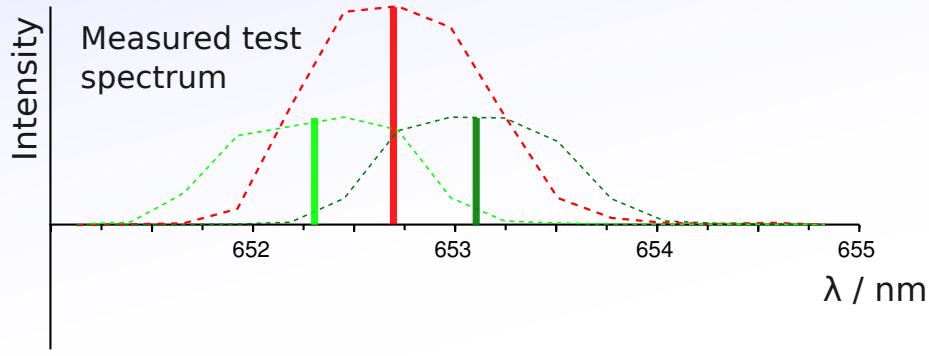

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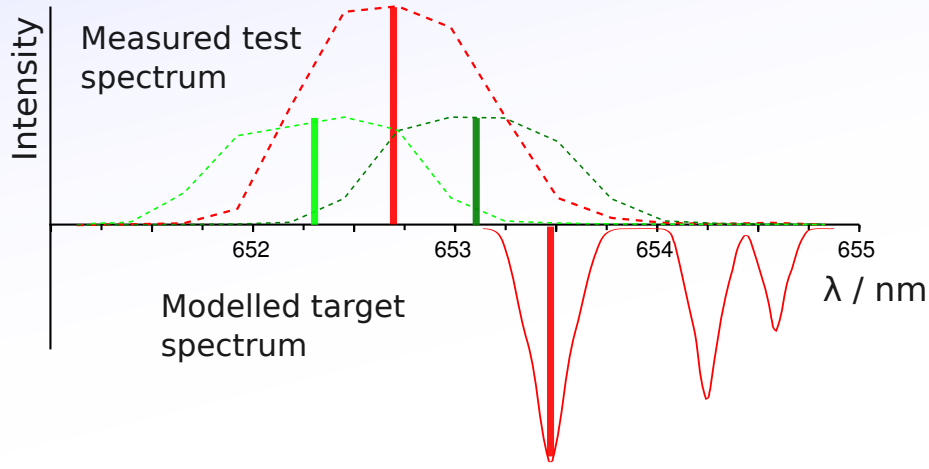

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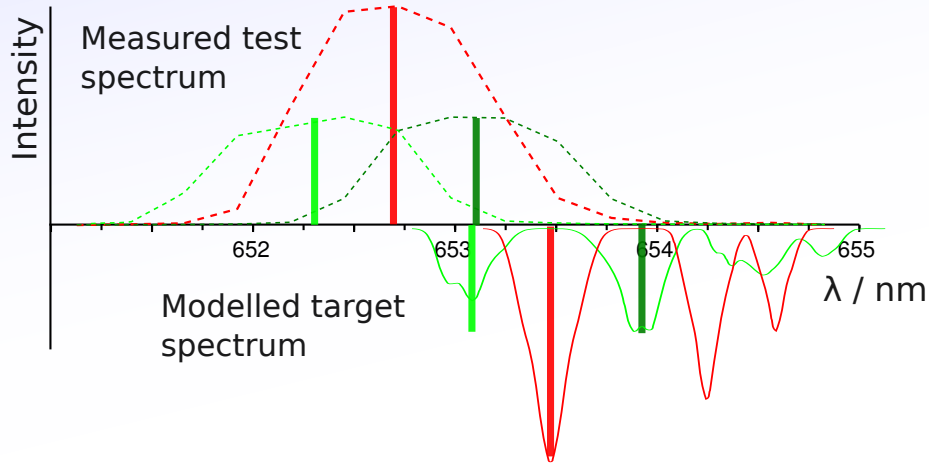

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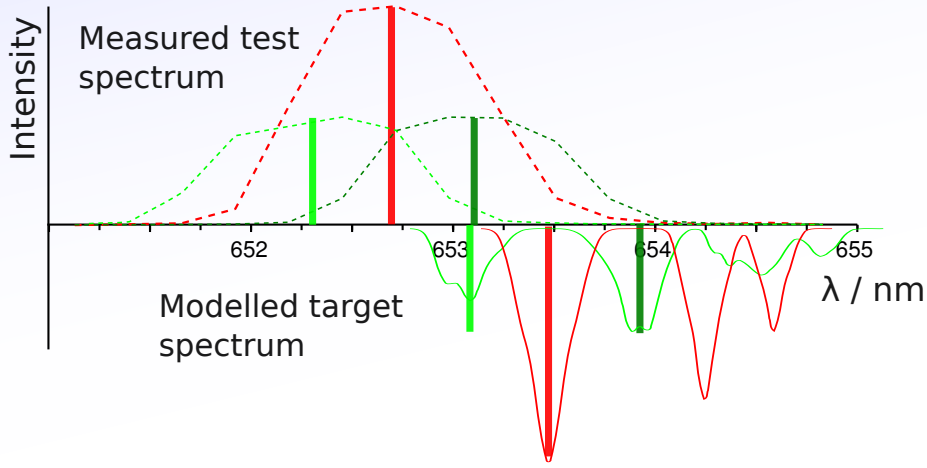
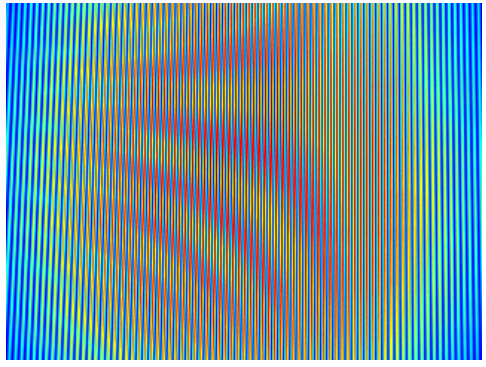
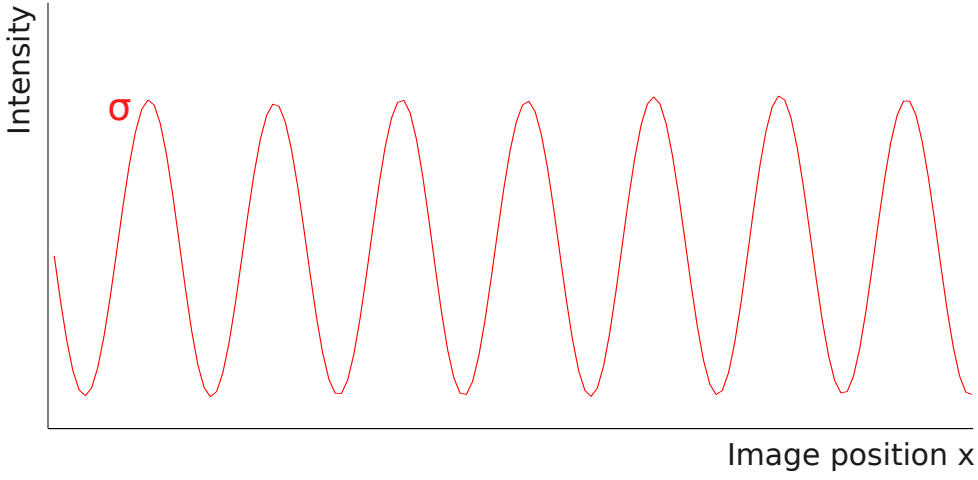


Fringes produced by a single displacer plate:

σ (θ = 0°)





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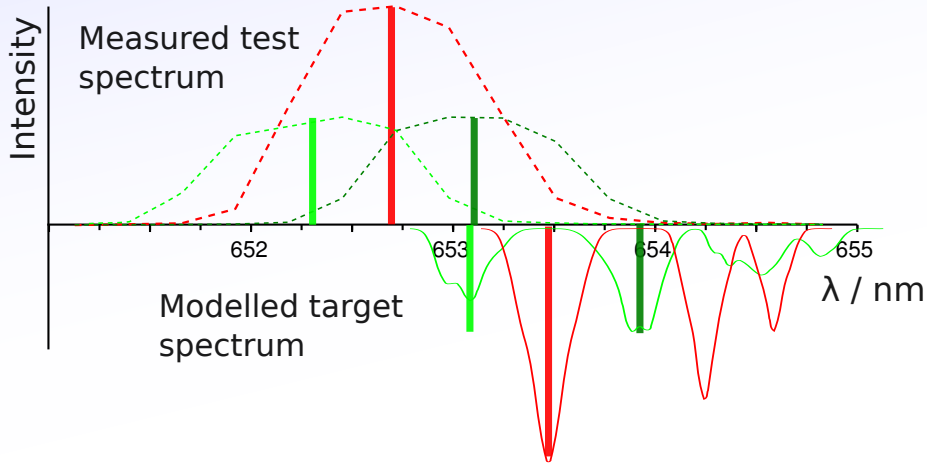

Fringes produced by a single displacer plate:

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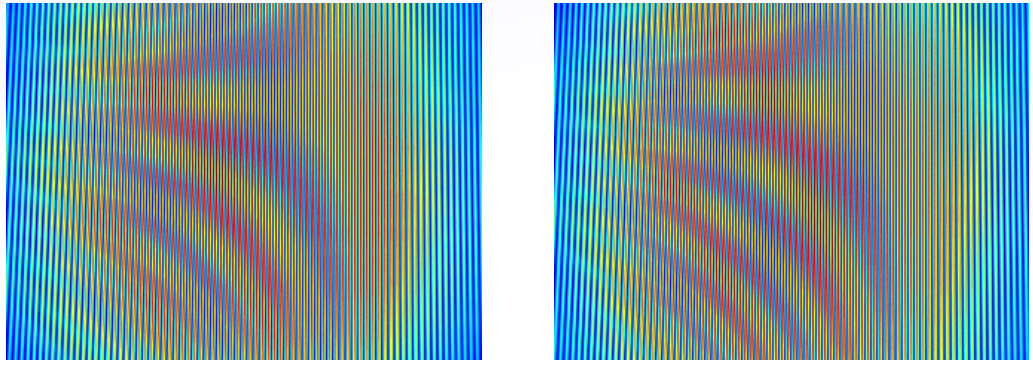

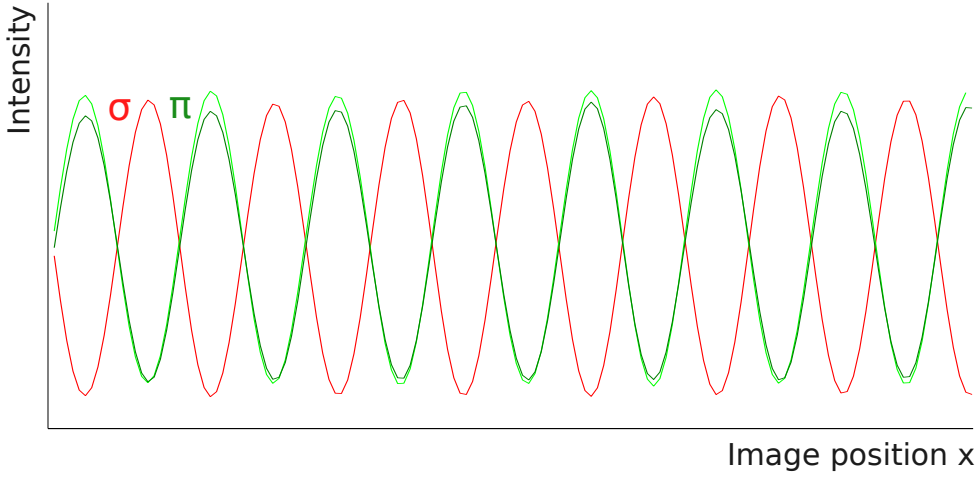

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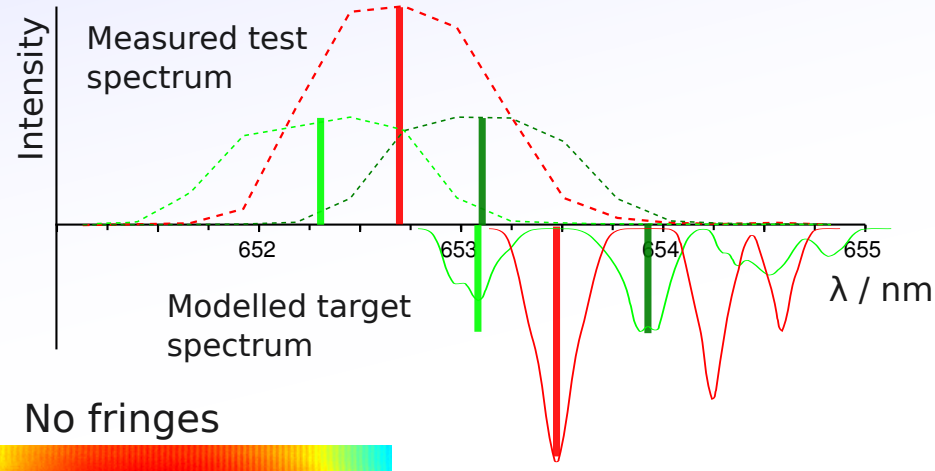

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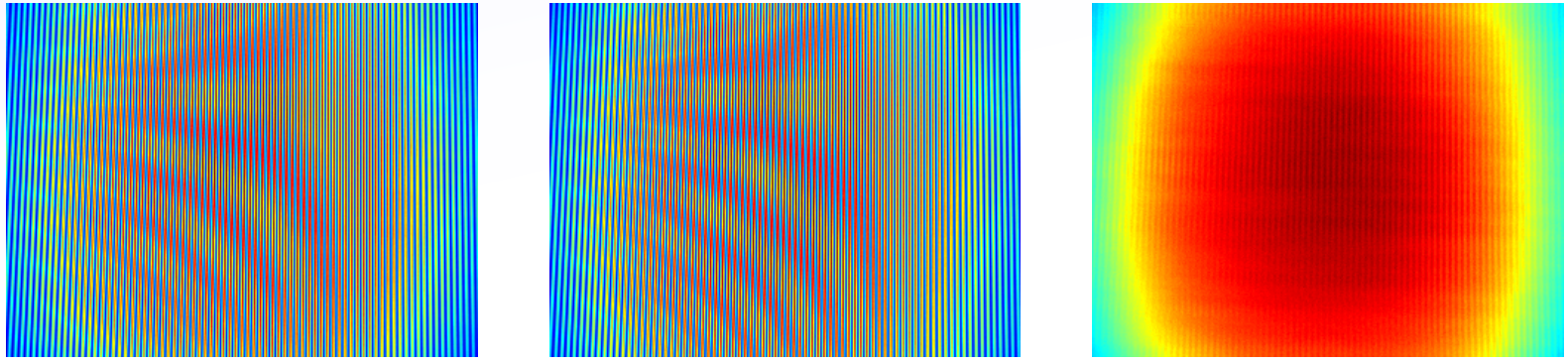

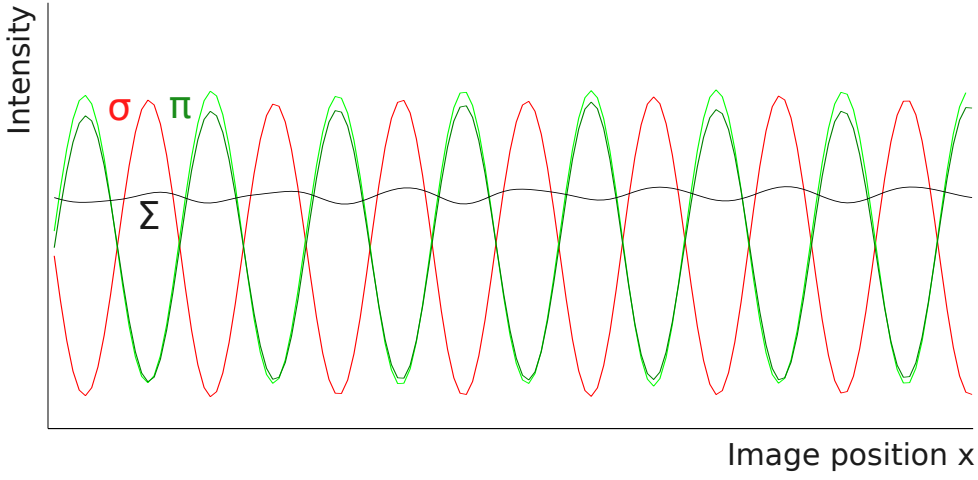

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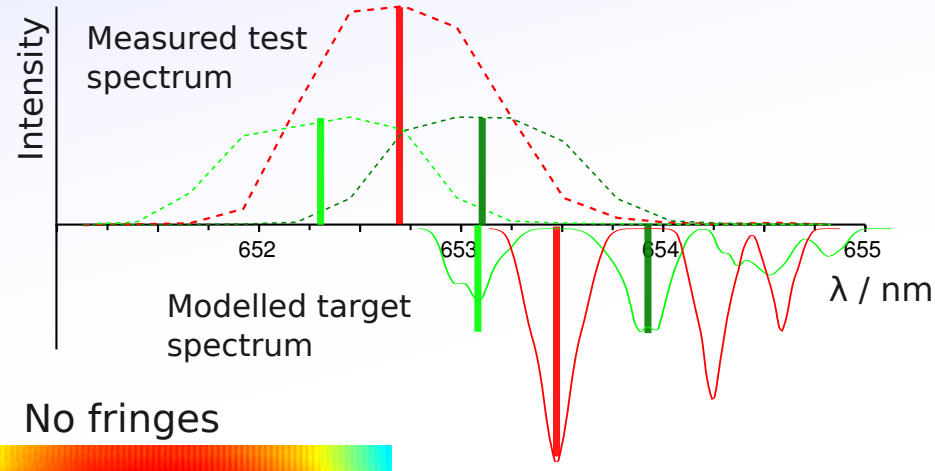

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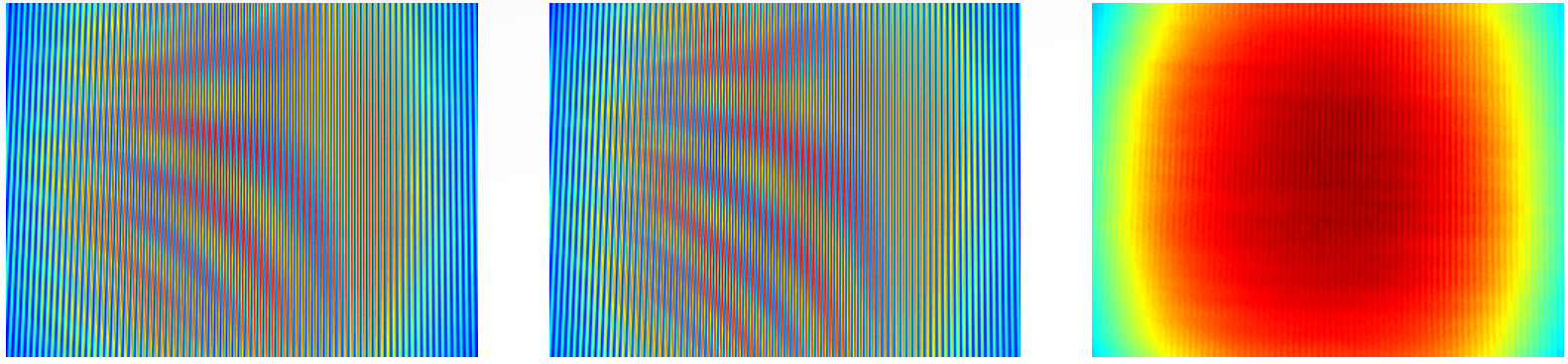
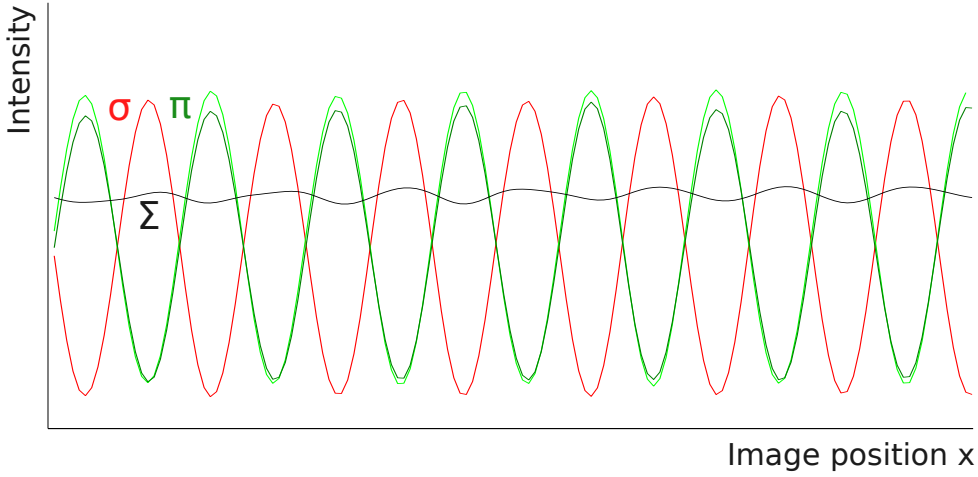
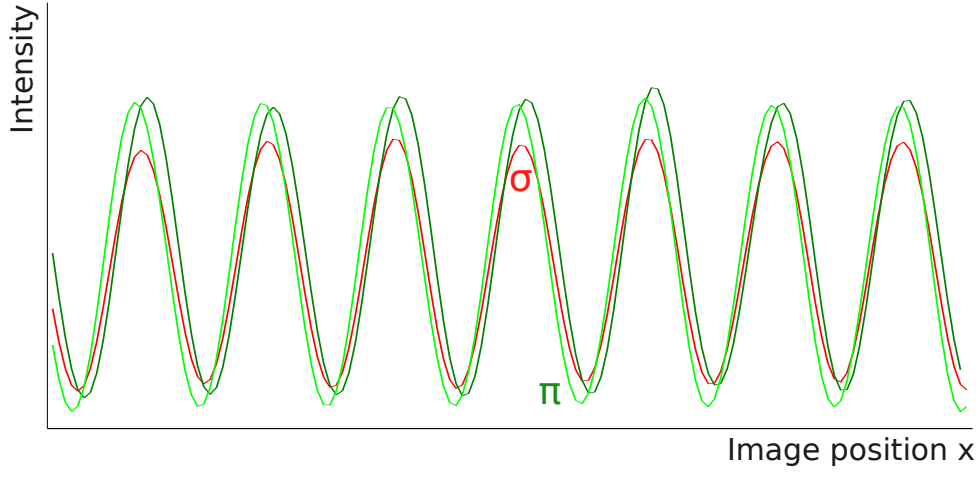


With delay plate, phase of π's roughly align to σ:

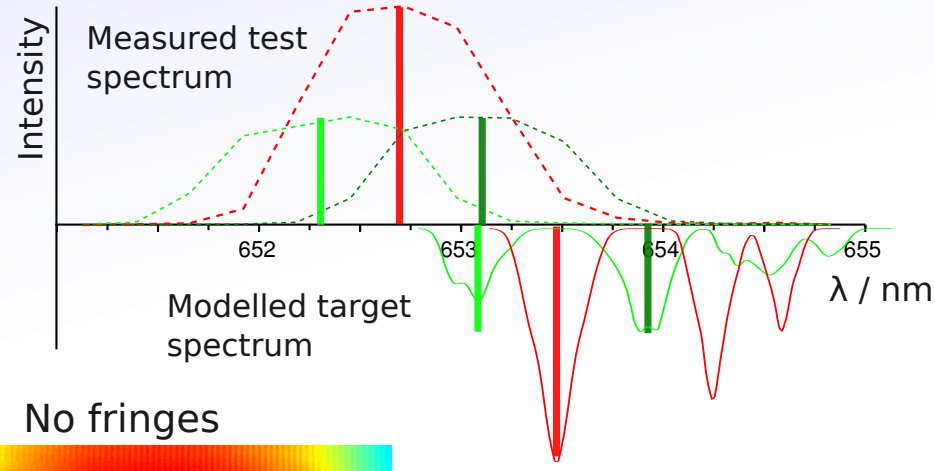




Test Setup

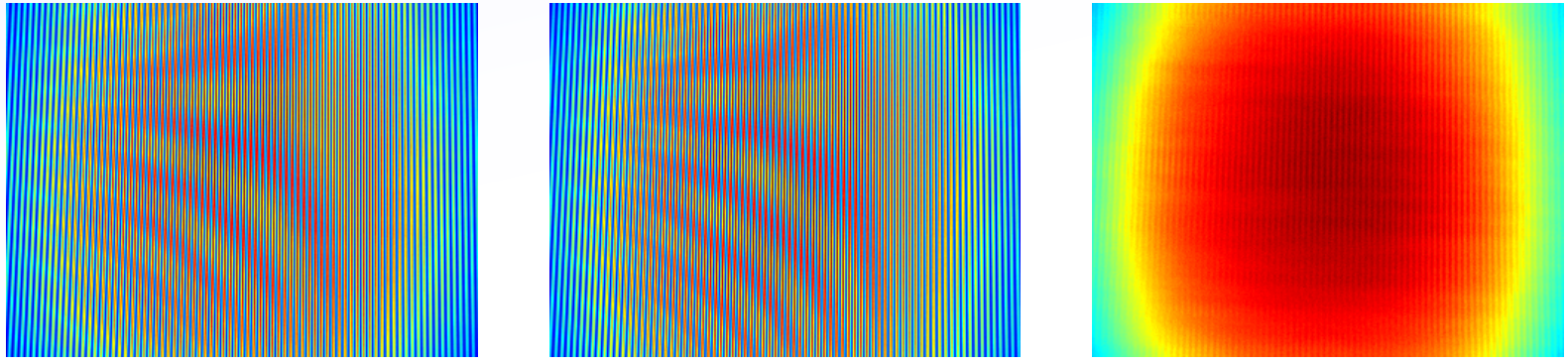
Spectrum is set up to roughly mimick AUG MSE spectrum.

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



Fringes produced by a single displacer plate:

σ (θ = 0°) + π^+ + π^- (θ = 90°) = No fringes



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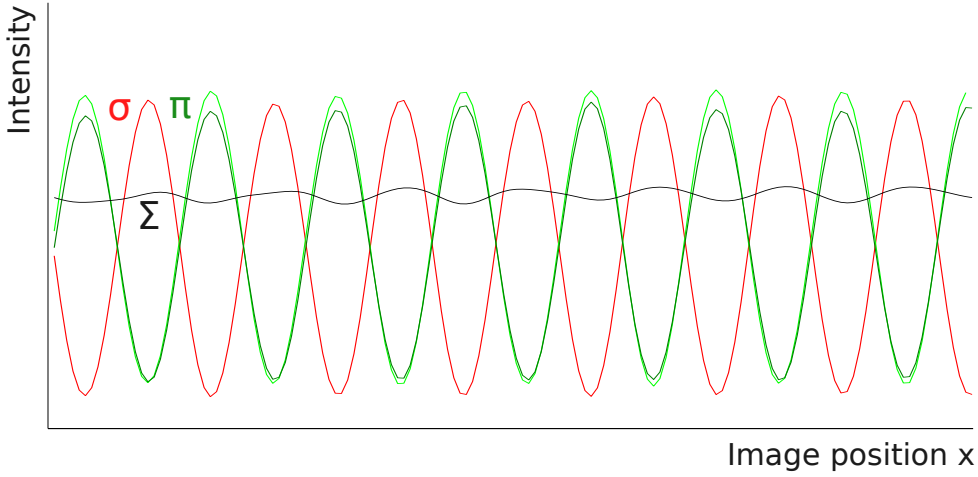
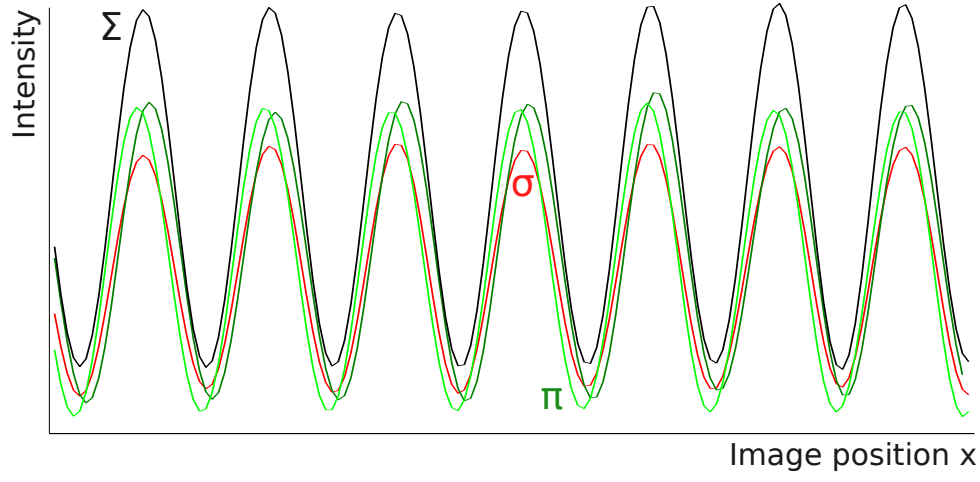
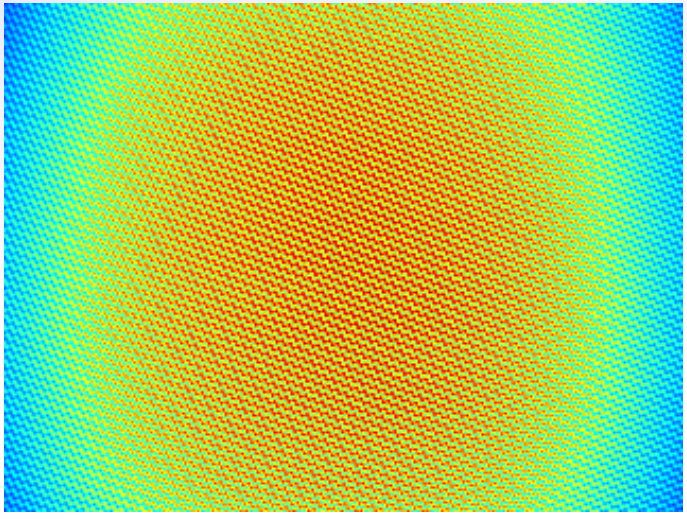




Full Fringes and Demodulation

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



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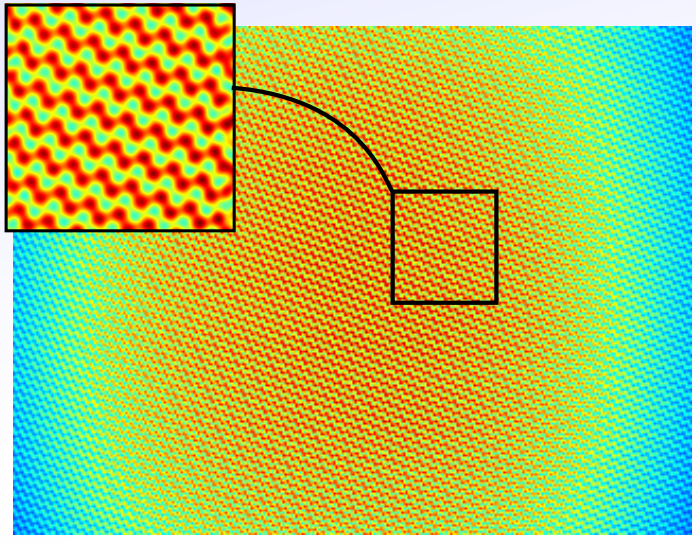

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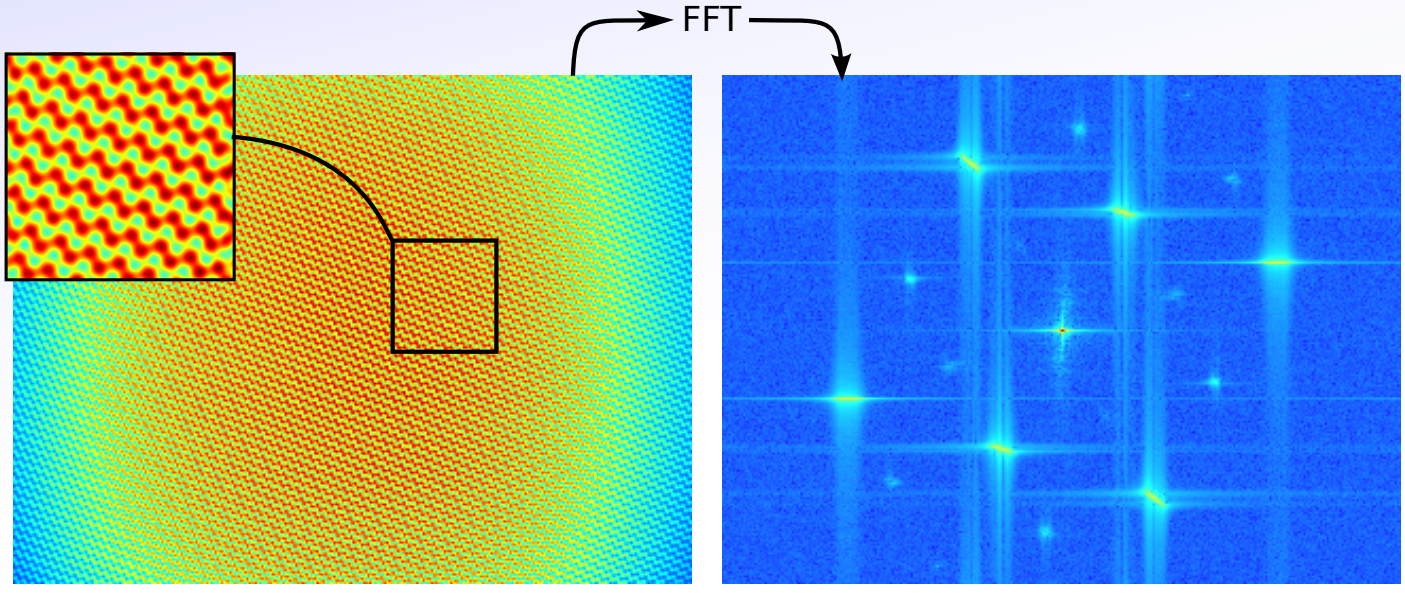

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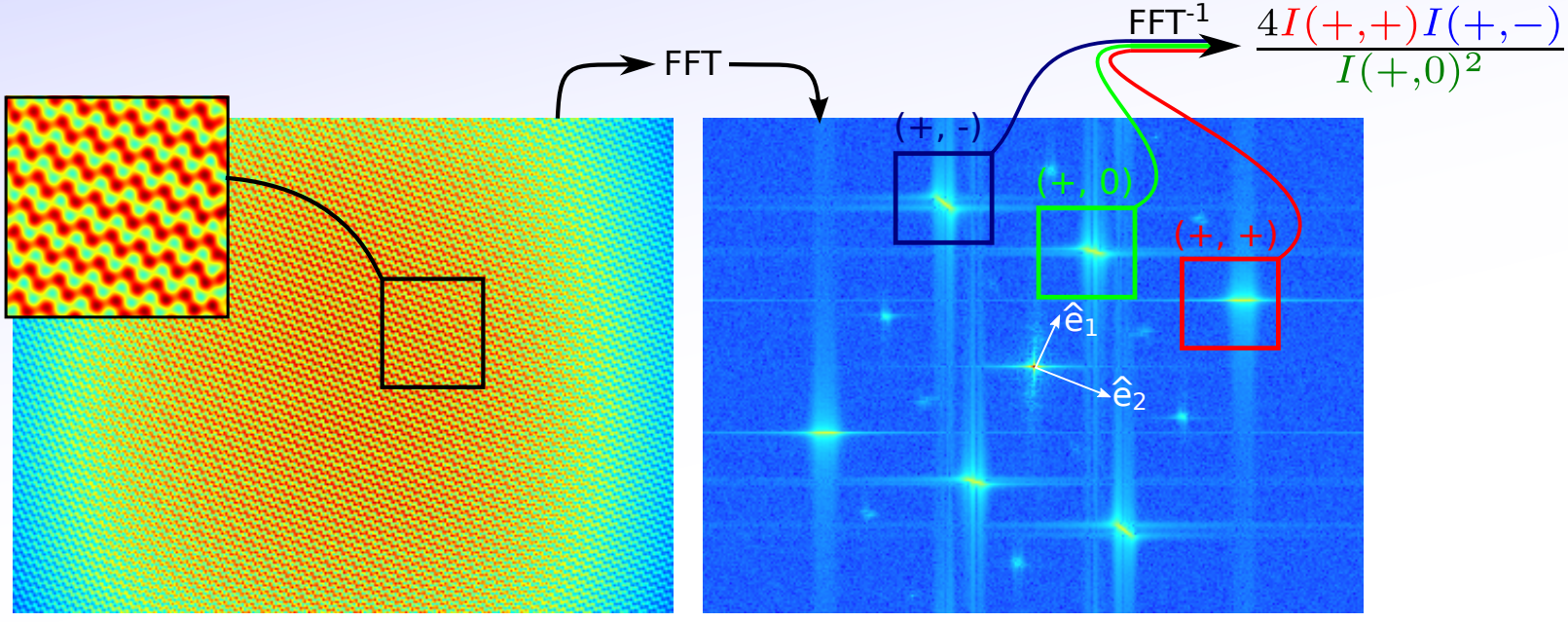

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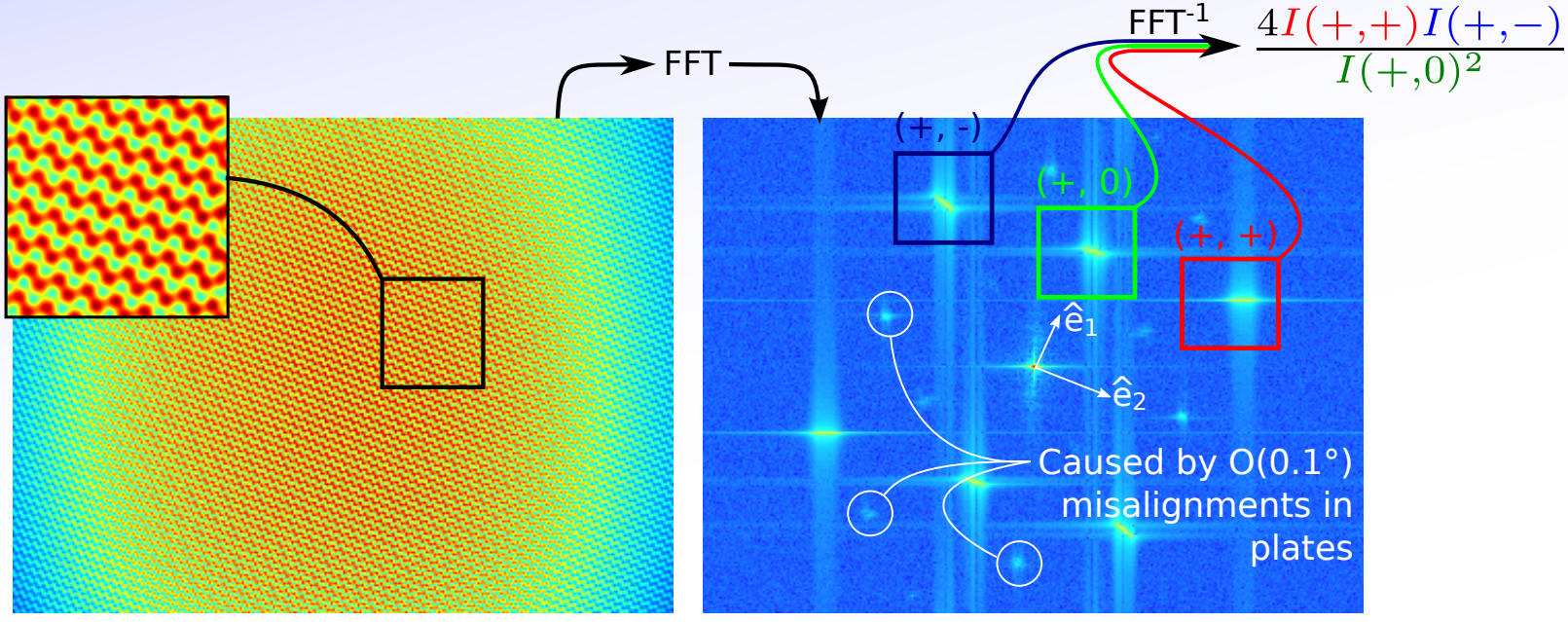

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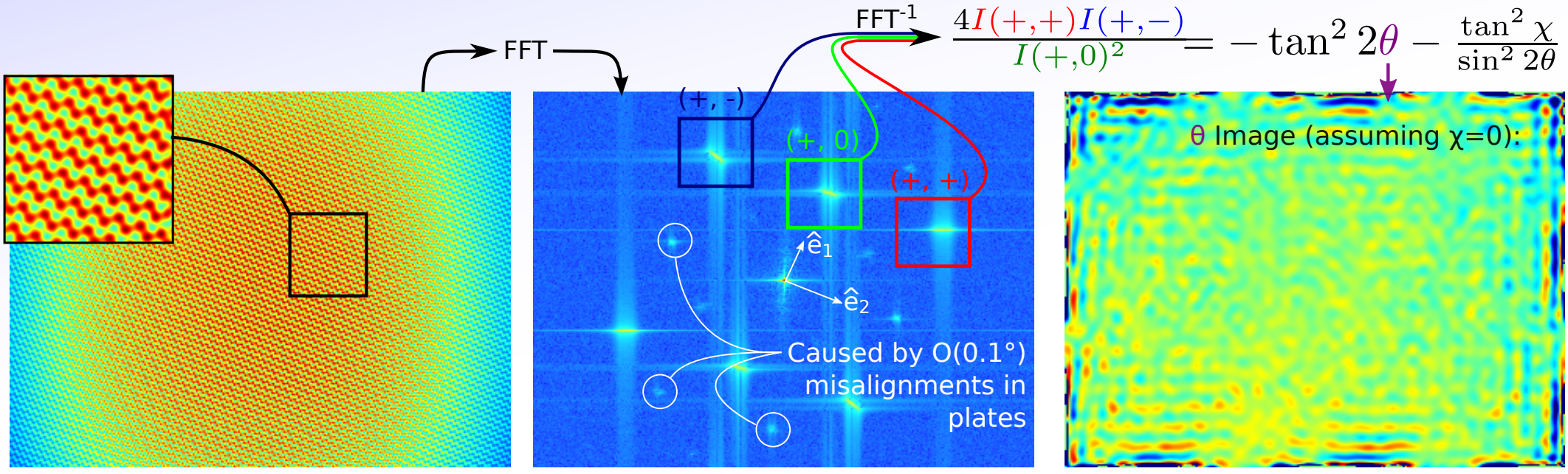

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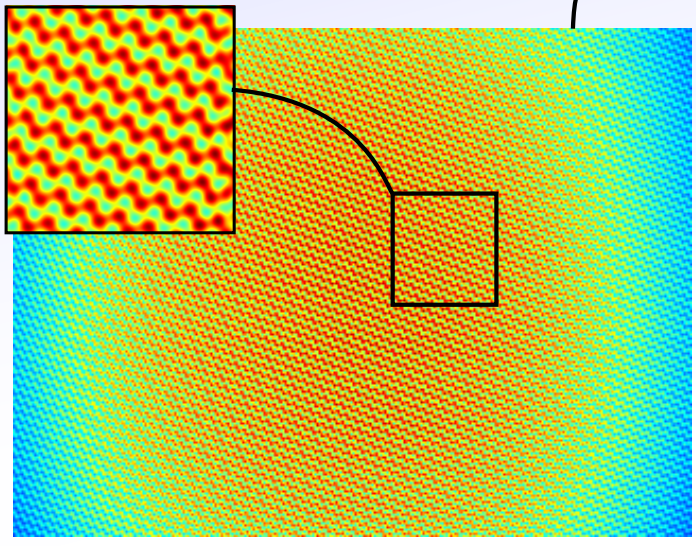
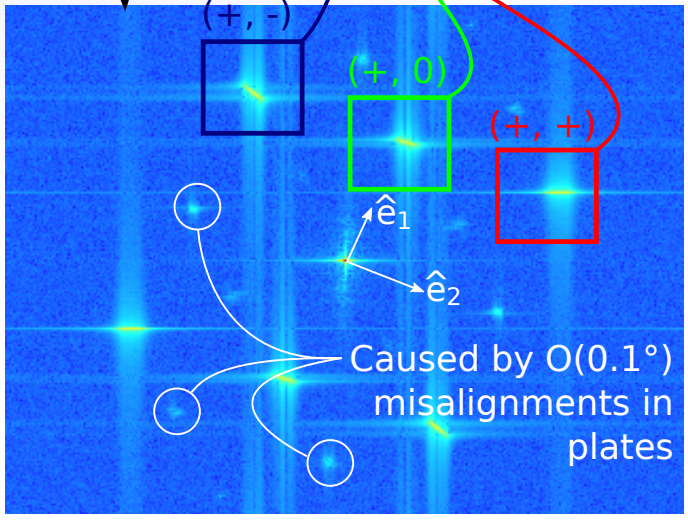
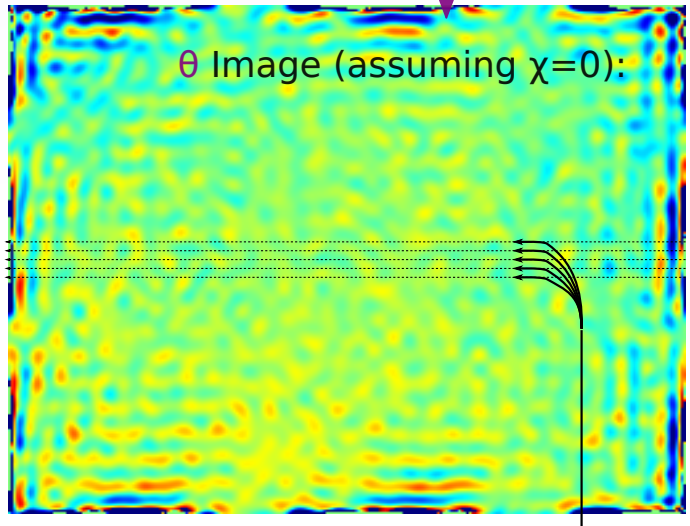


FFT →

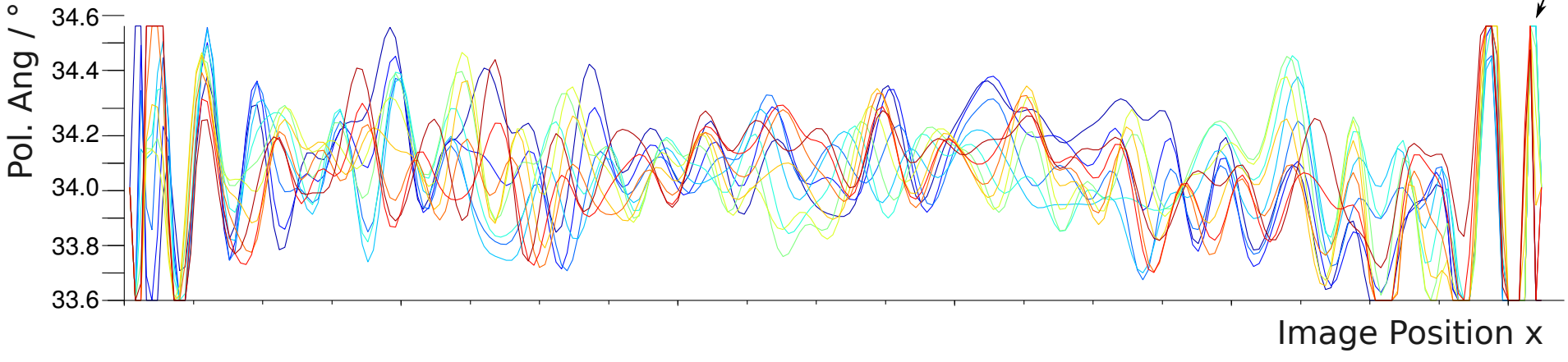


FFT^{-1} →

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

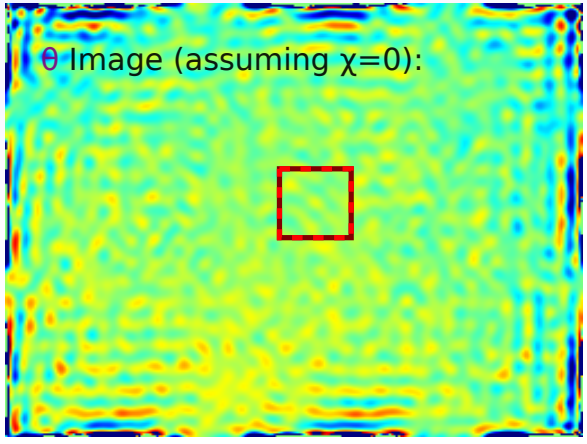


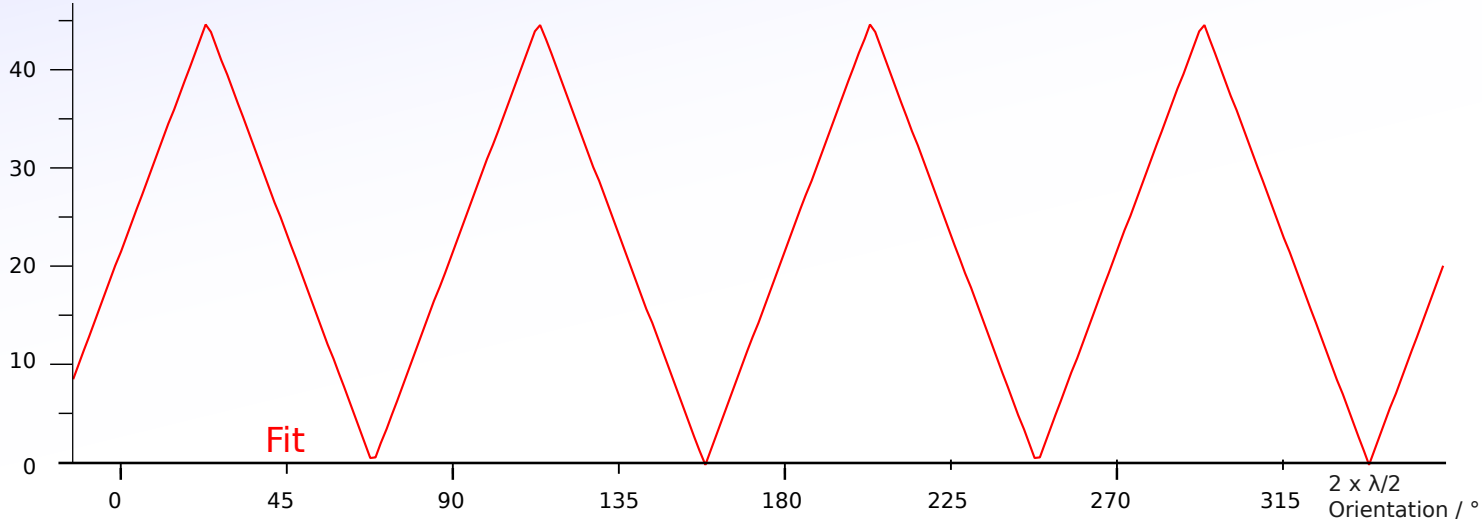
Pixel accuracy is degraded by edge effects etc. It might be possible to reduce this by improving the demodulation procedure later, but for now averaging 3-4 fringes works.



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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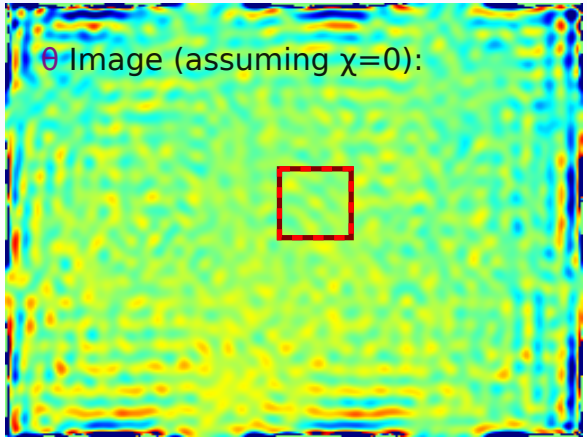

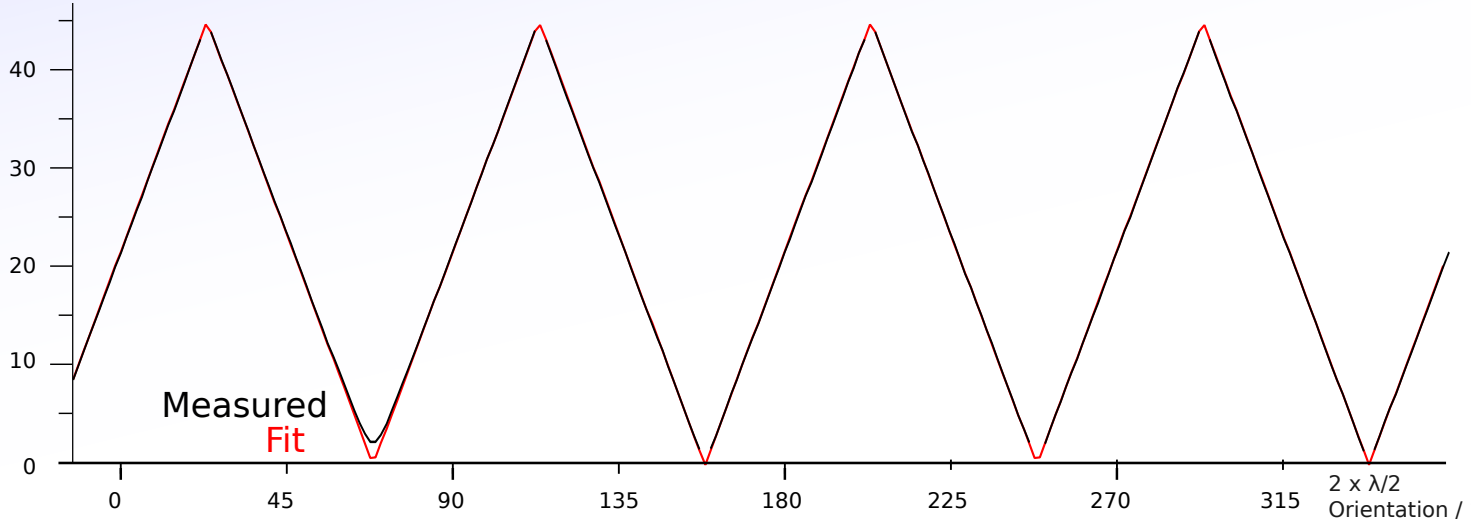

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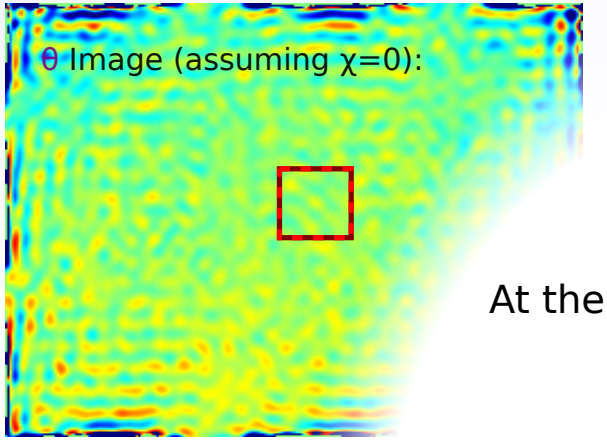
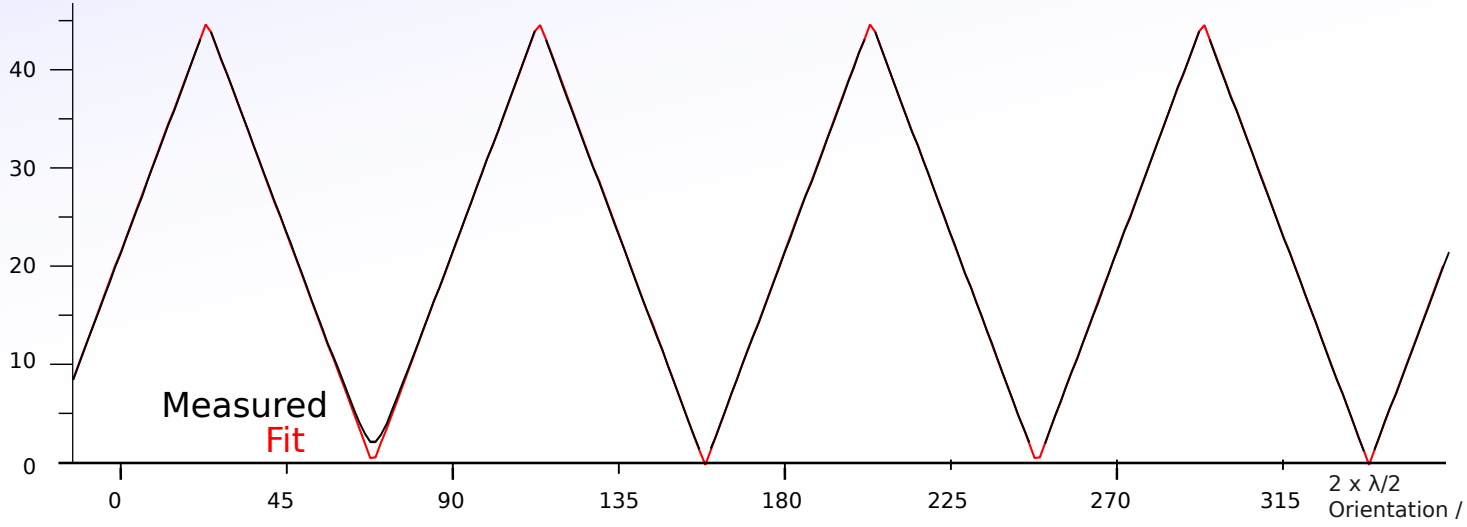
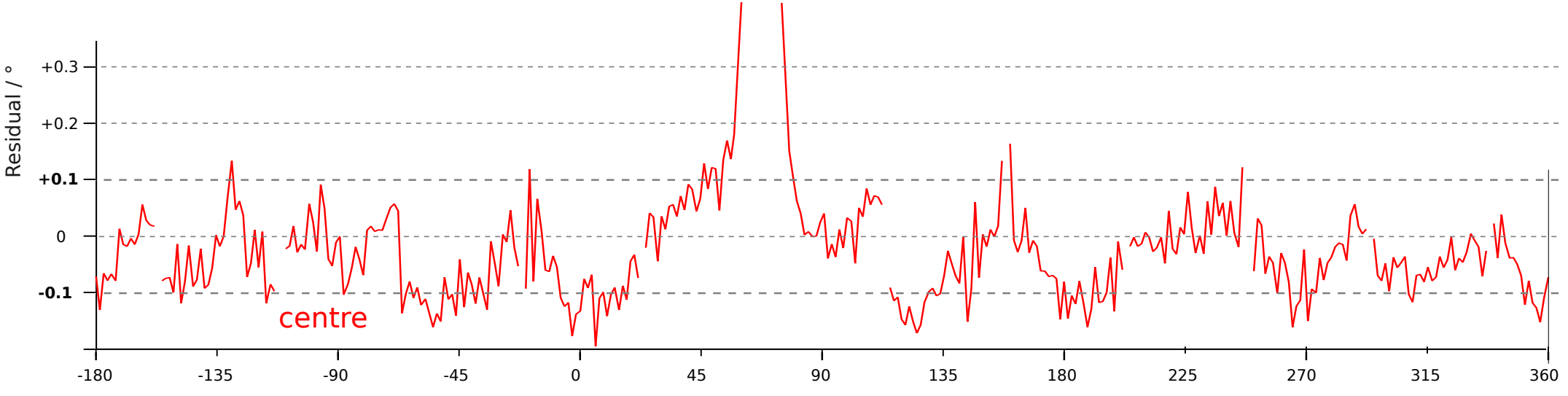




At the centre of the image, the residual is at the desired ±0.1°.



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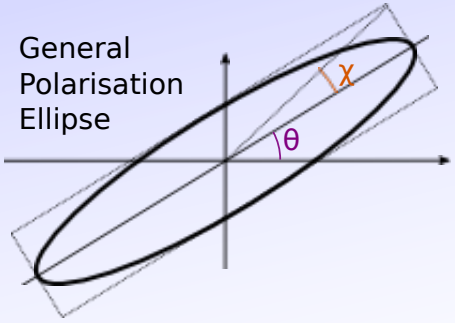

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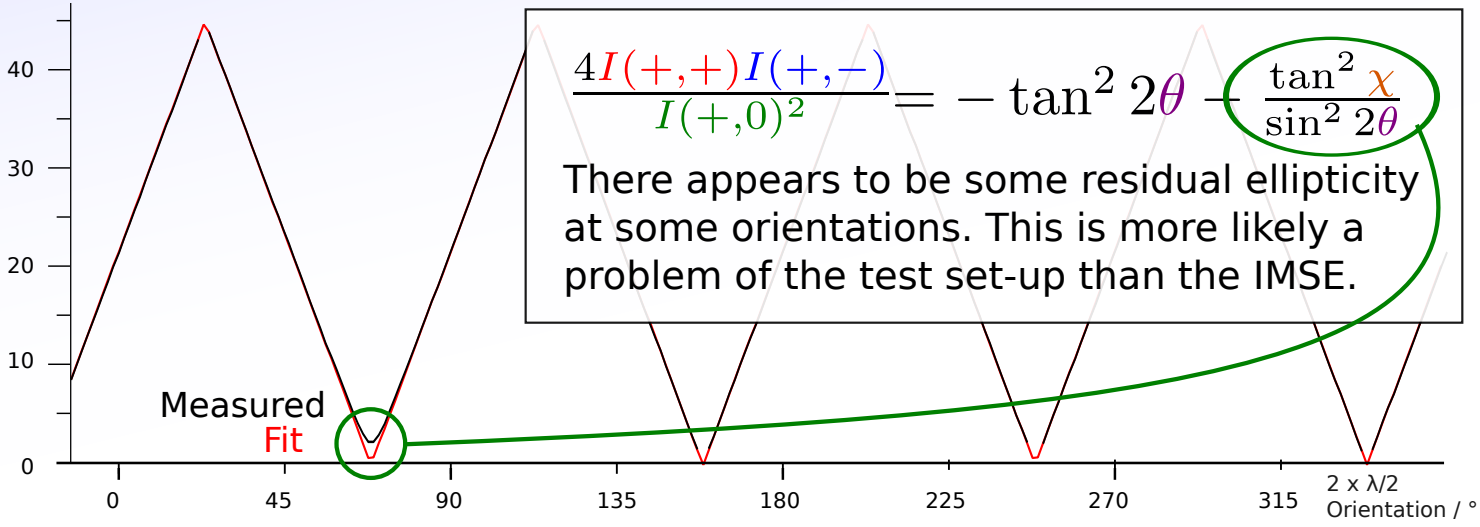

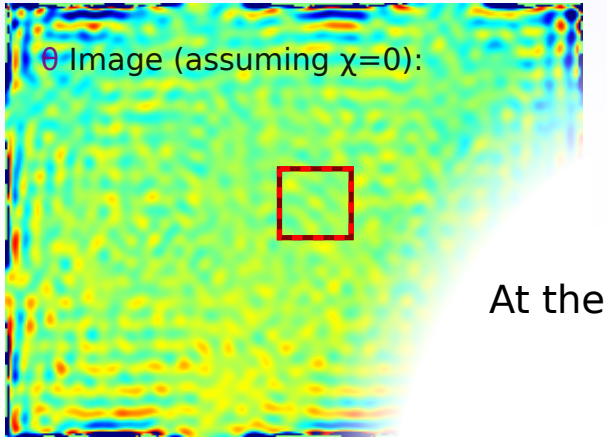

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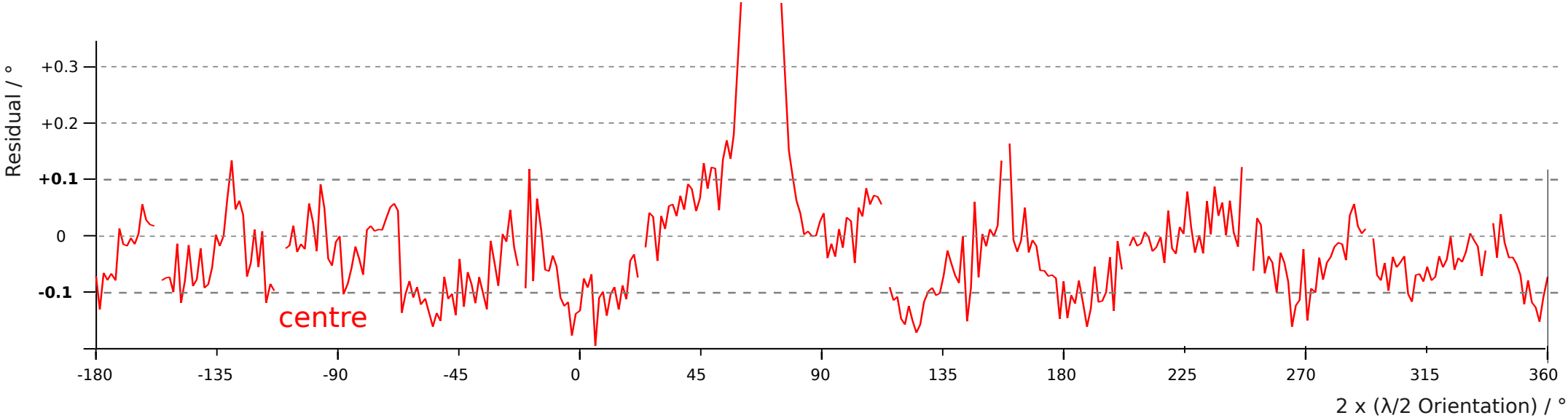

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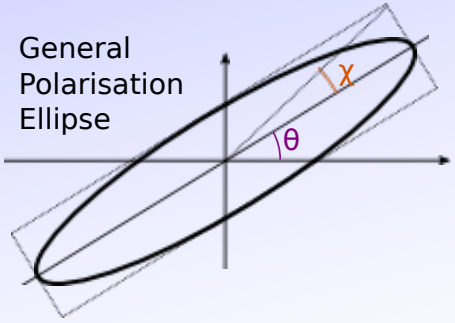

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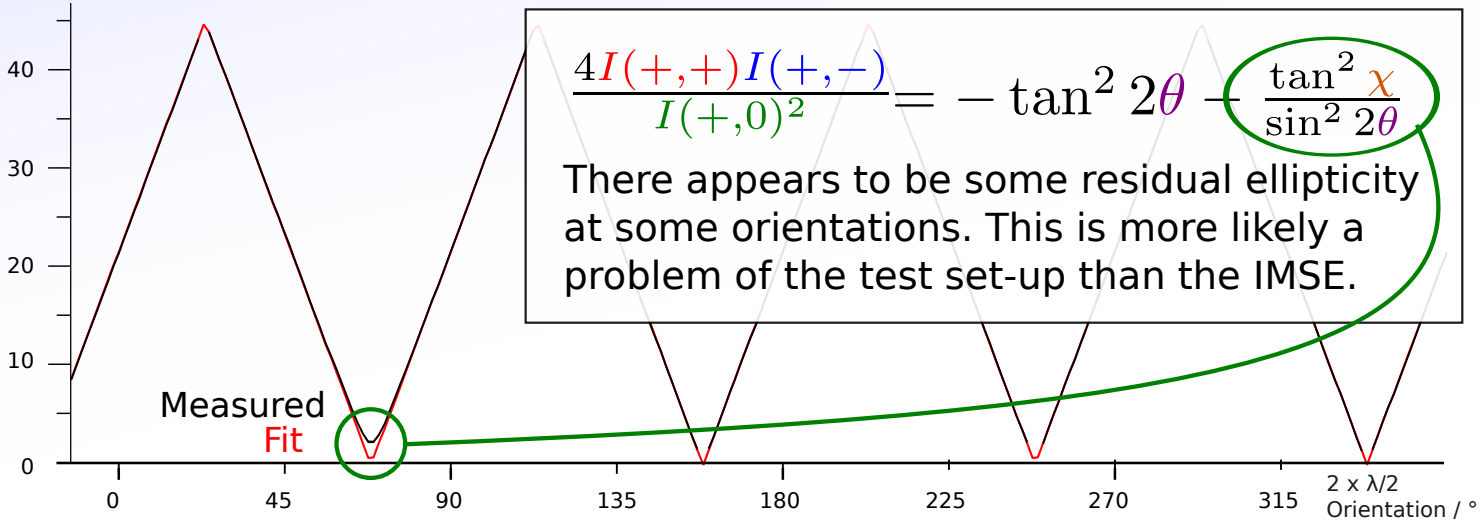
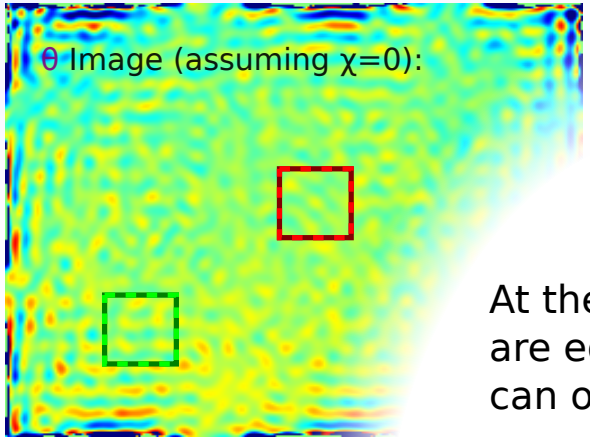
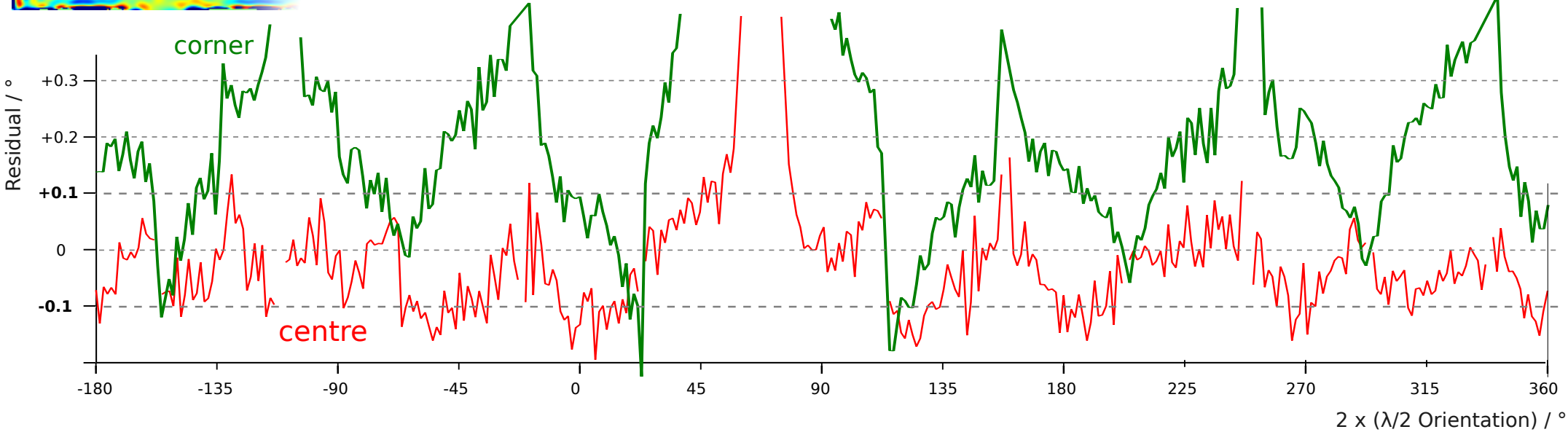


$$\frac{4I(+,+)I(+,-)}{I(+,0)^2} = -\tan^2 2\theta - \frac{\tan^2\chi}{\sin^2 2\theta}$$

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.



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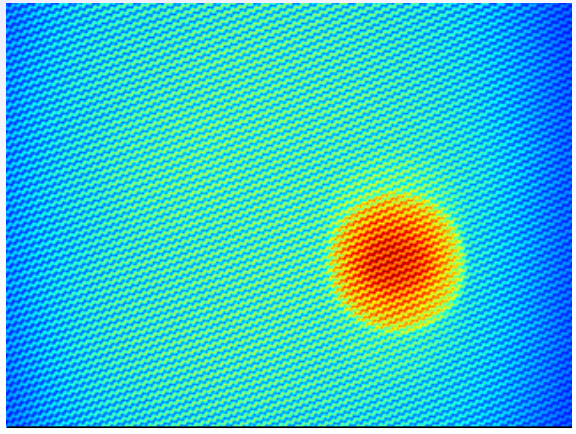

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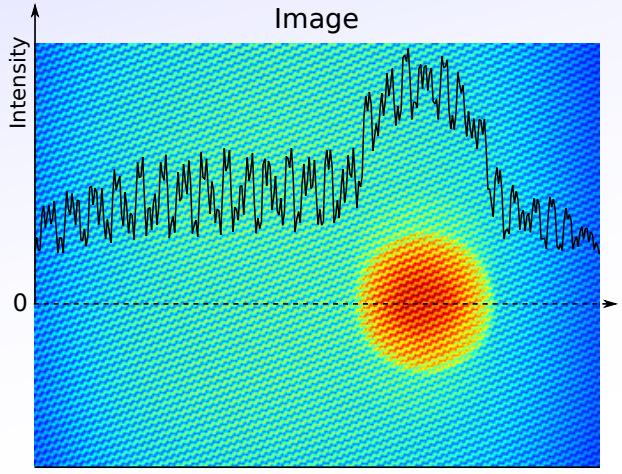

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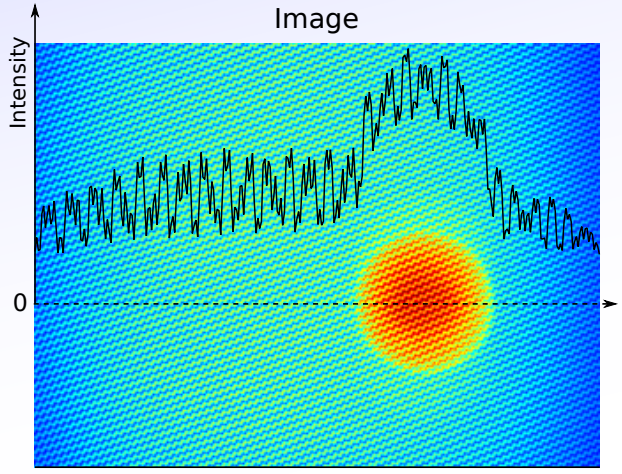

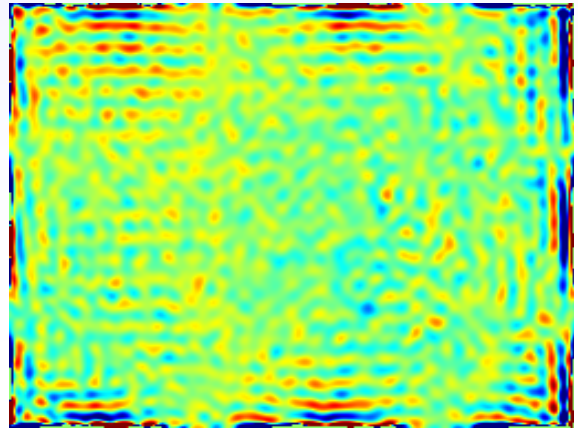

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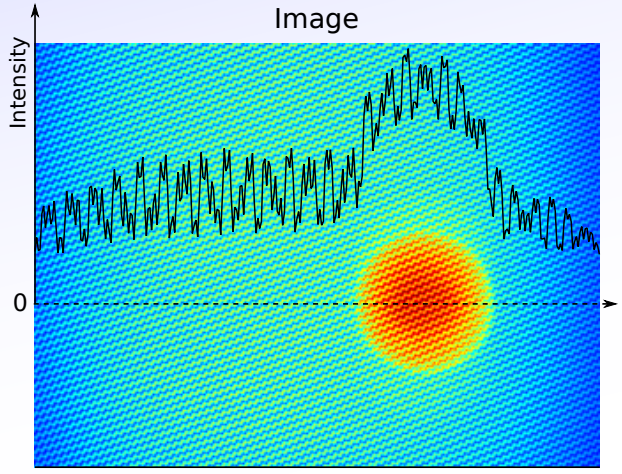

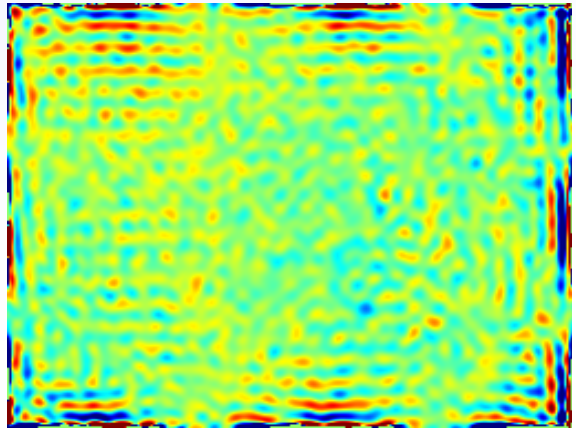

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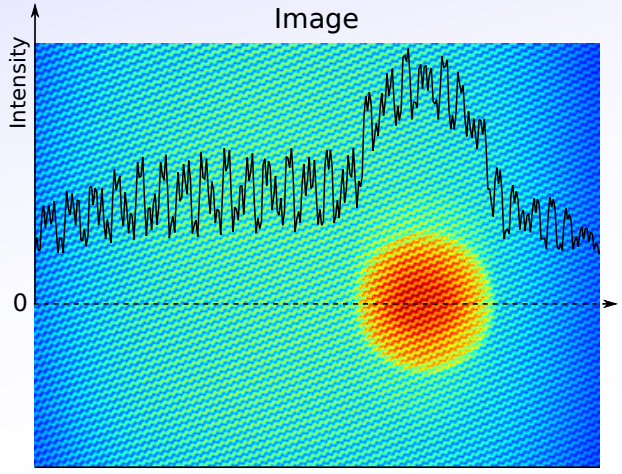

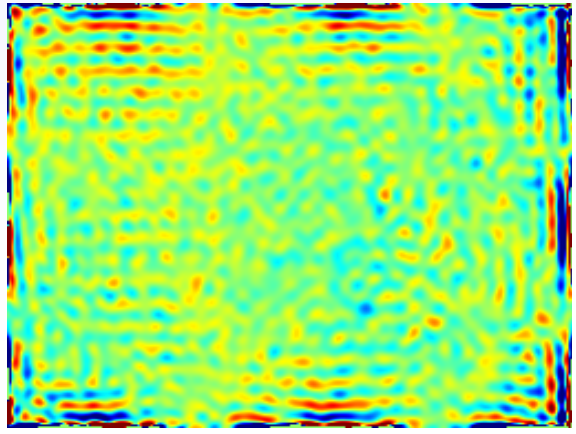

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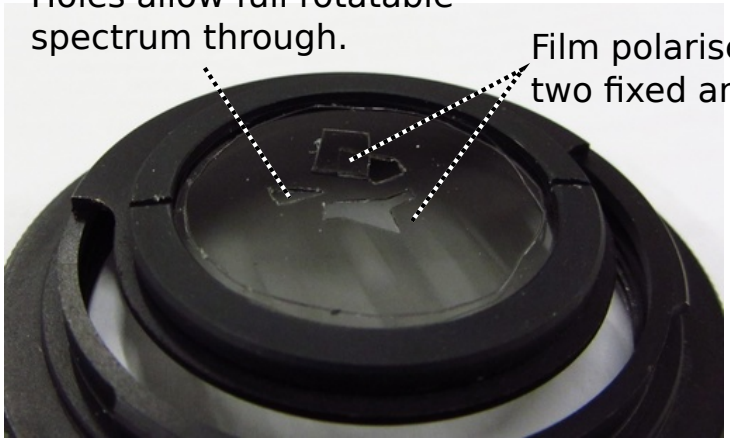

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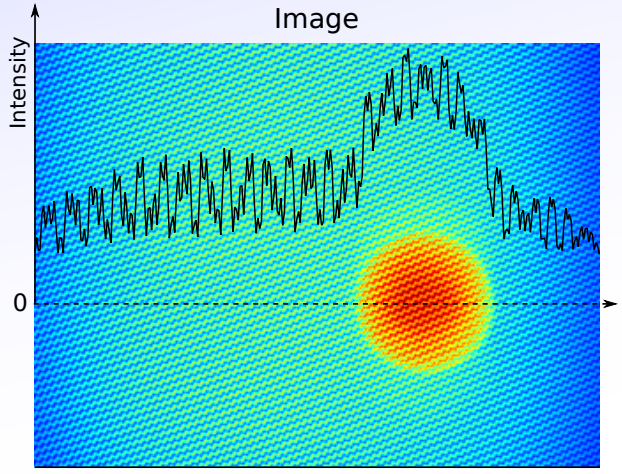

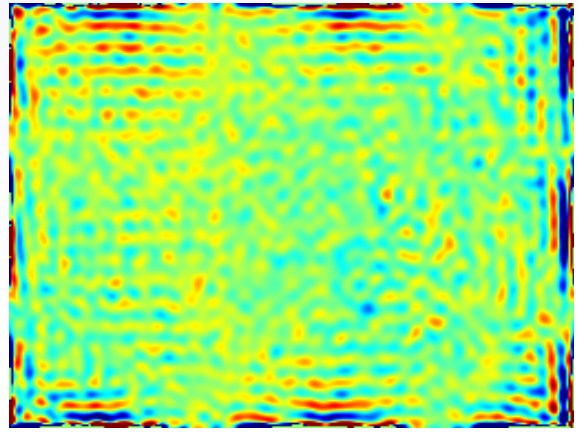

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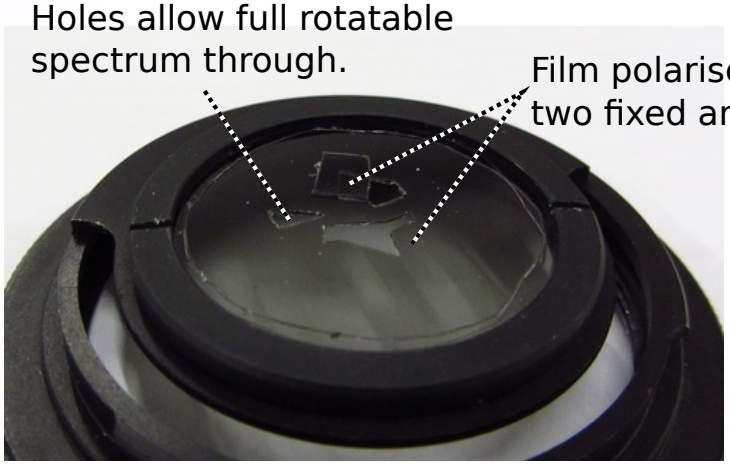

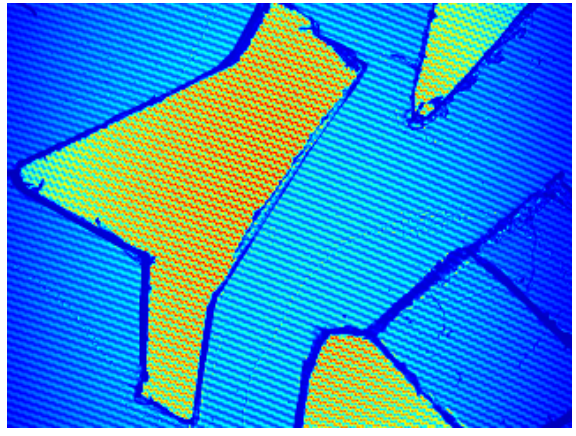

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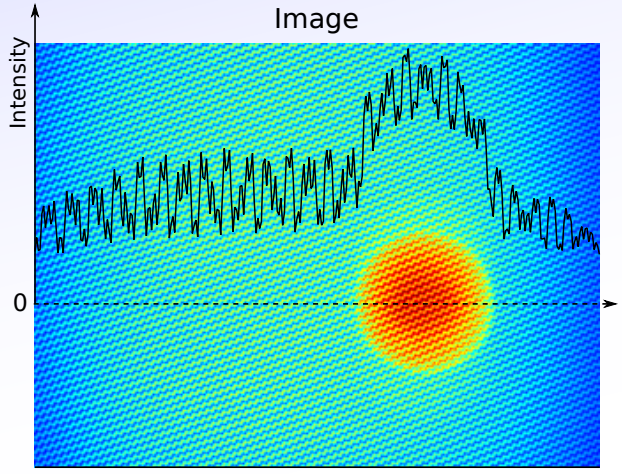

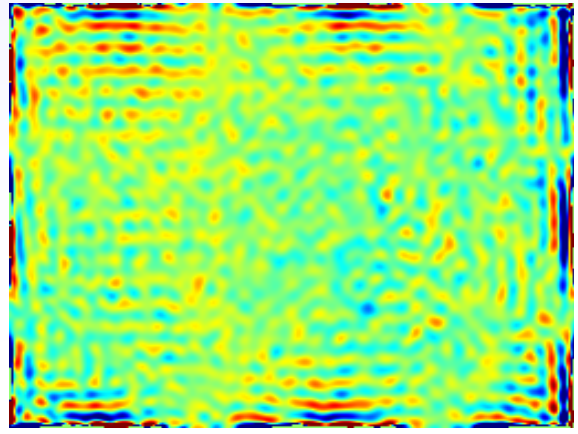

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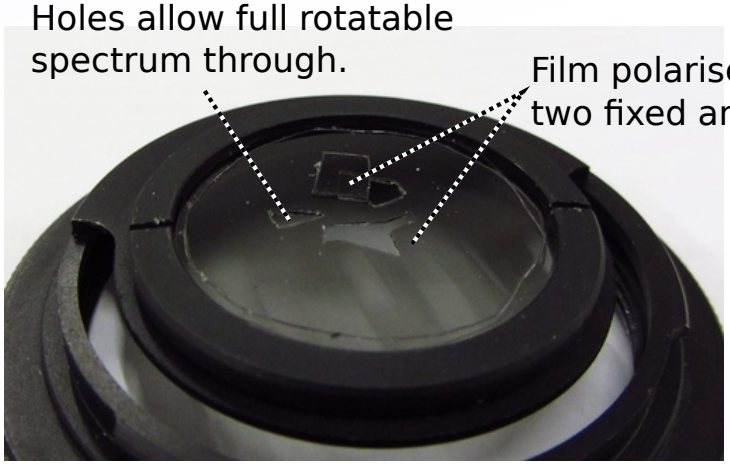

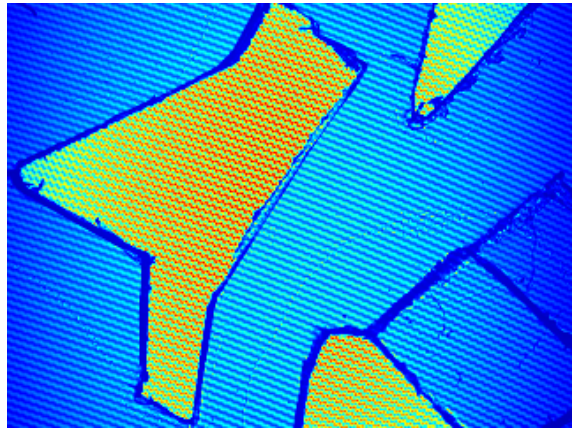

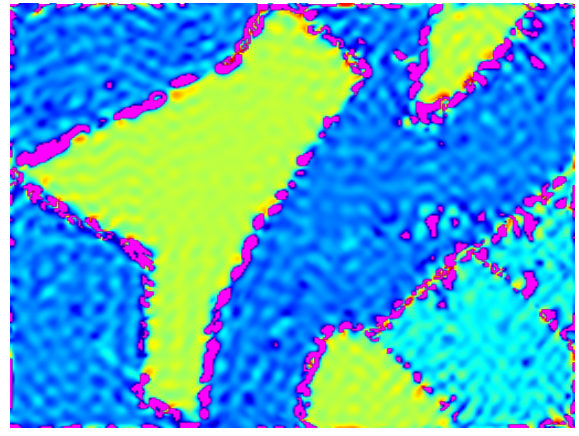

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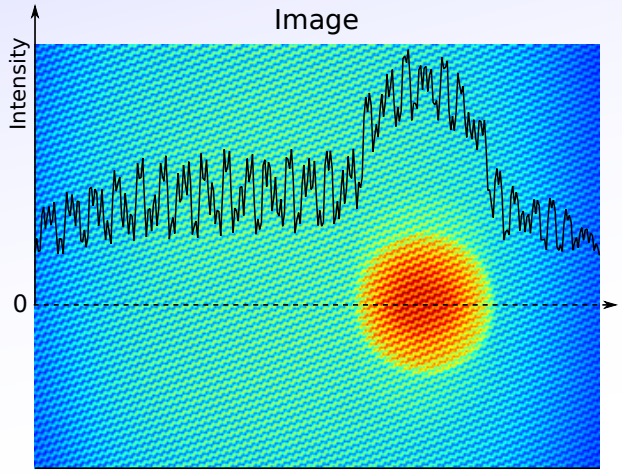
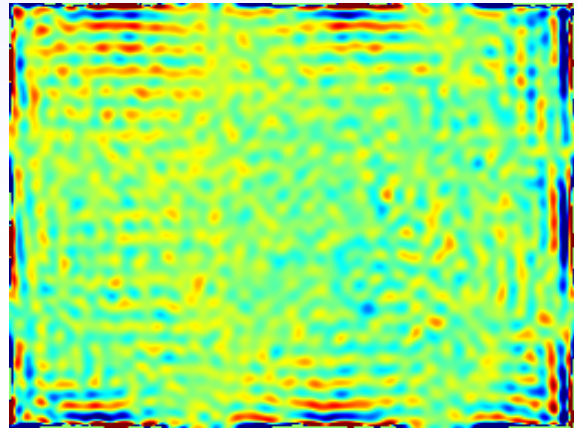
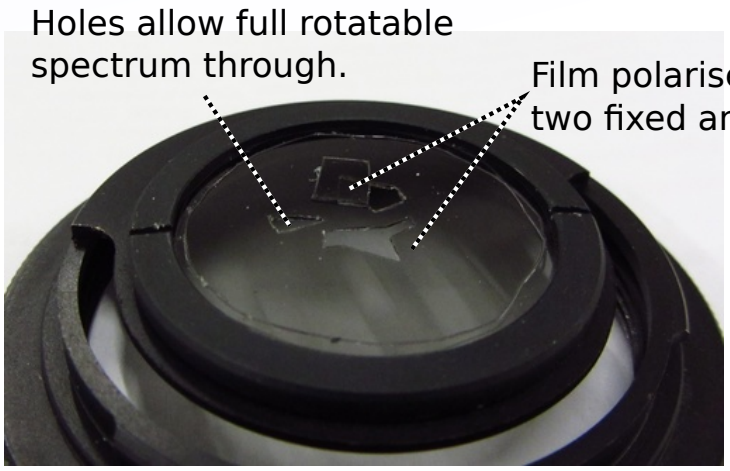
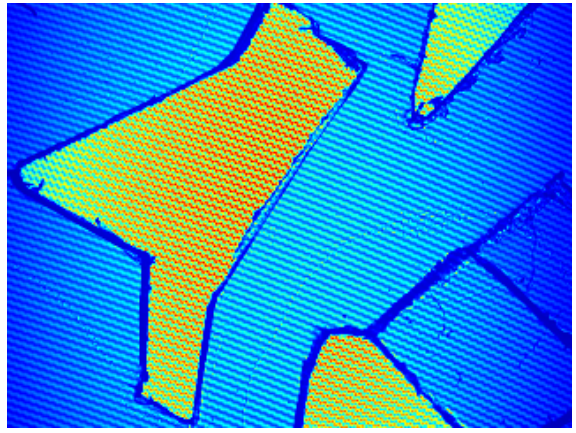
Effect on demodulated angle is smaller then existing noise level.

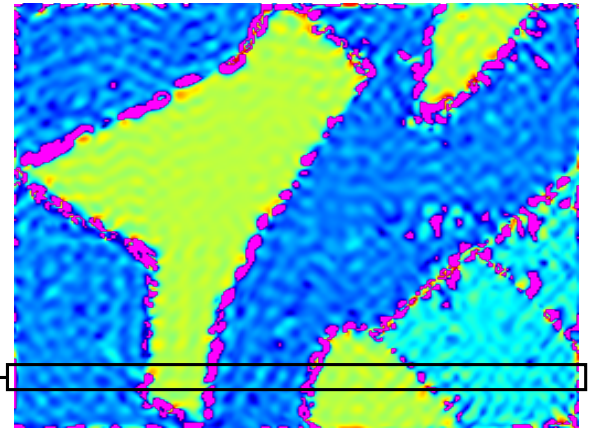


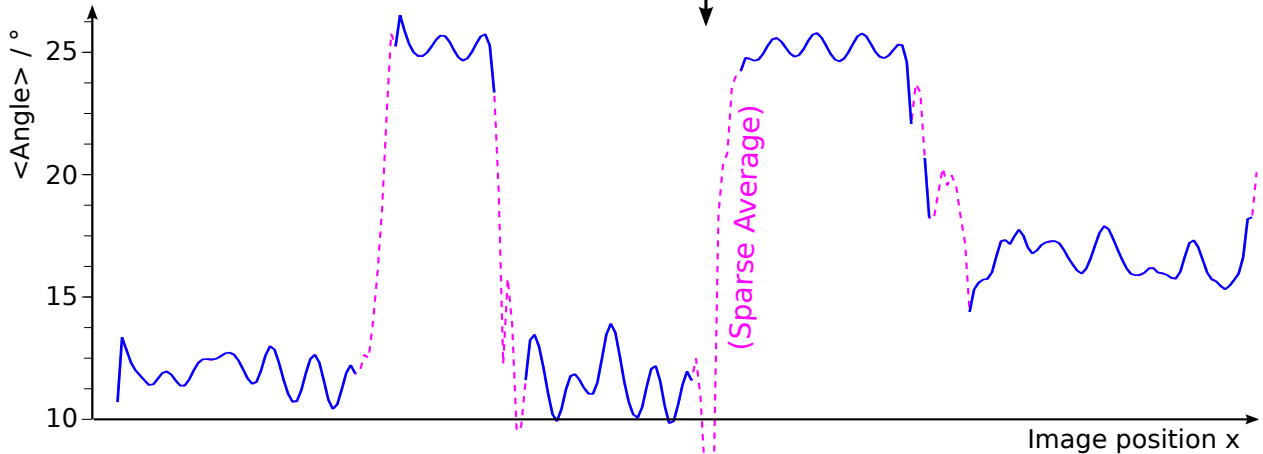


To test spatial variation of polarisation, insert a mask made of polarising film at the virtual image plane:









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.

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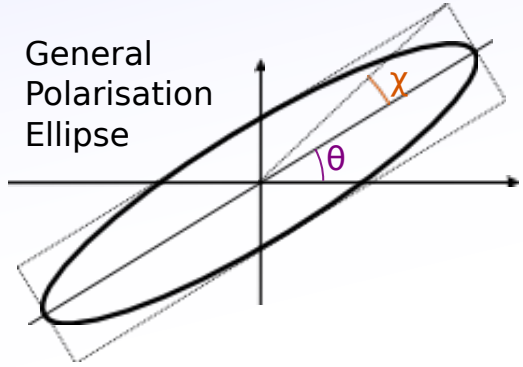

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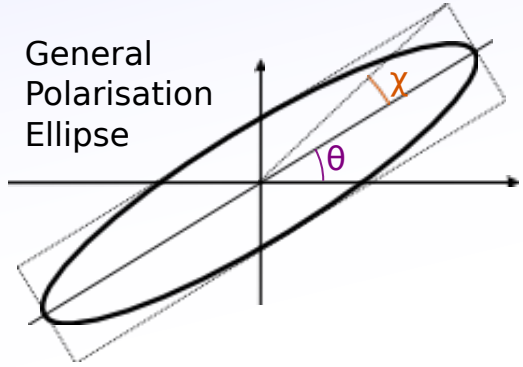

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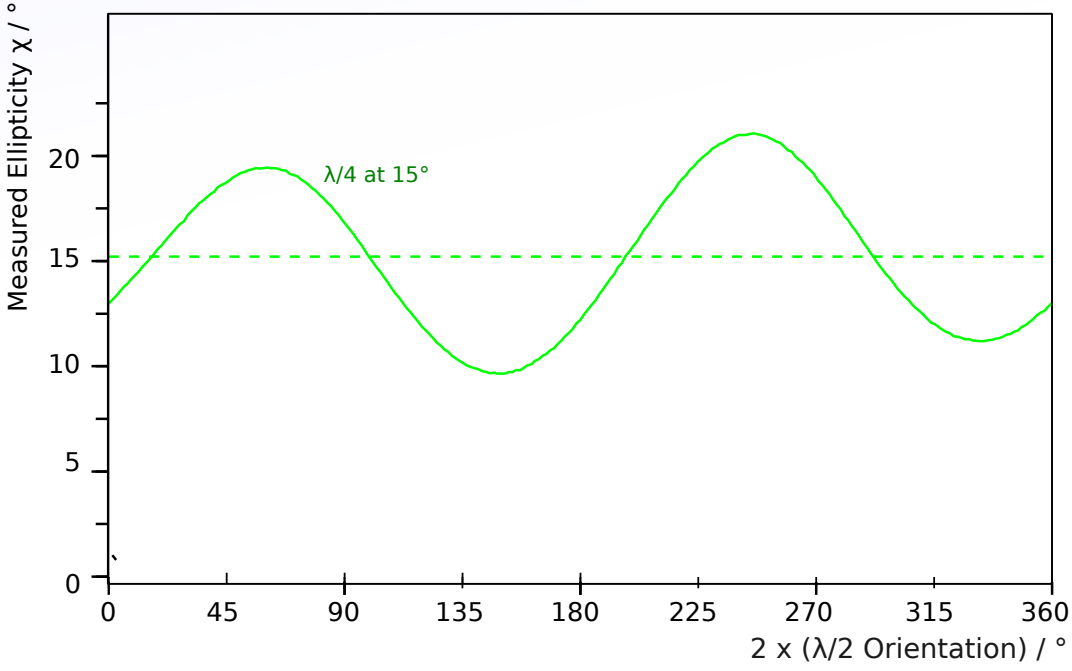

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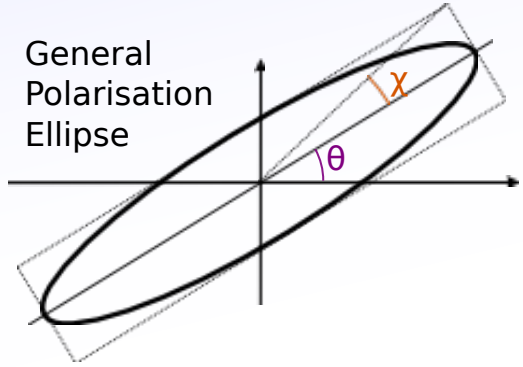

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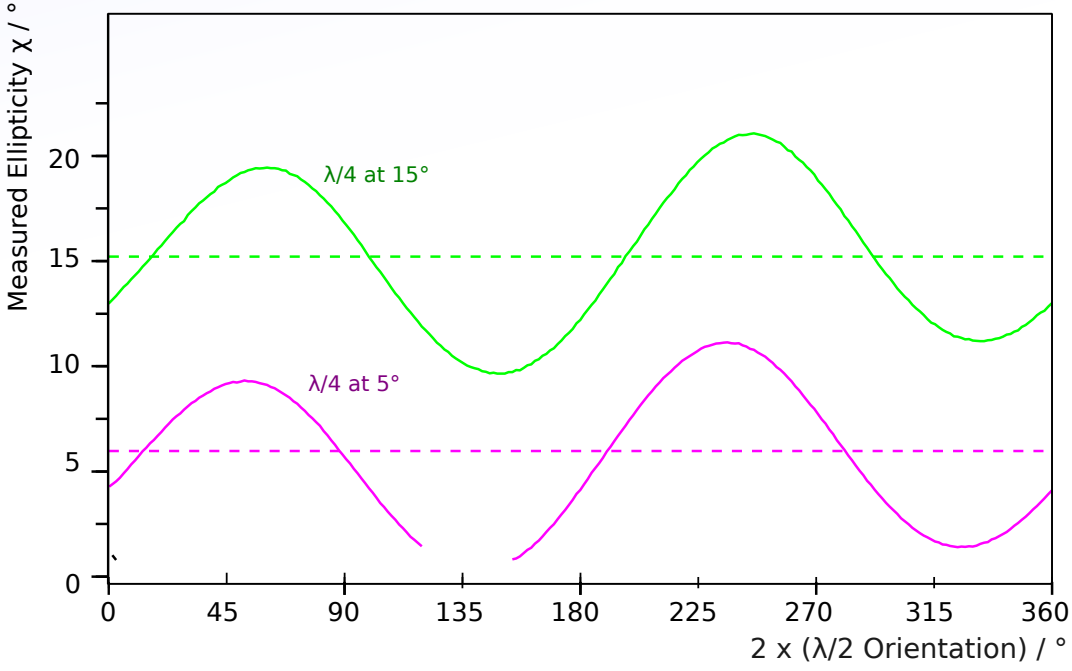

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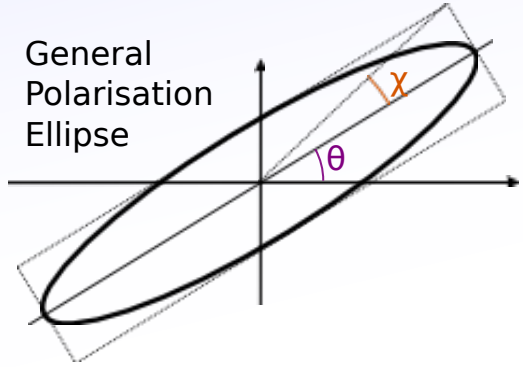

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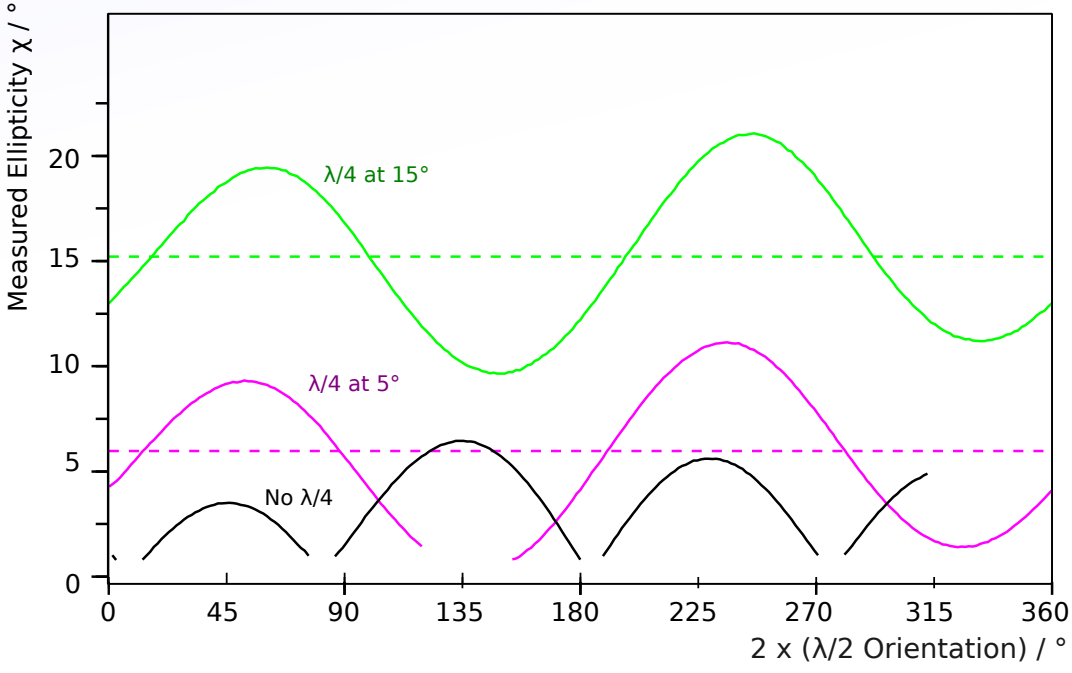

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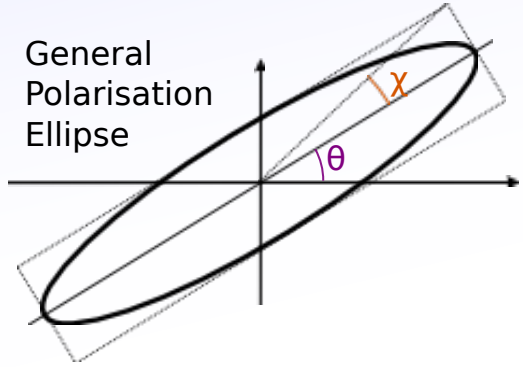

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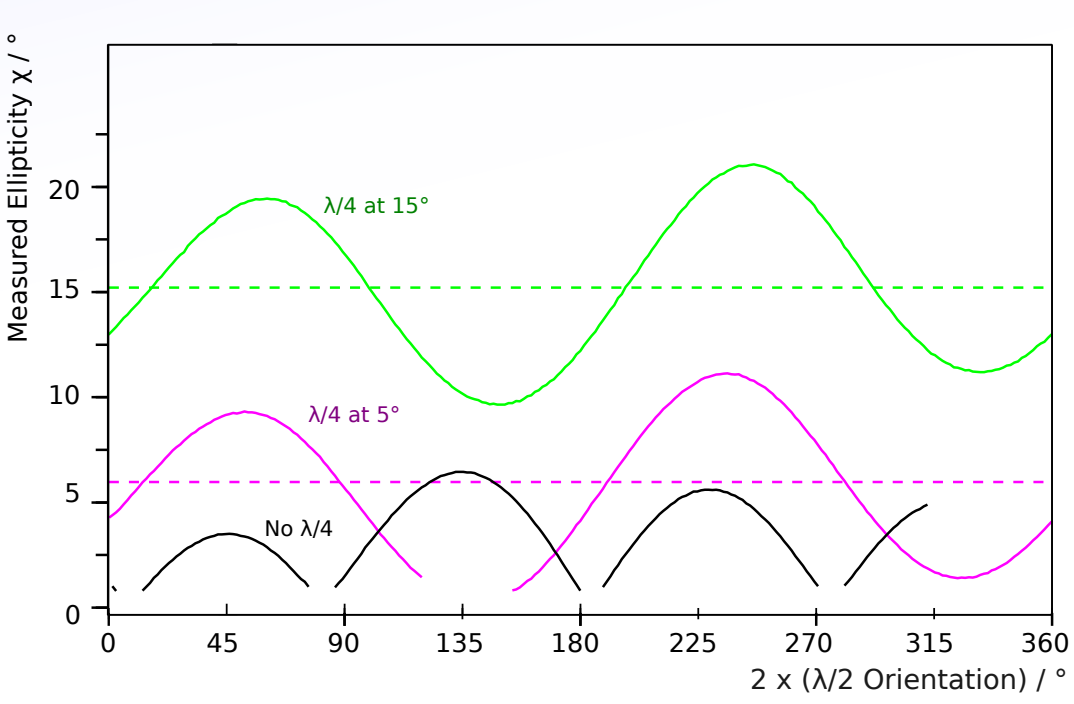

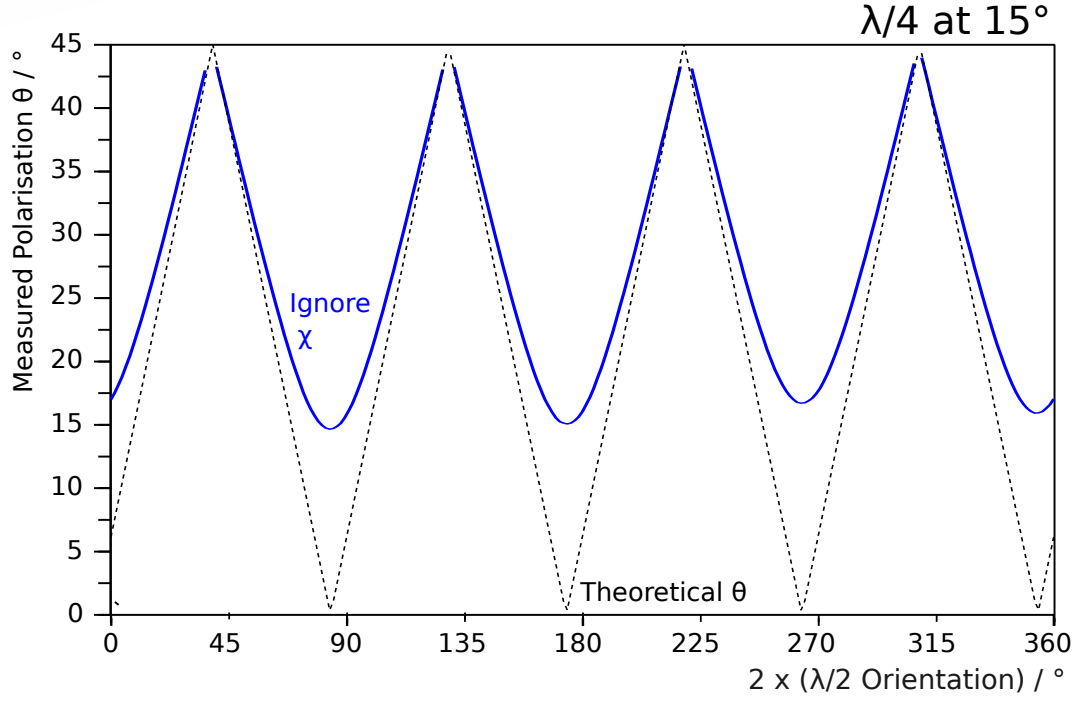

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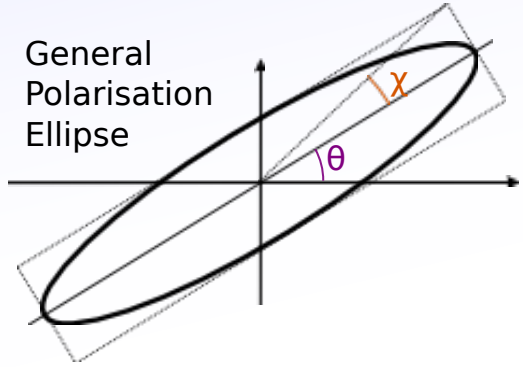

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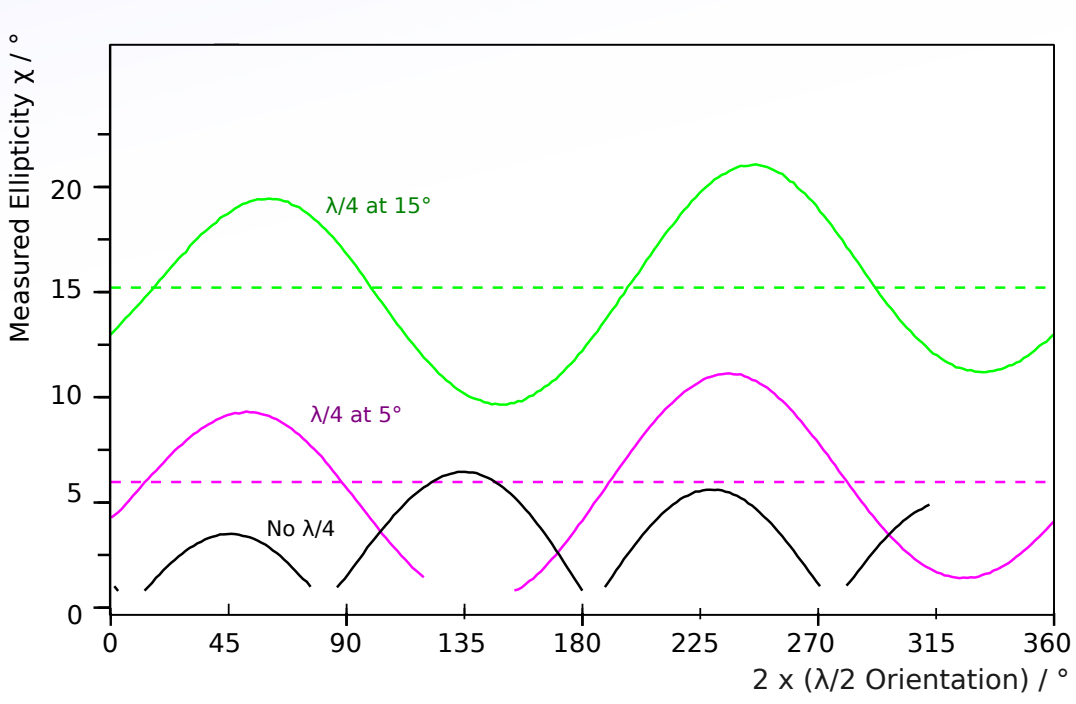

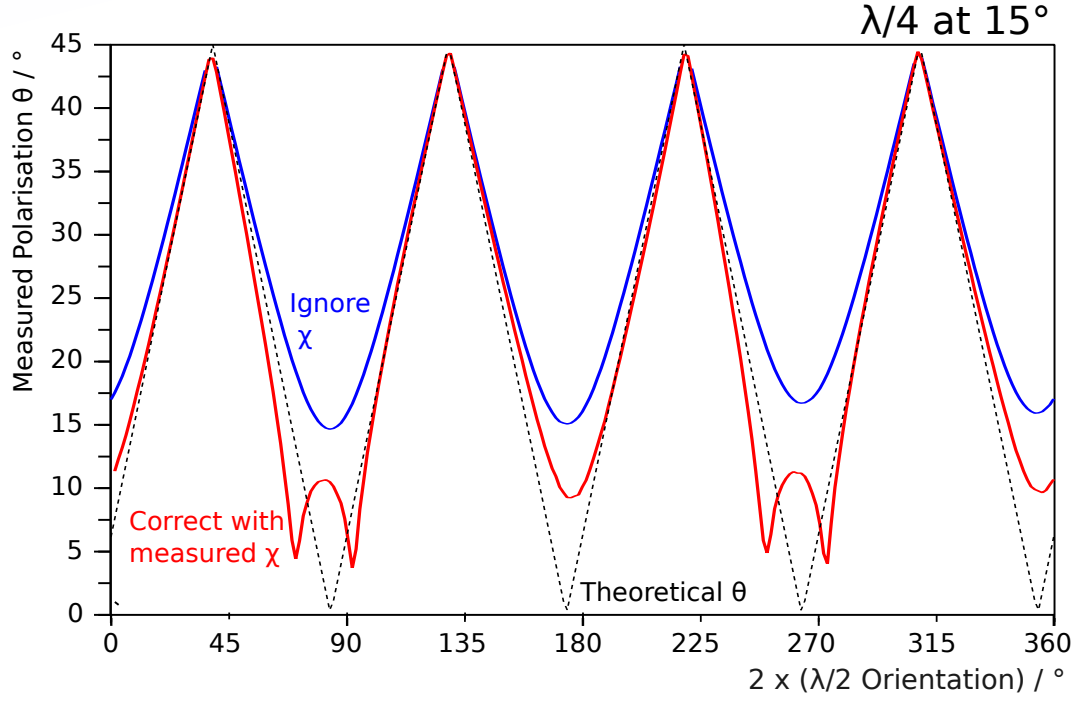

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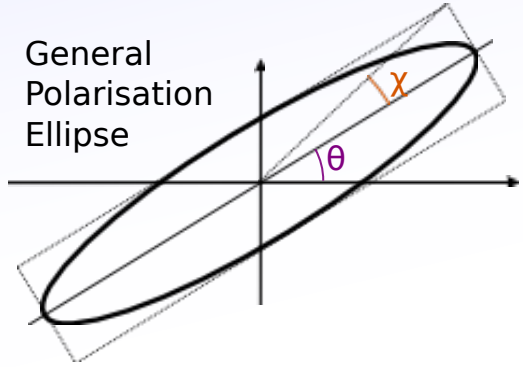

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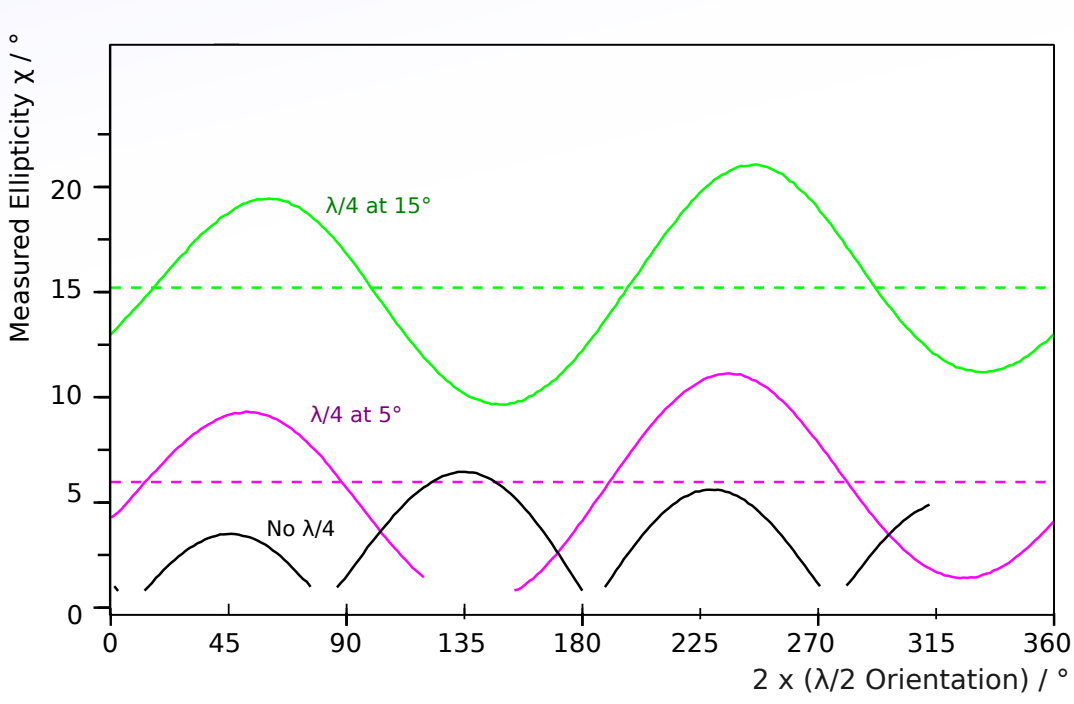

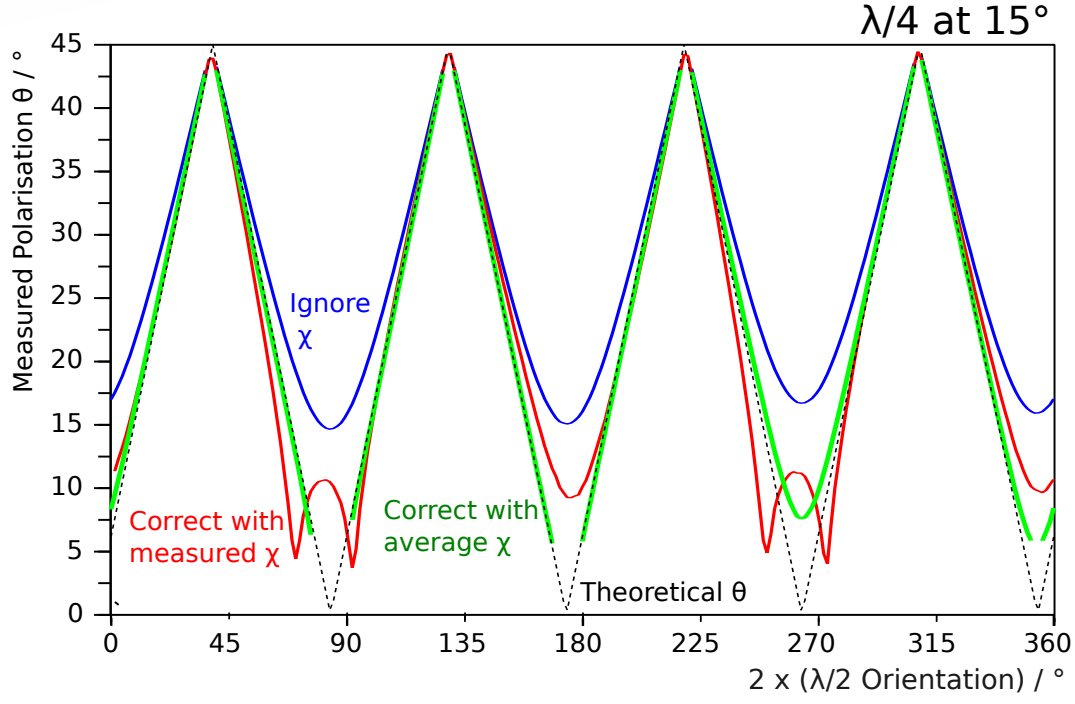

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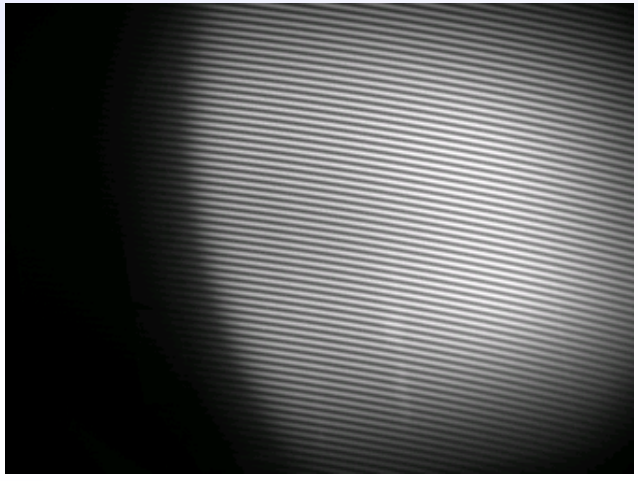

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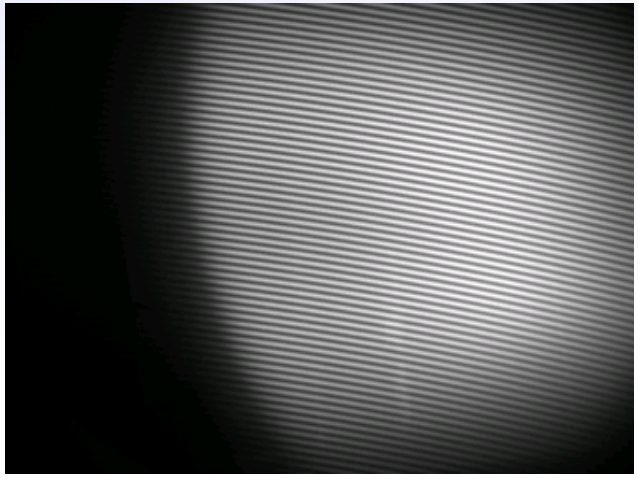

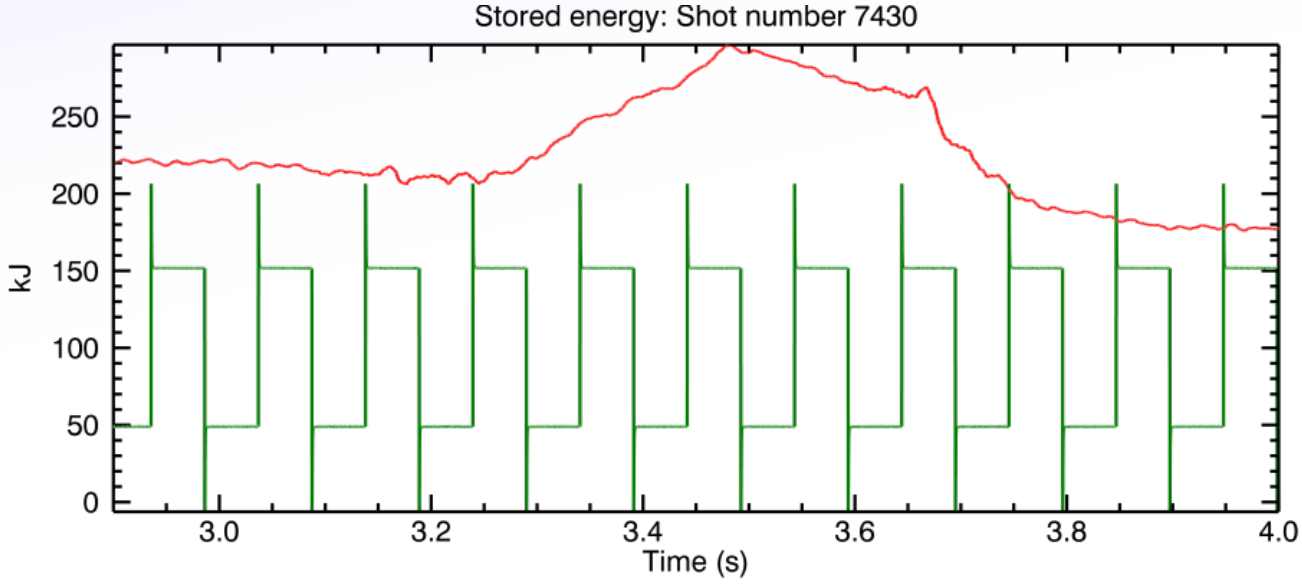

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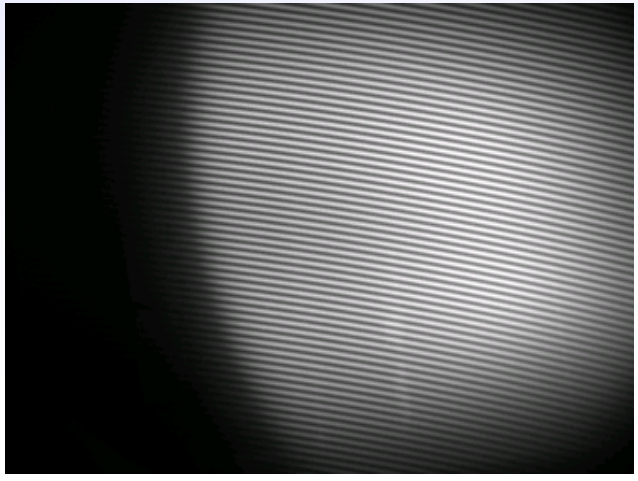

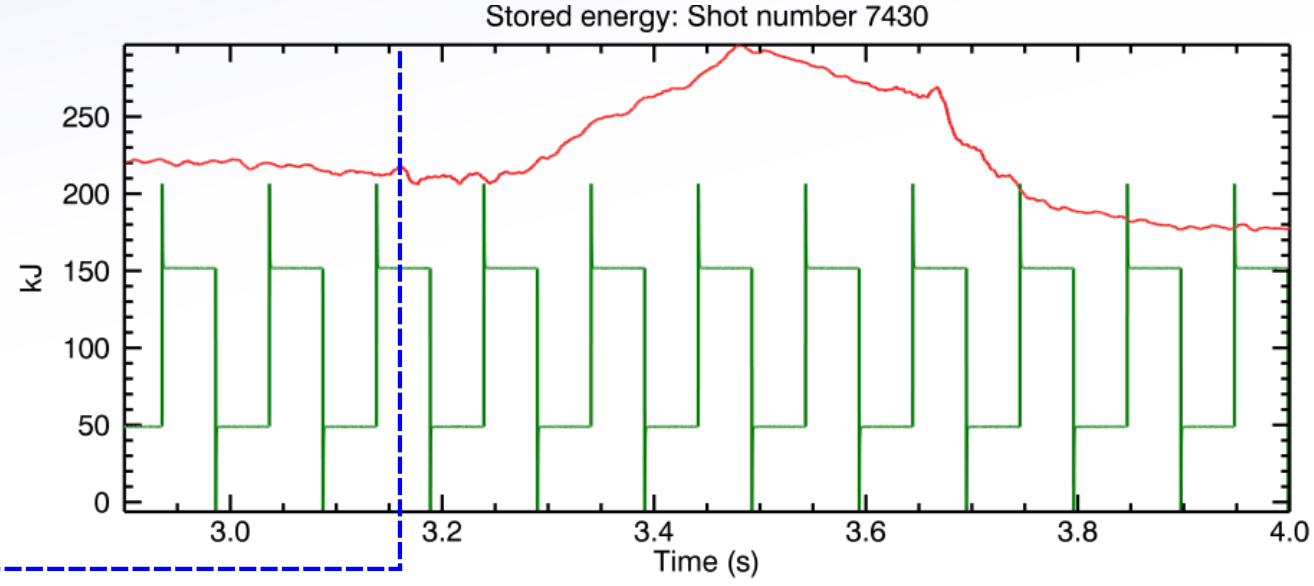

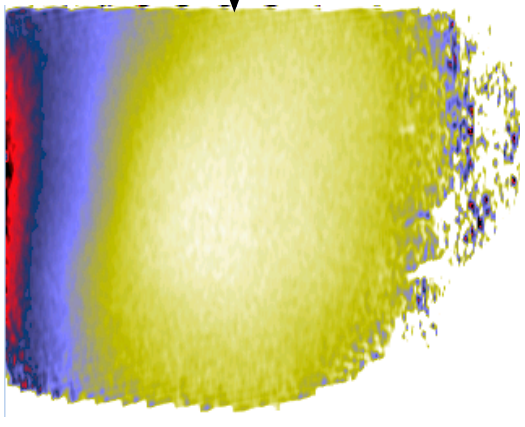

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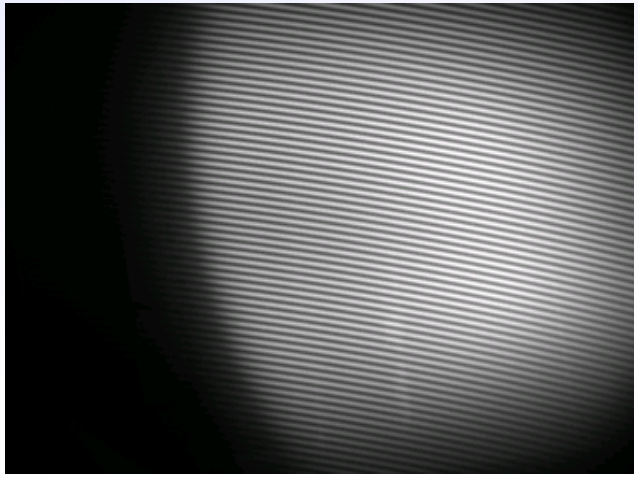

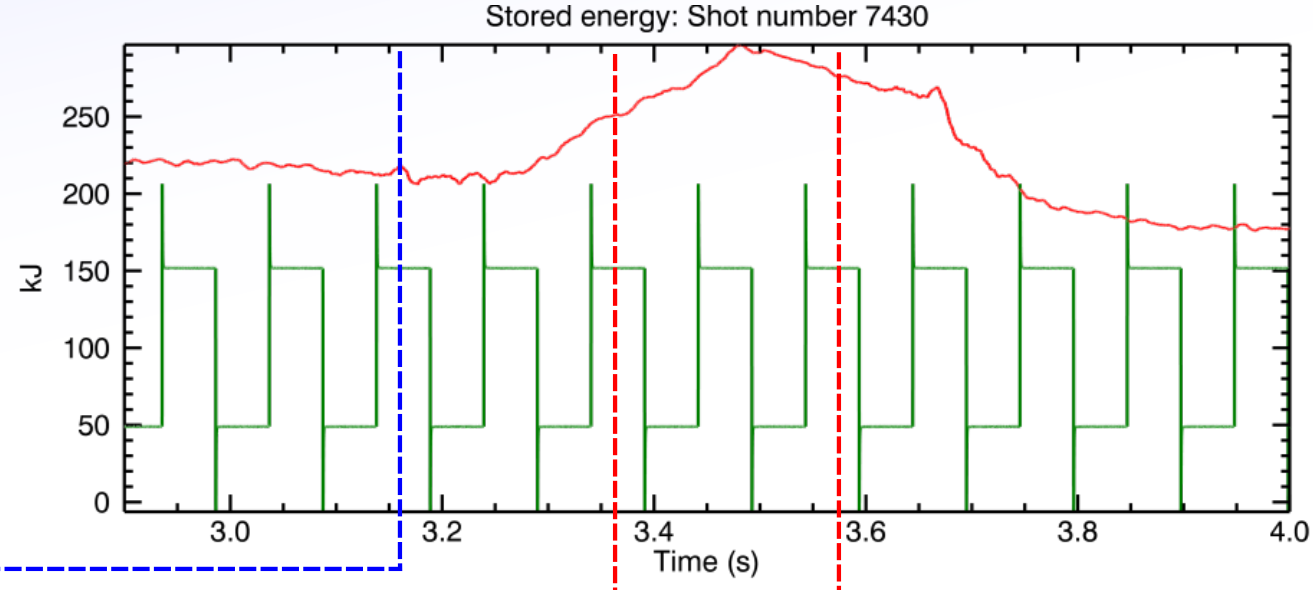

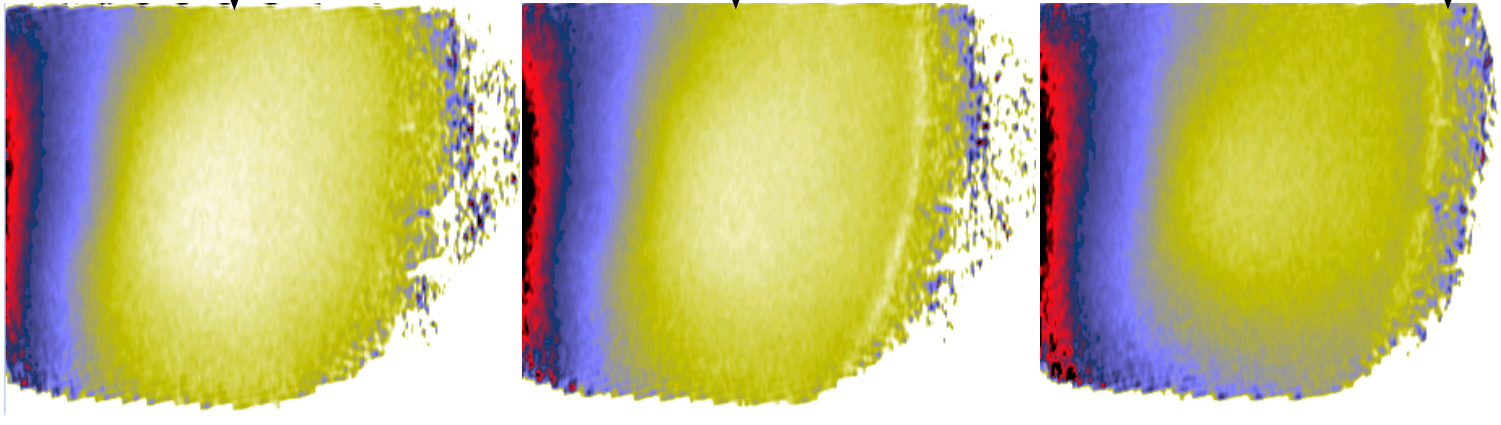

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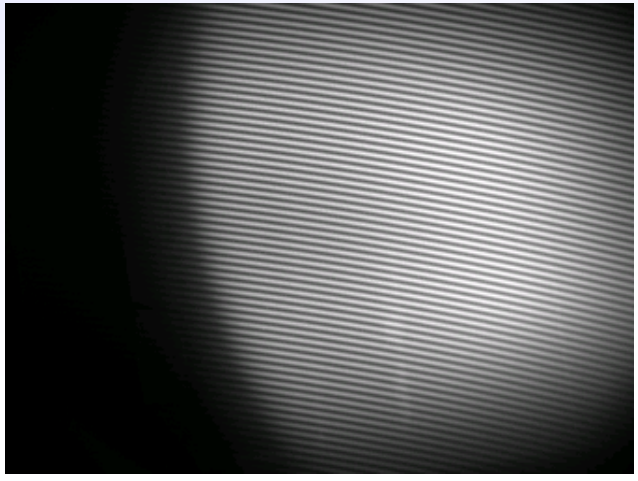
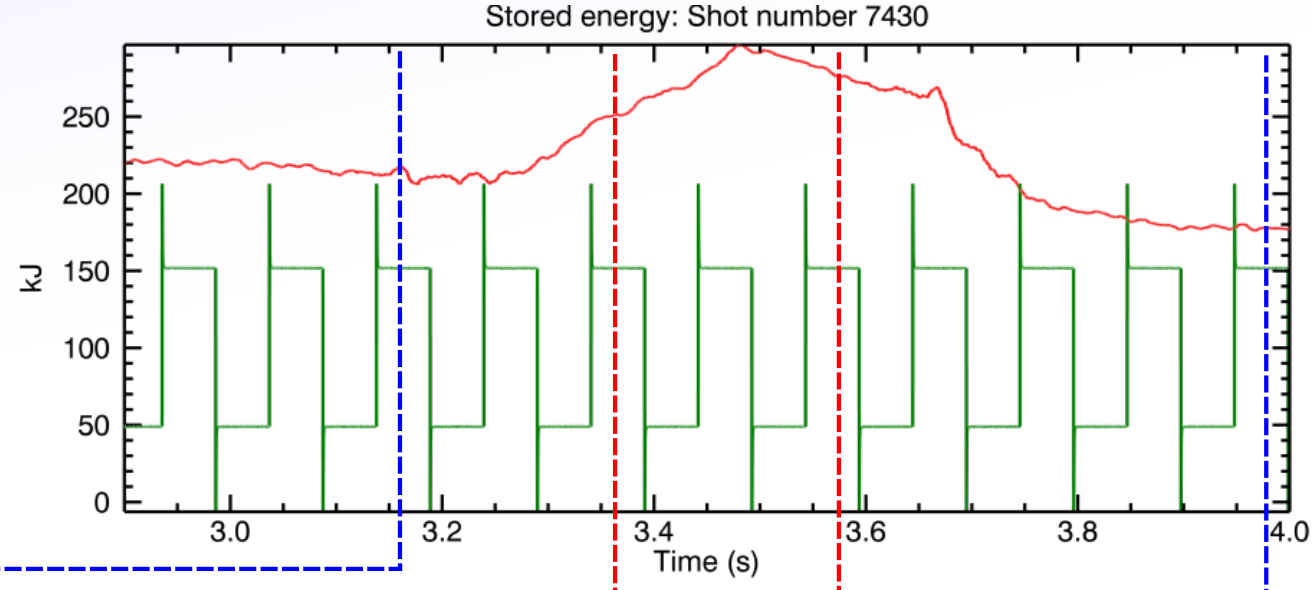
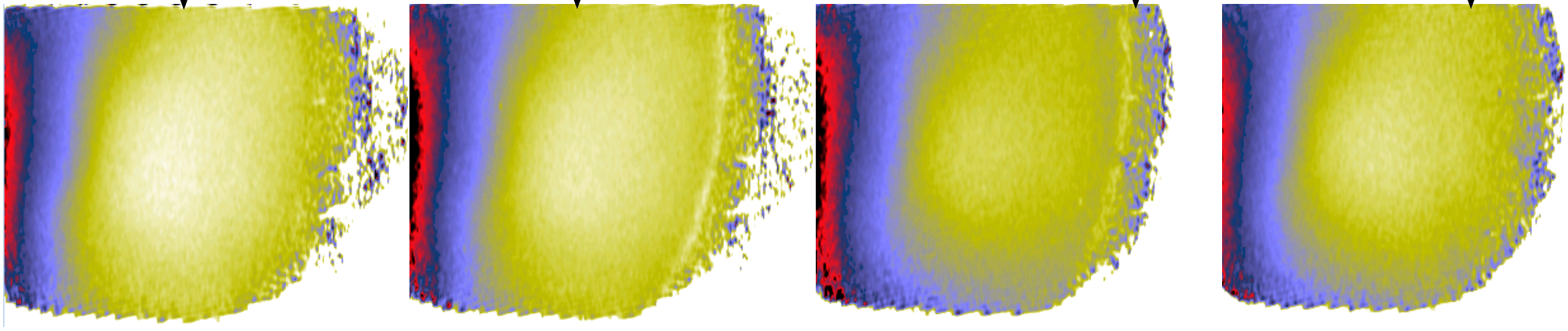




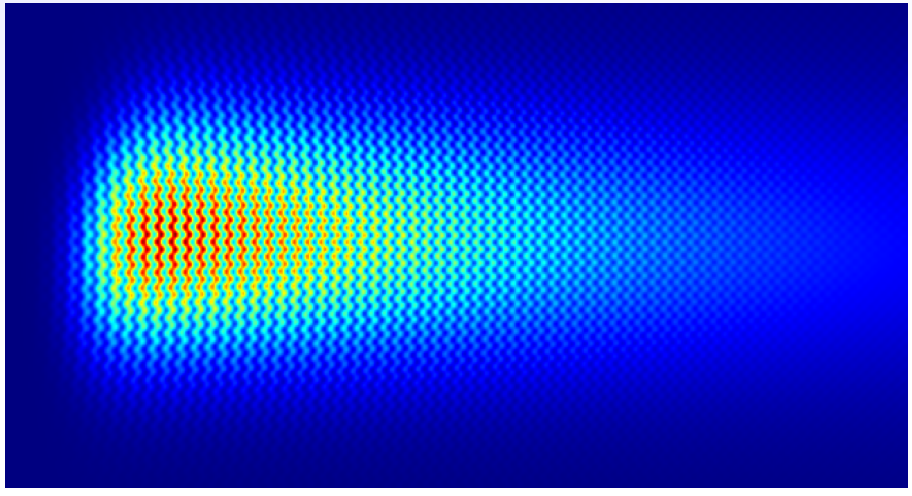


Angles are not yet calibrated, but H-mode pedestal is already clearly visible, and is probably a direct effect of the the pedestal current.

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°.



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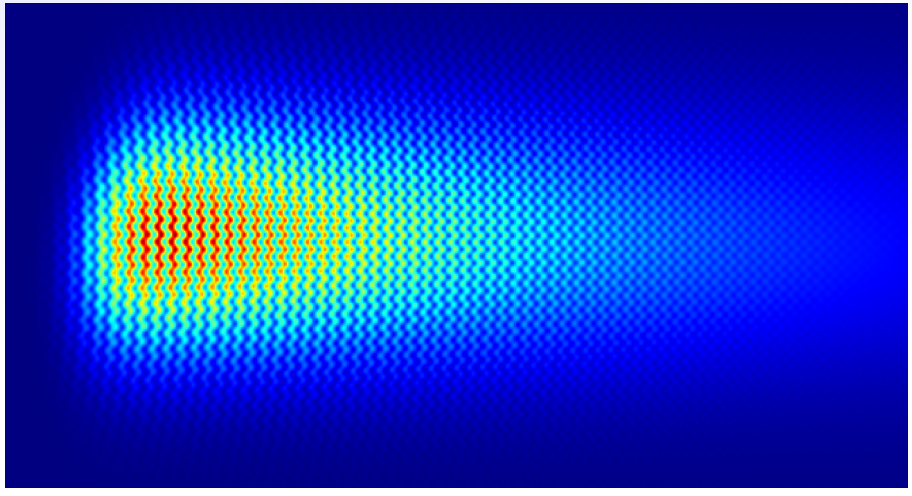

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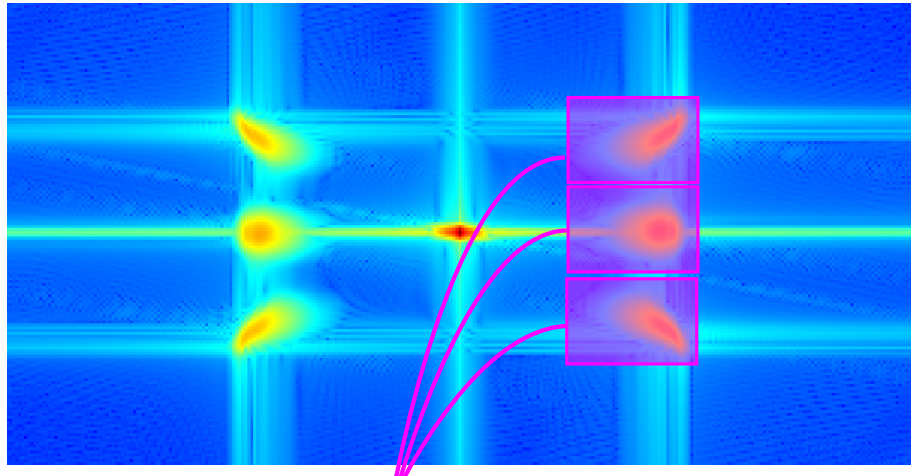

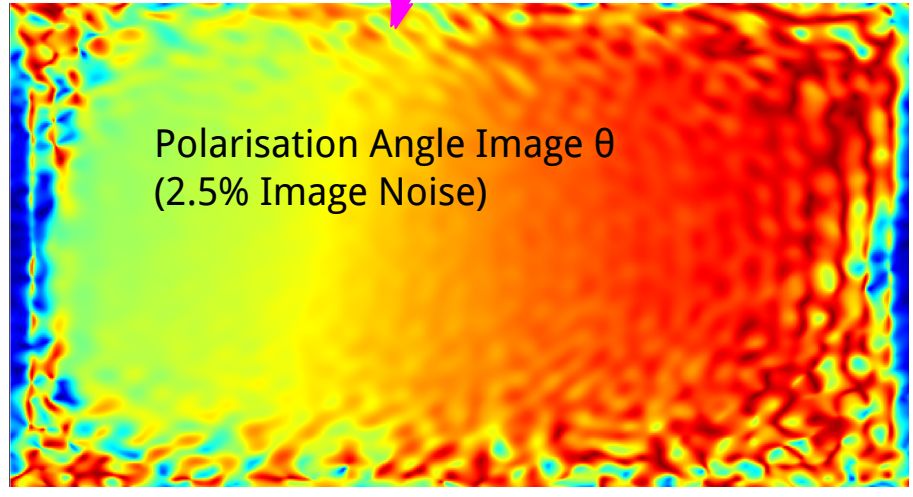

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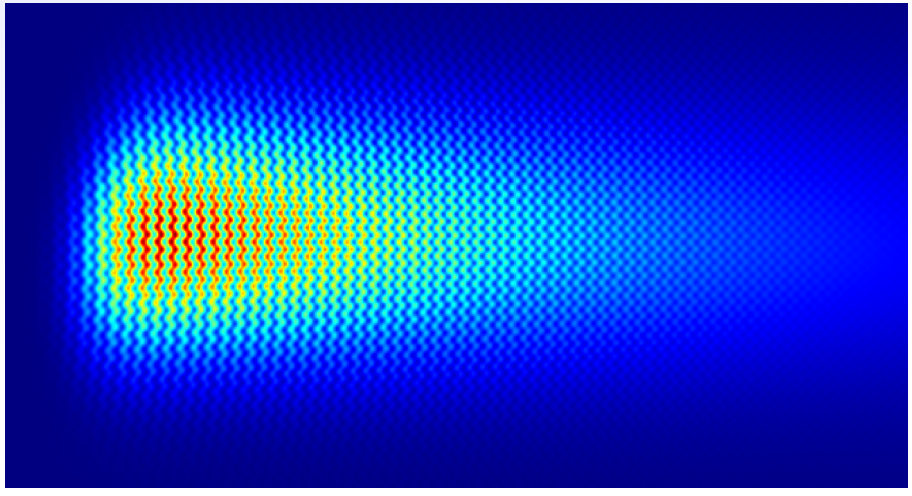

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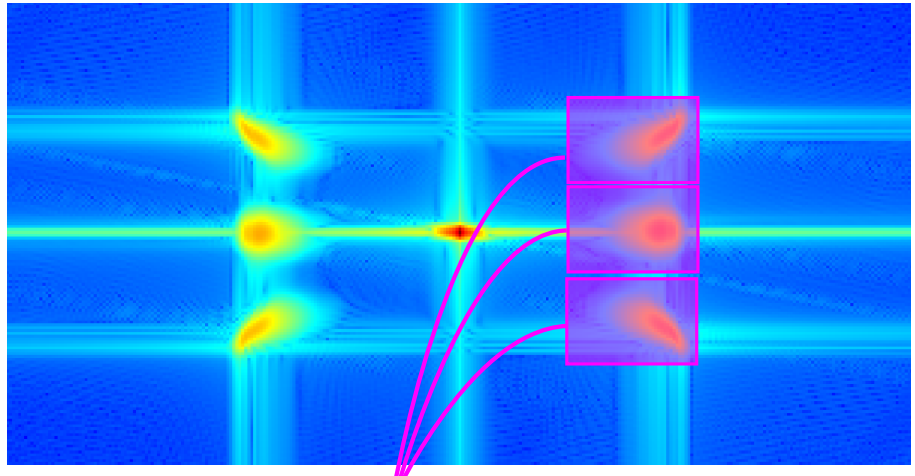

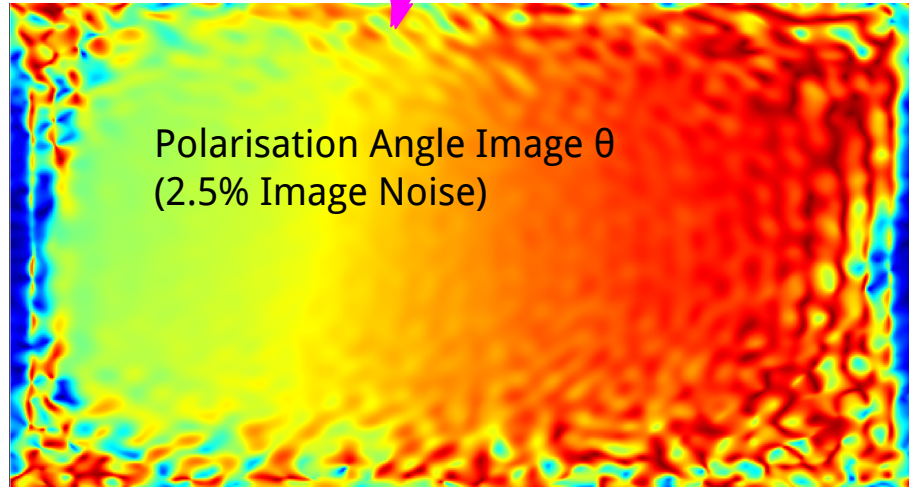

This includes an expected plasma effect not simulated in the hardware tests - the line integration of the spectrum over the beam width.

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).

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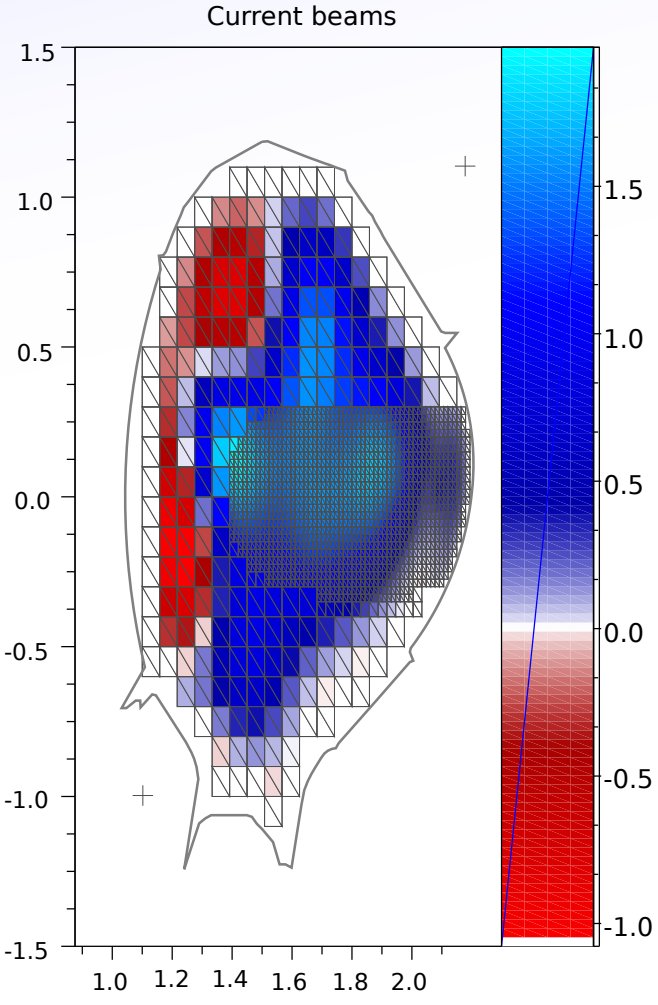

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+ AUG Magnetic pickup data
+ Irregular grid support (My PhD)
+ Gaussian process priors (J.Svensson)
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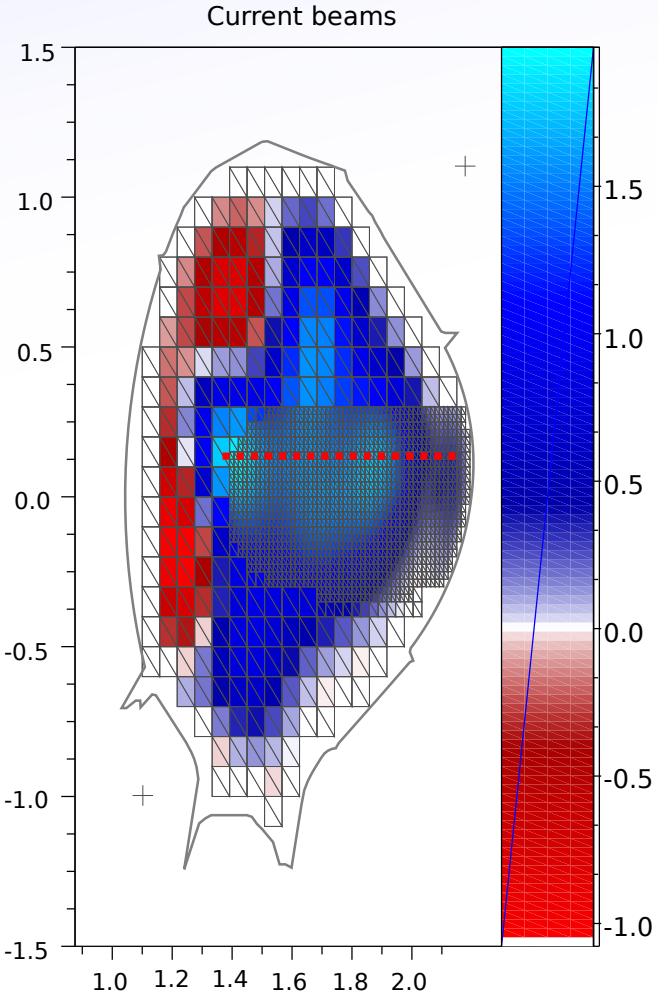

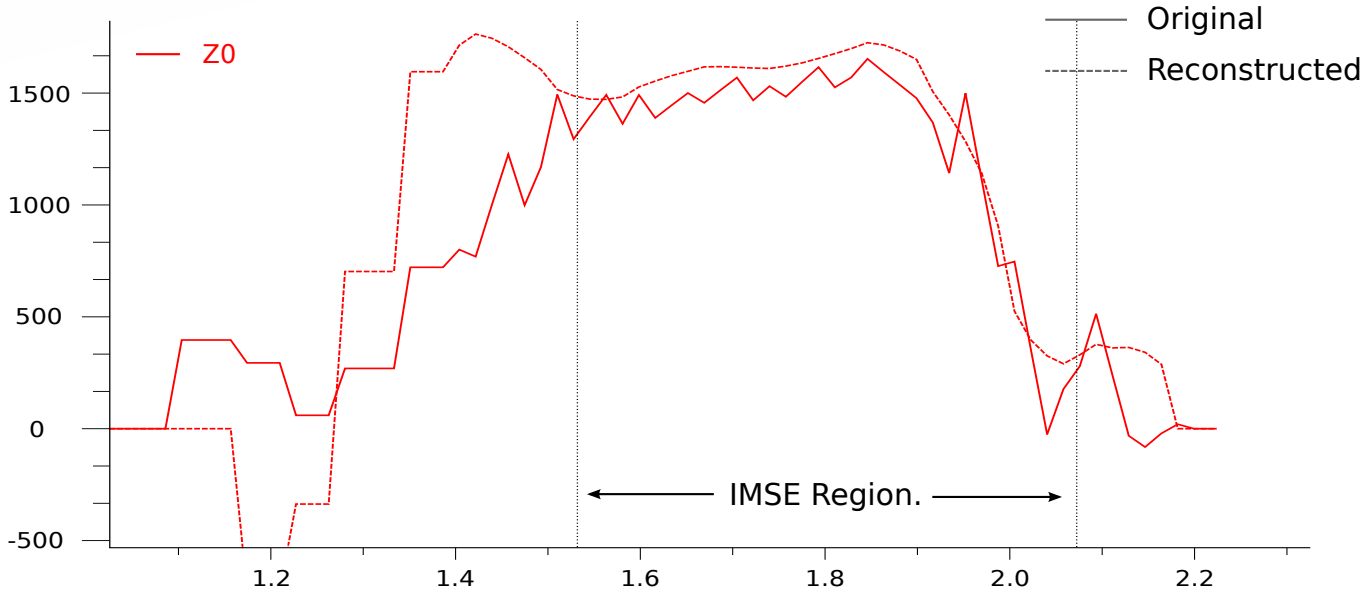

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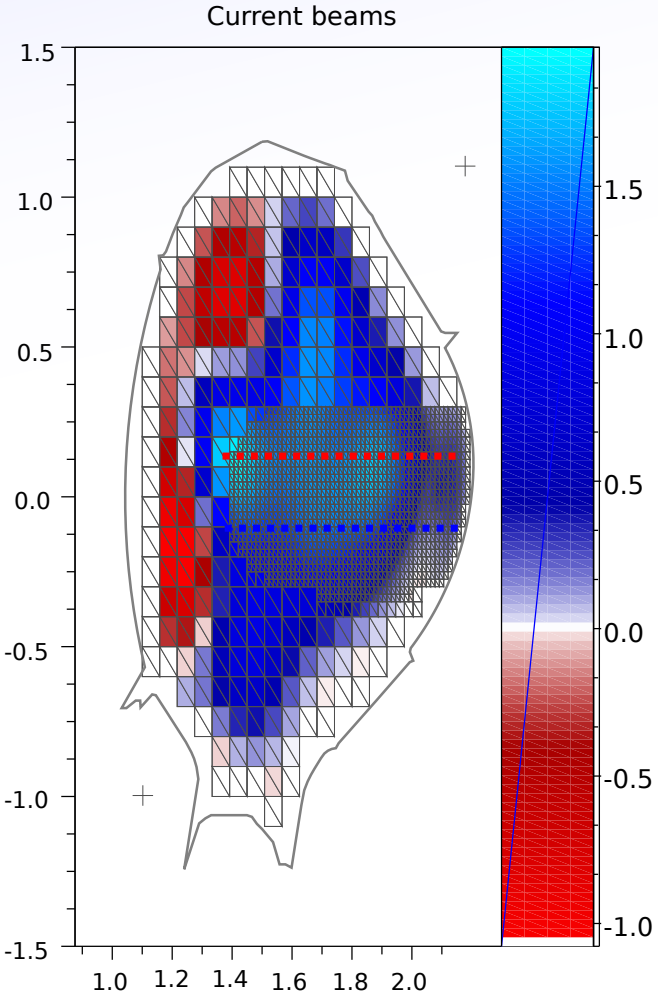
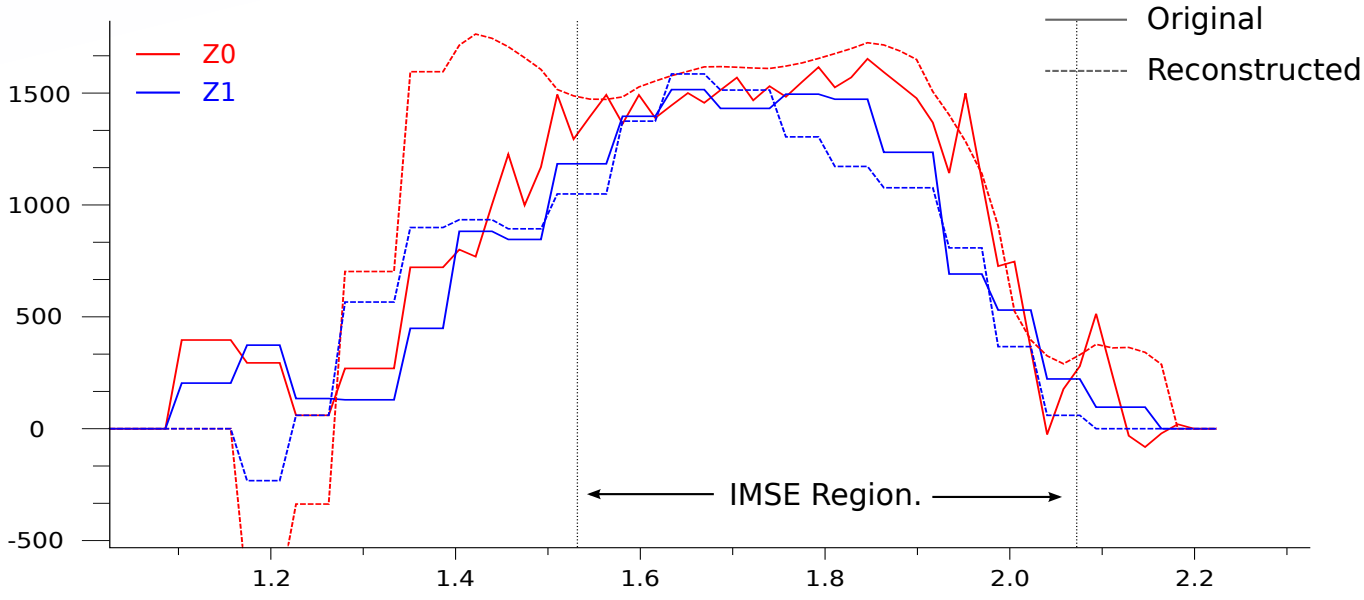
Simulate pickups and a 60x40 grid of IMSE polarisation measurements (θ) with 0.3° error then invert back to Jϕ:





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).

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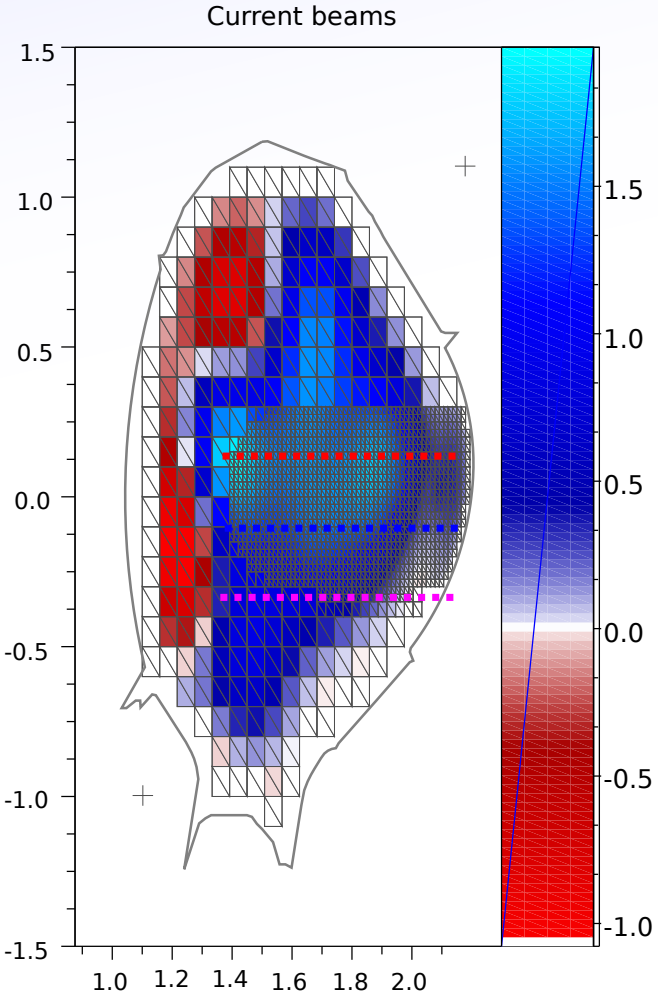

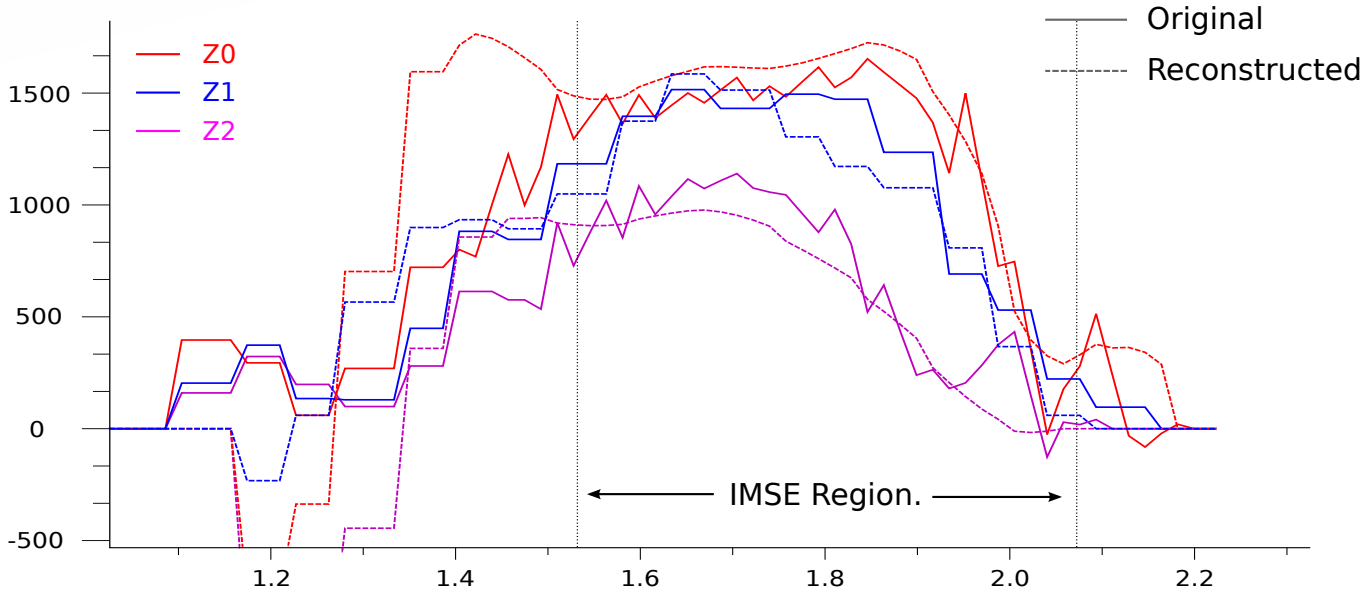

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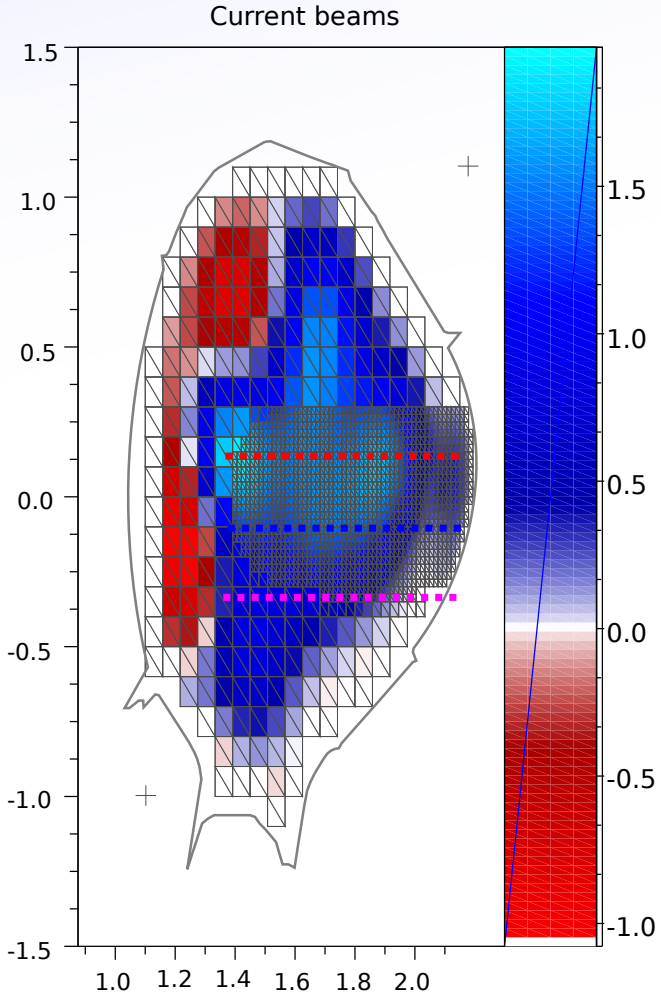

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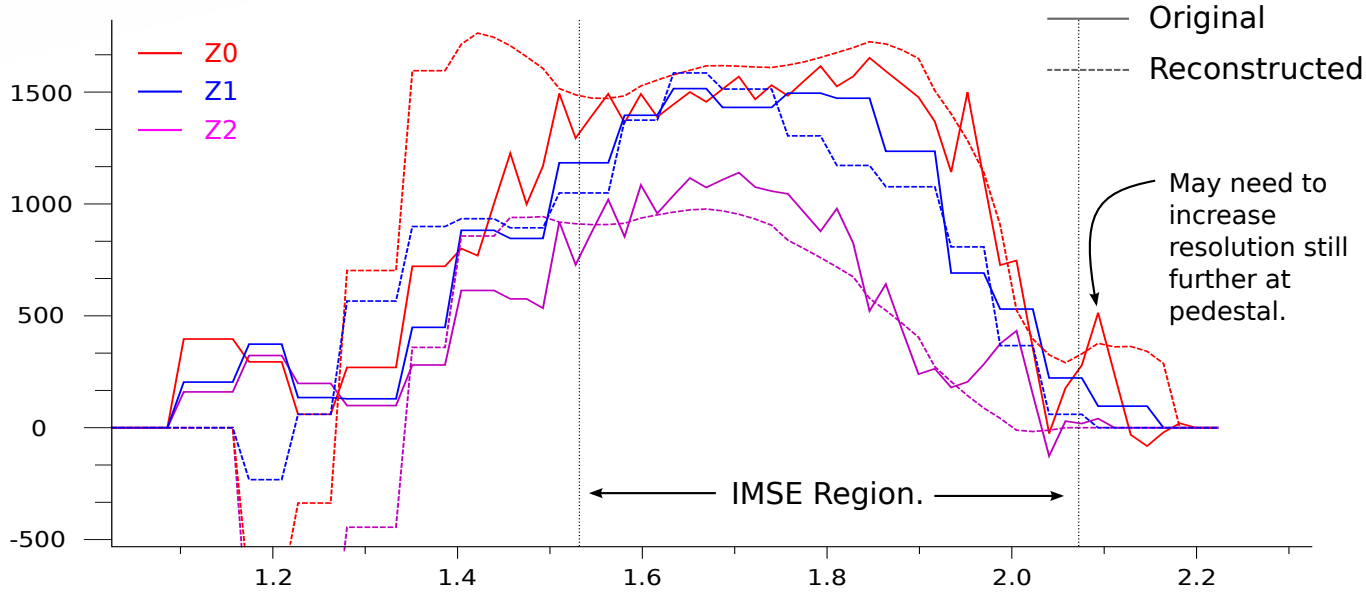

Initial results indicate that it is possible to recover the $j_\phi(R, Z)$ to at least a good resolution for studying the bulk plasma (e.g. testing different equilibrium models etc). This is *much* better than is currently possible. Resolution is processing limited - Higher resolution may be possible,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

Oliver Ford
IPP Greifswald

Status

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- ✓ 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)

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- ✓ 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.