Max-Planck Institut
für Plasmaphysik

Motional Stark Effect Imaging:

Development Progress and Initial Tests

O. P. Ford,[1] J. Howard,[2] R. Wolf [1]

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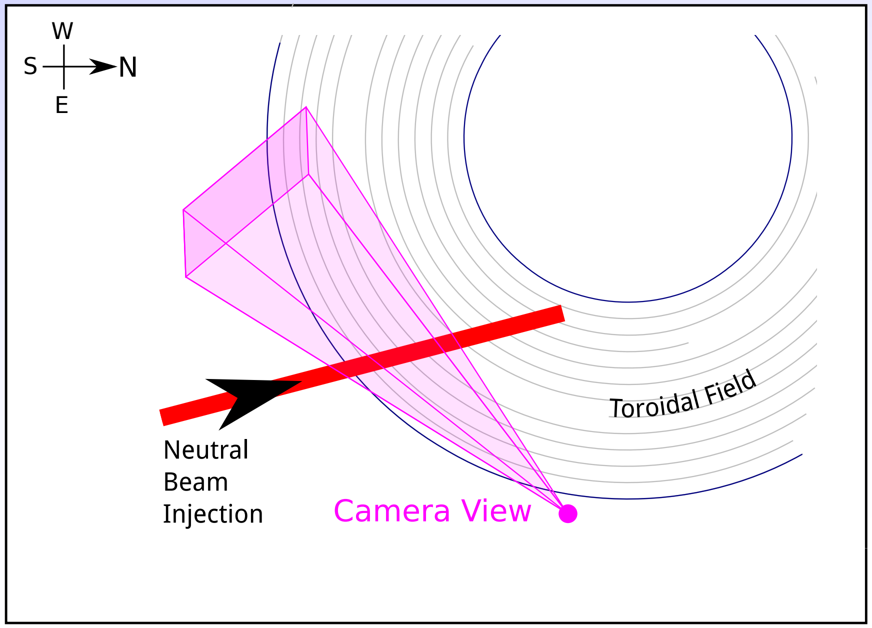
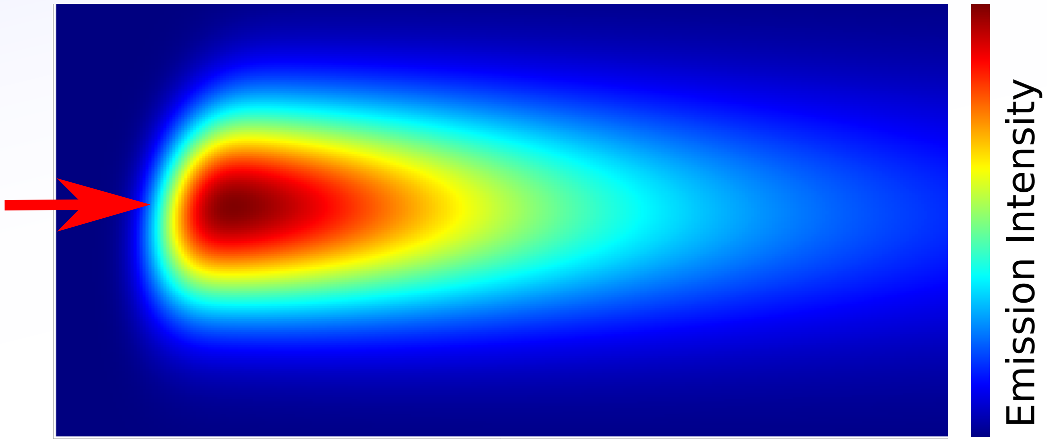
2: Plasma Research Laboratory, Australian National University, Canberra

- Basic Principal
- Concept and Accuracy Tests
- Optics Design

Introduction - Motional Stark Effect



Neutral beam atoms injected into plasma.
Excited by plasma, then emit Hα/Dα radiation.



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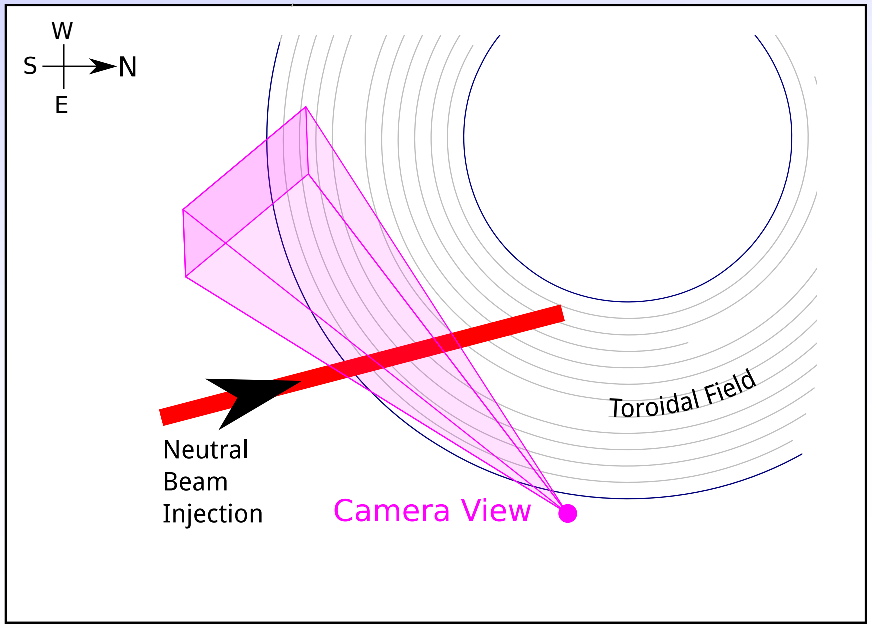

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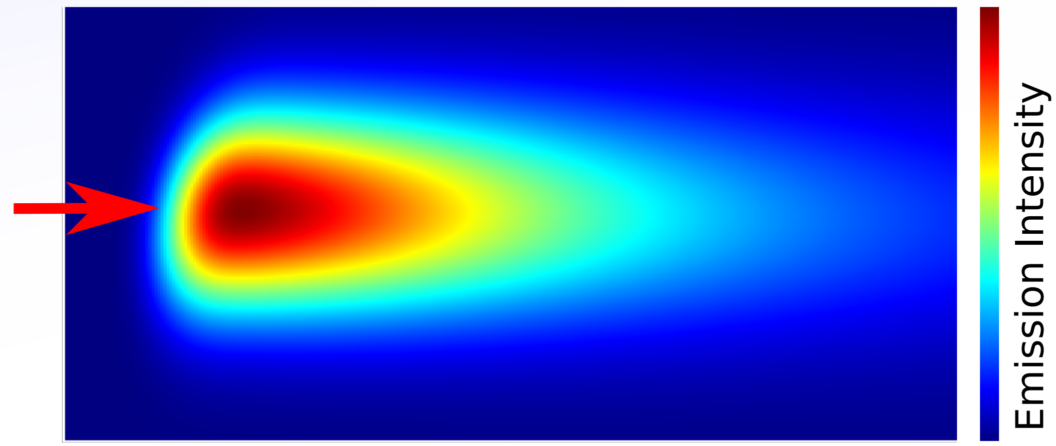
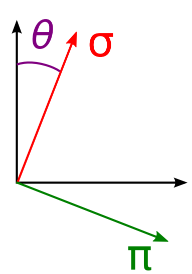
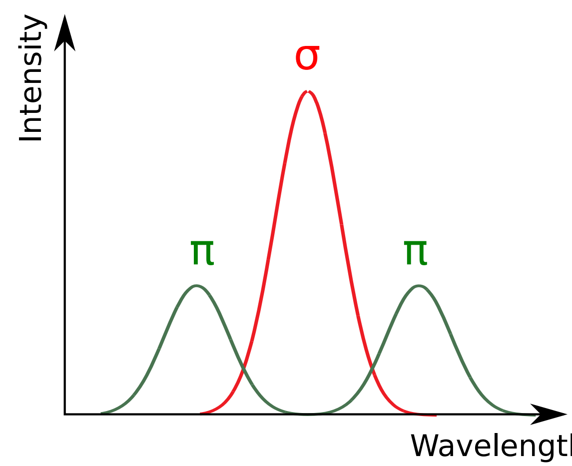


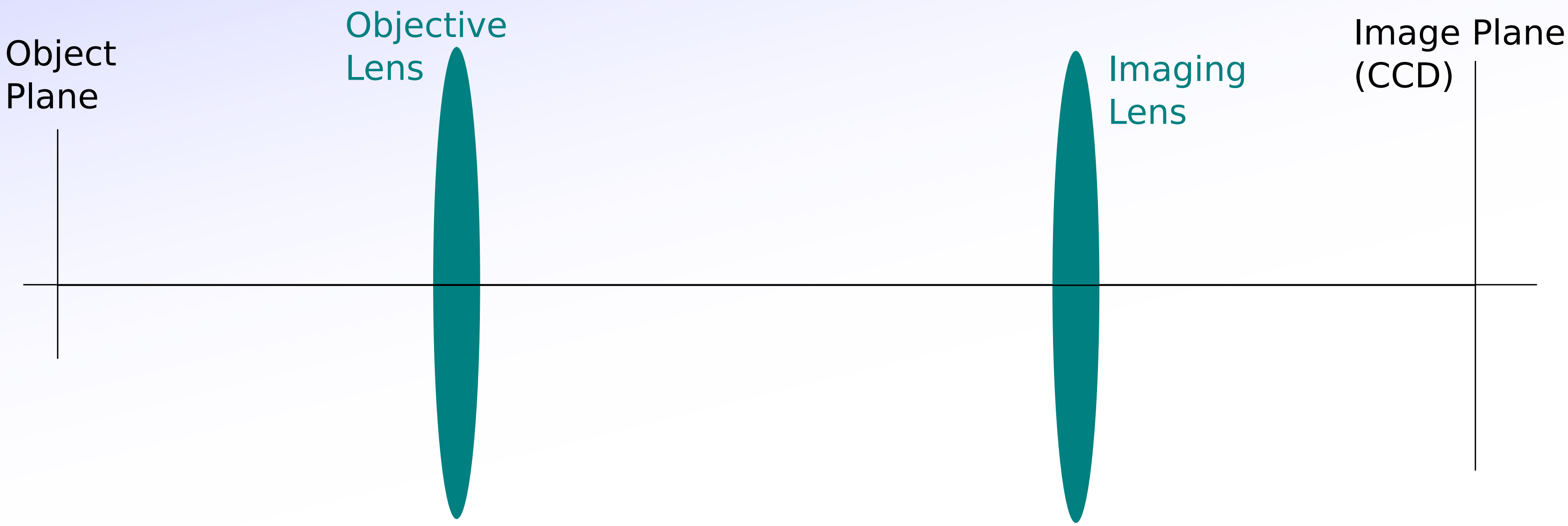
Polarisation of σ related to magnetic field direction, but π is always perpendicular with almost the same intensity so measuring the polarisation gives an unpolarised result if not spectrally separated.

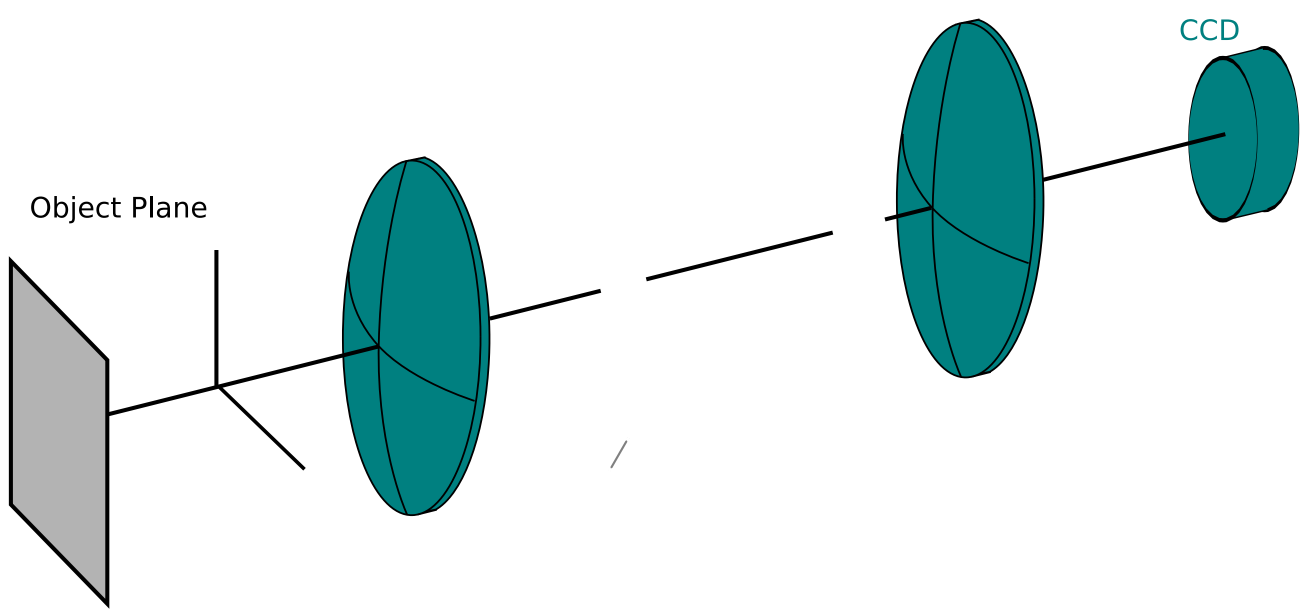




Inference Imaging with Displacer Plates

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





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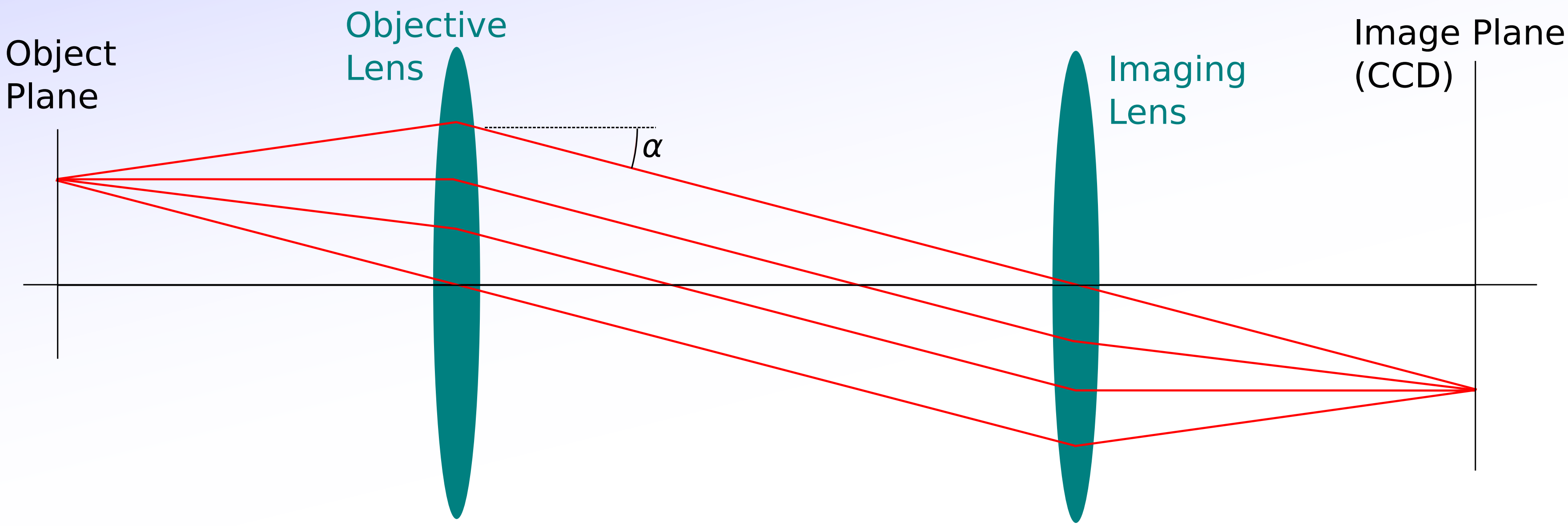

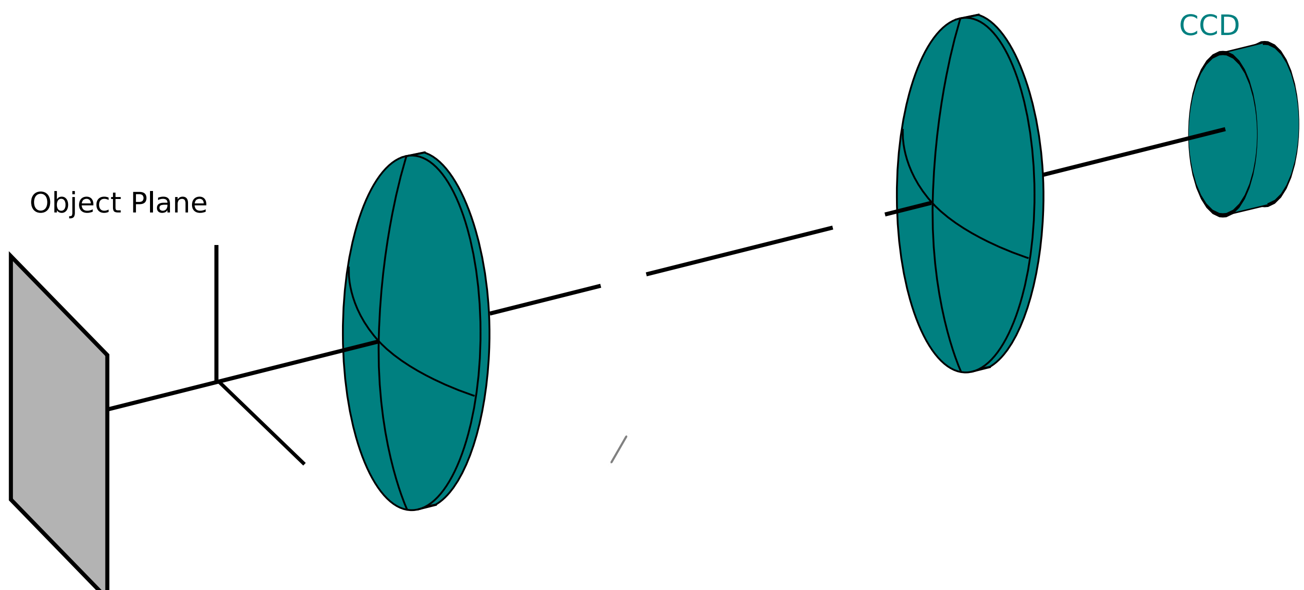

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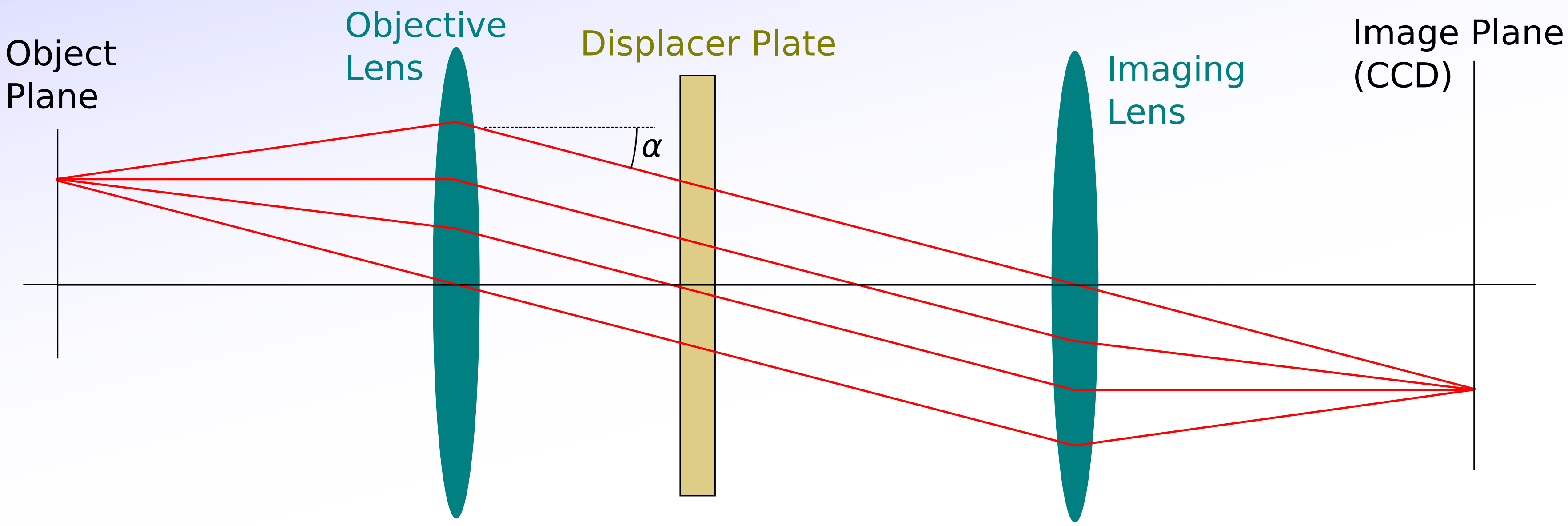

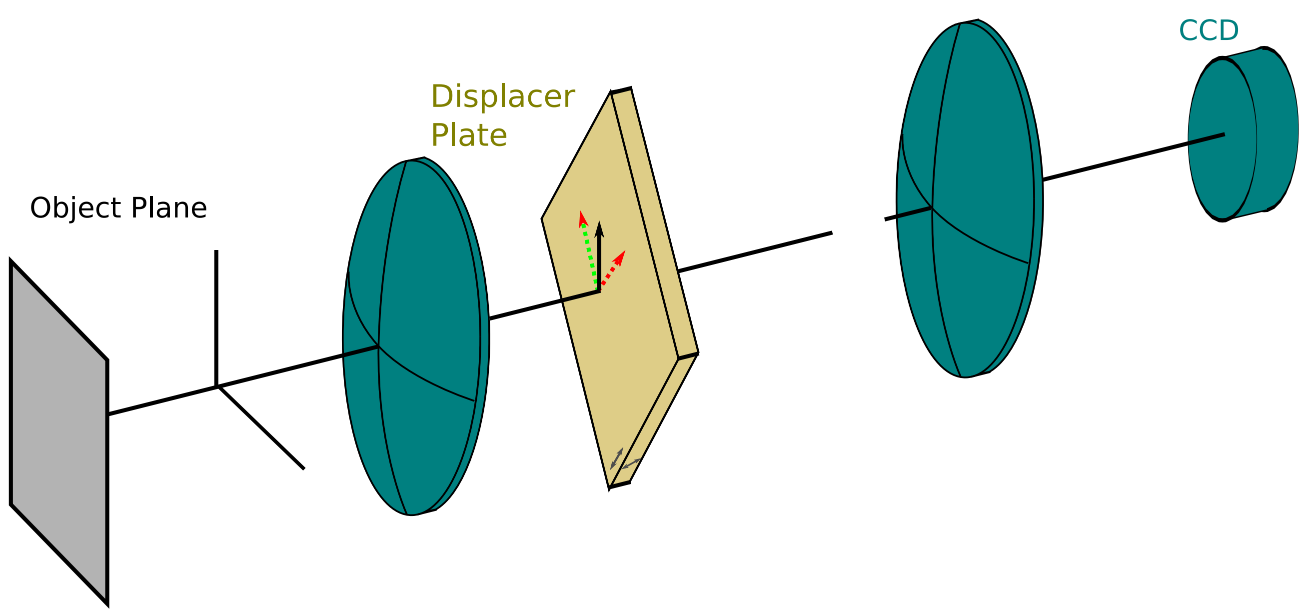

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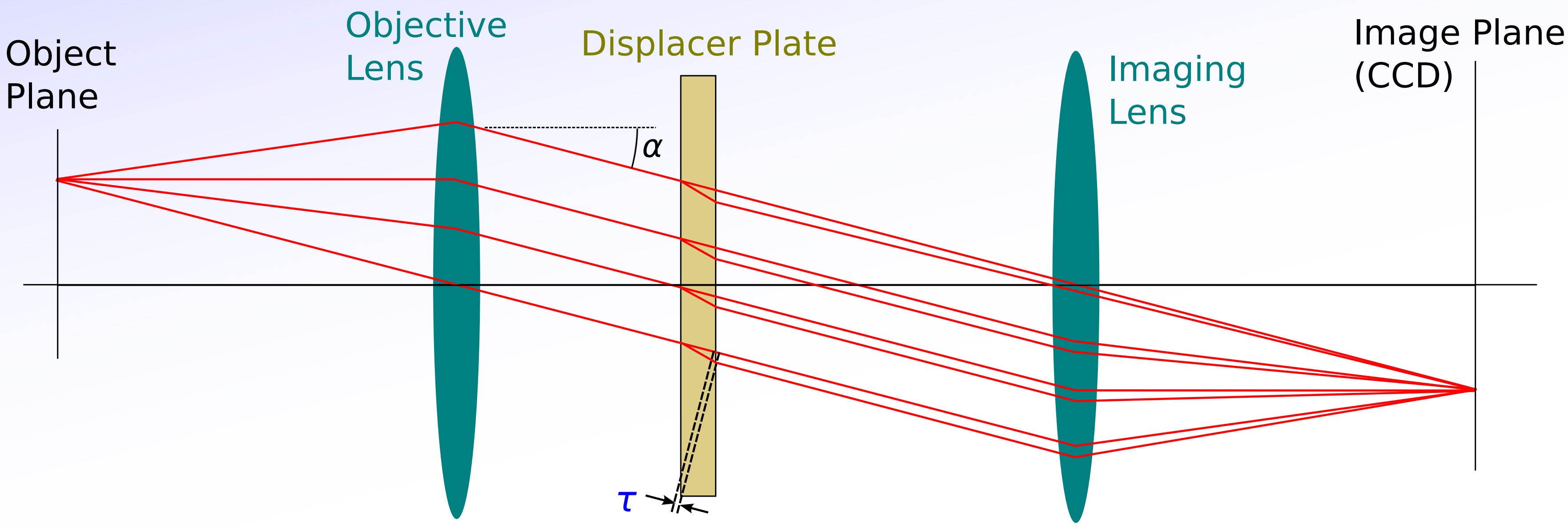

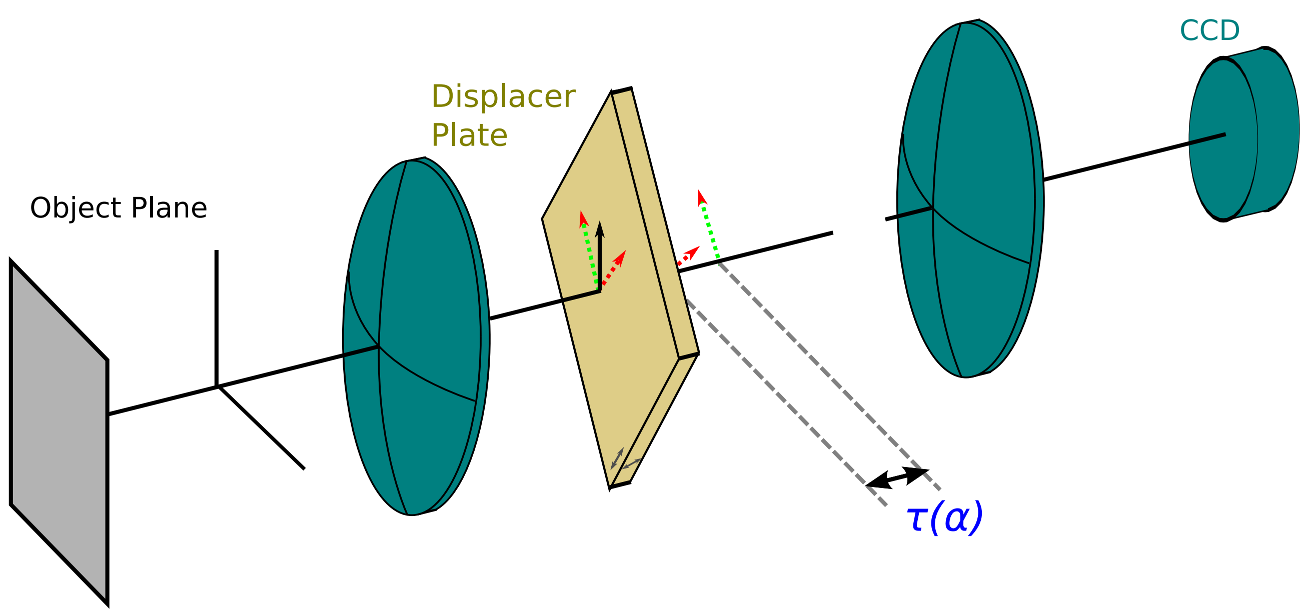

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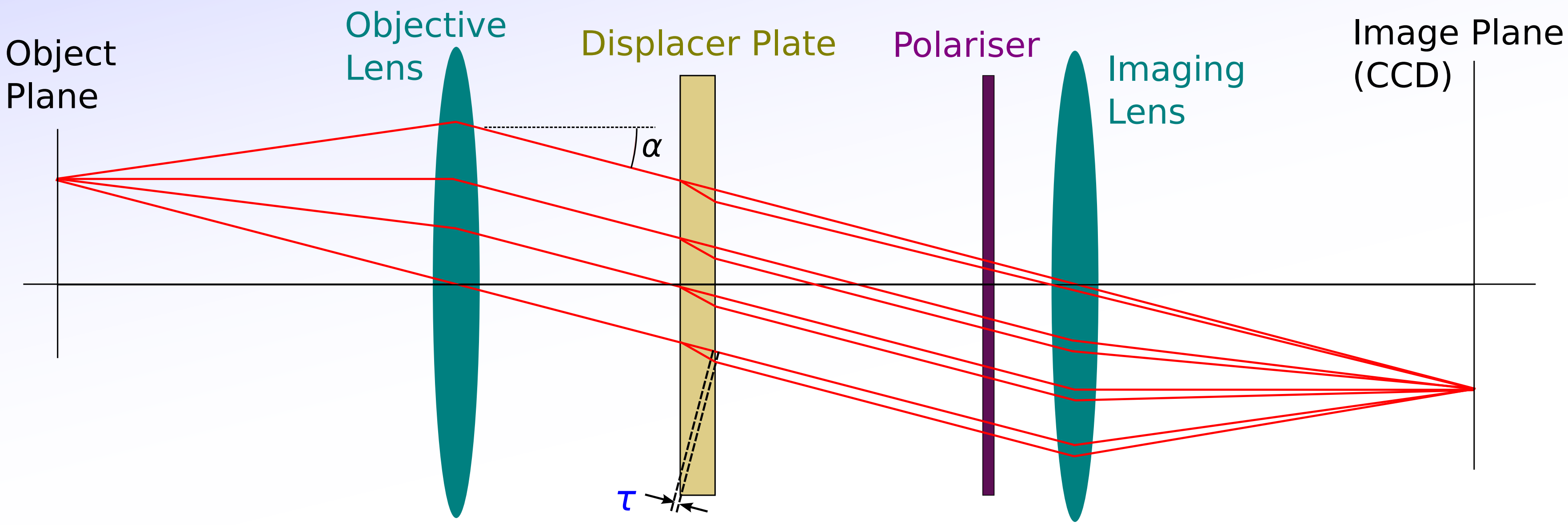

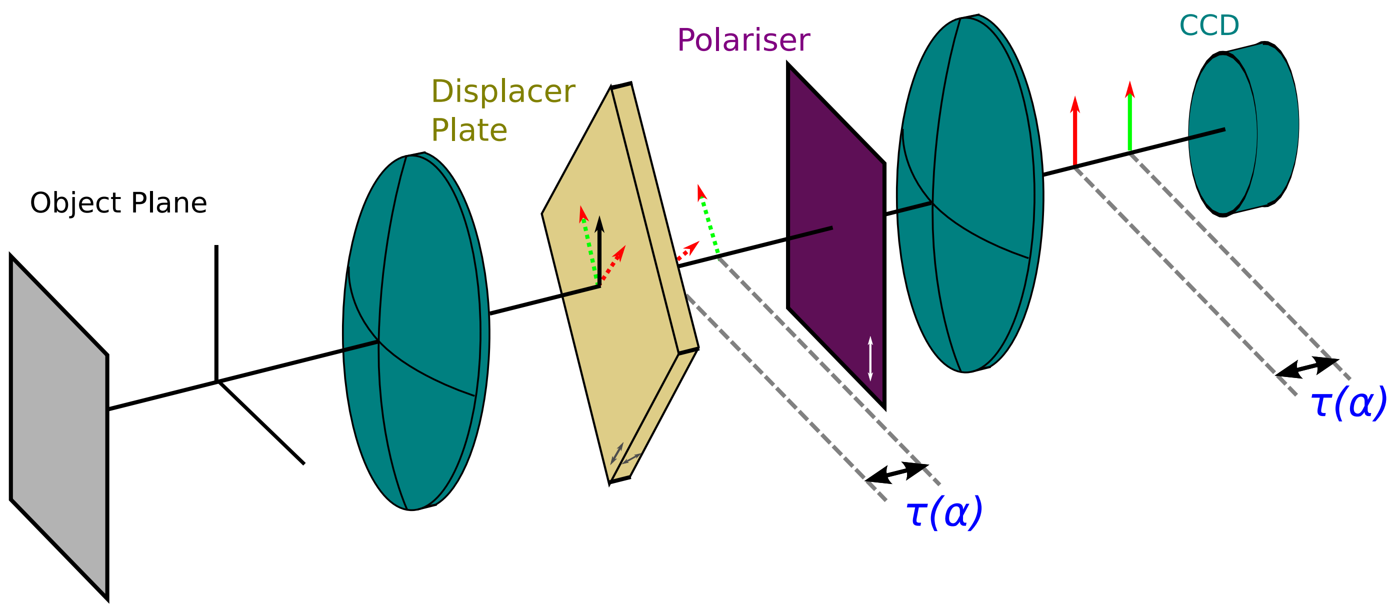

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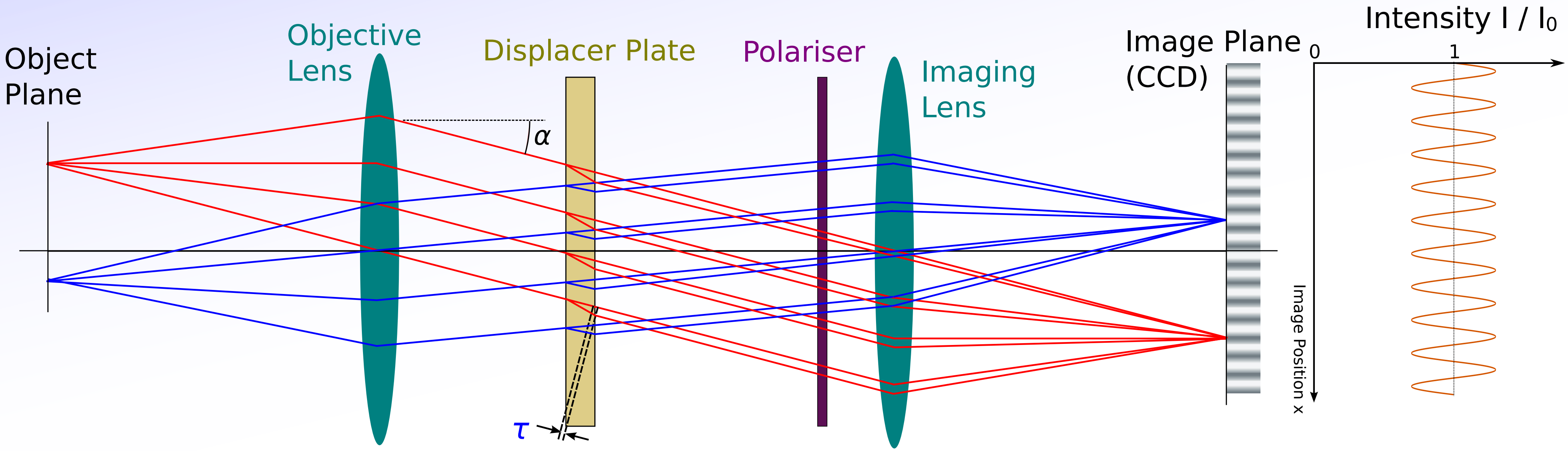

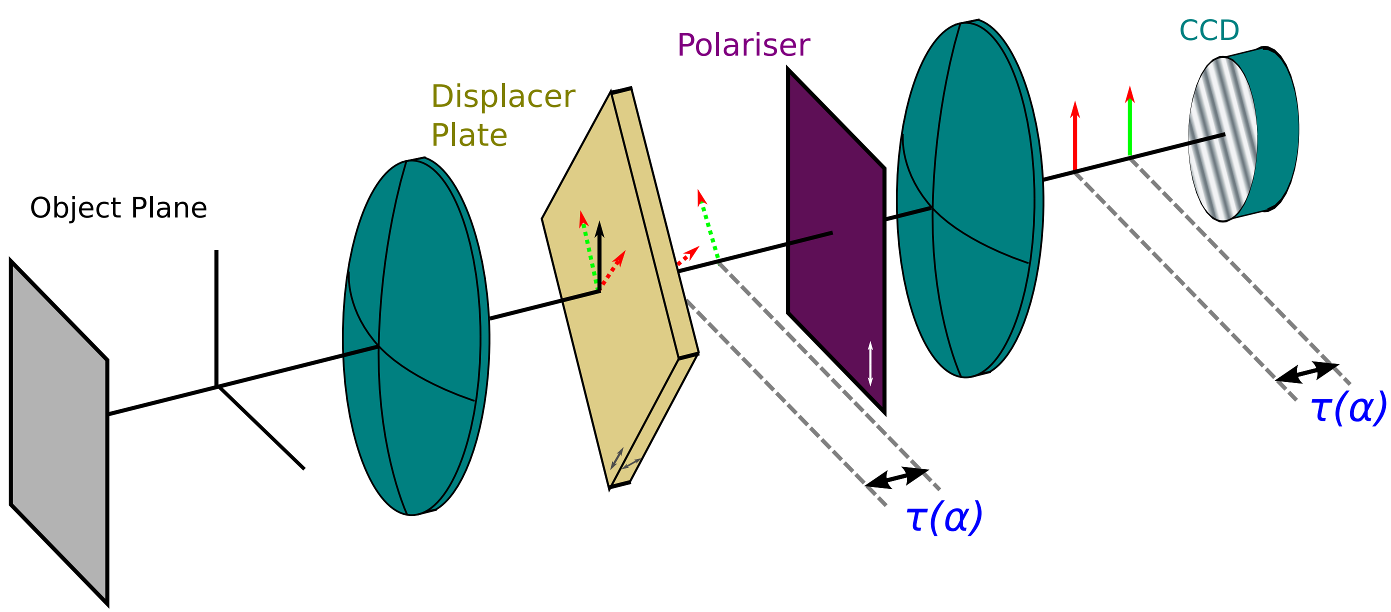

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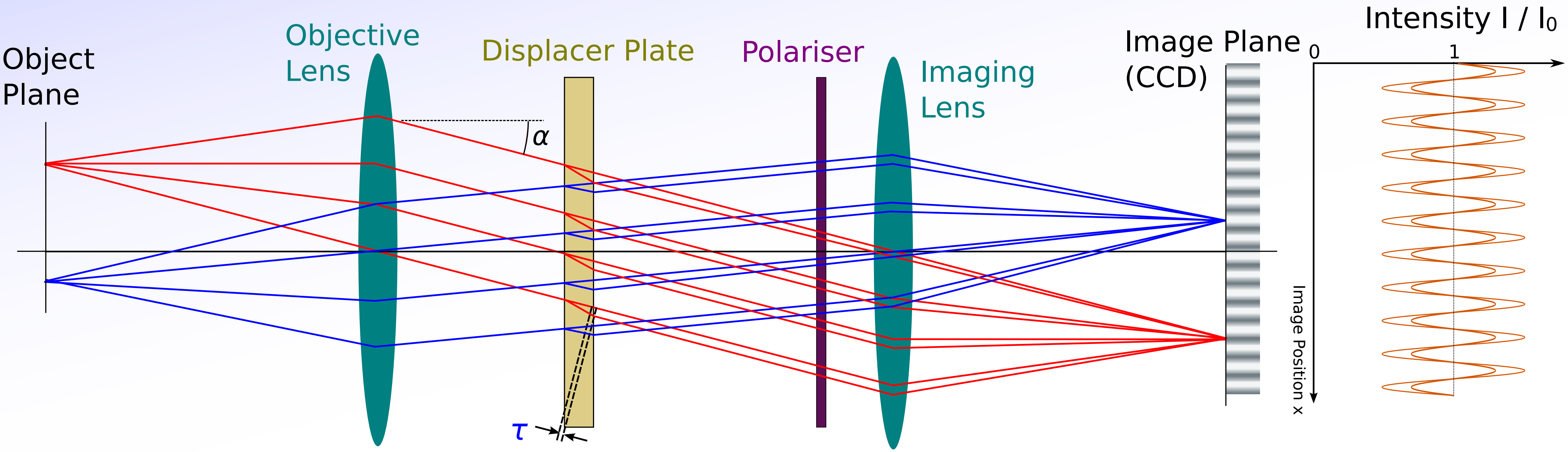
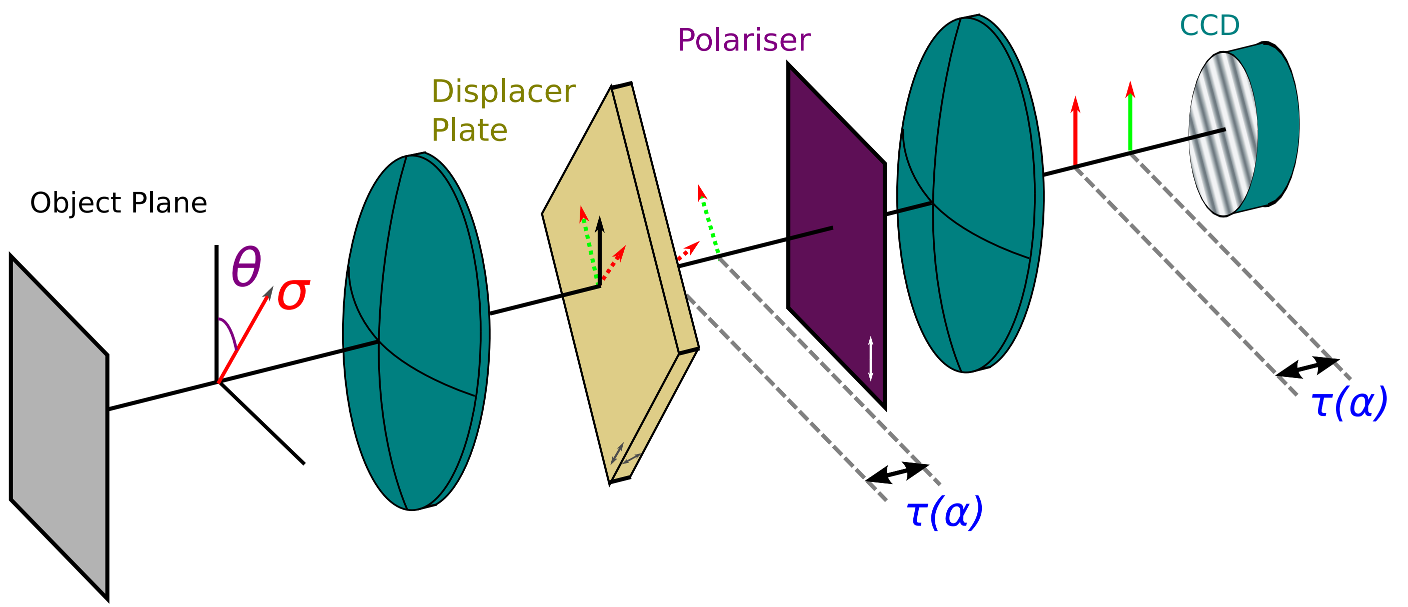


Oscillation amplitude proportional to polarisation angle.

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



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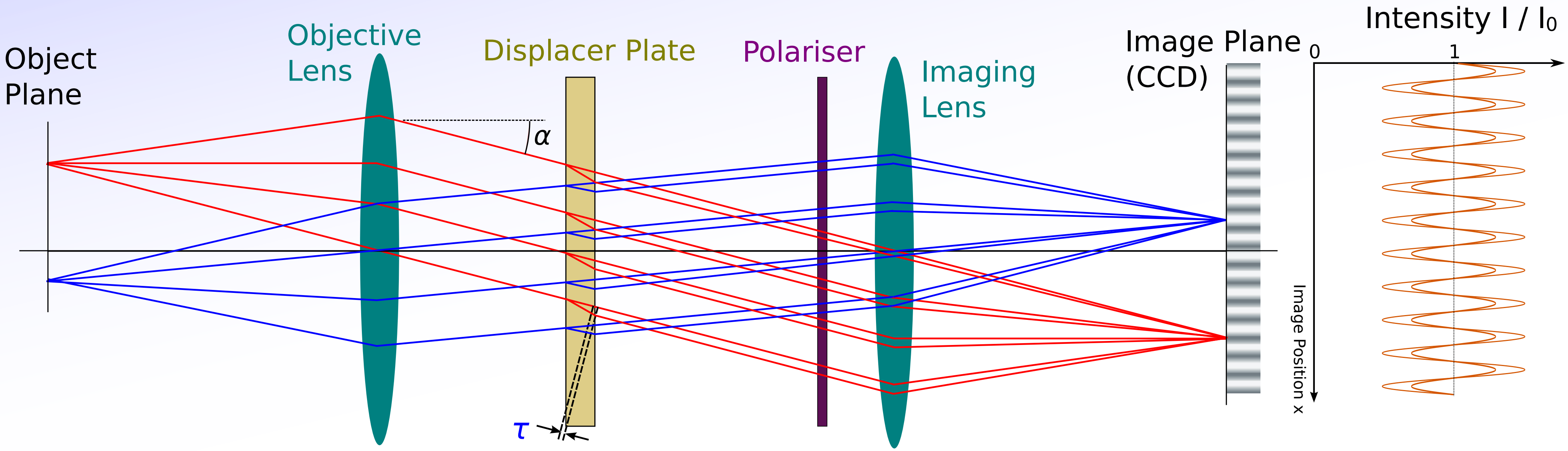
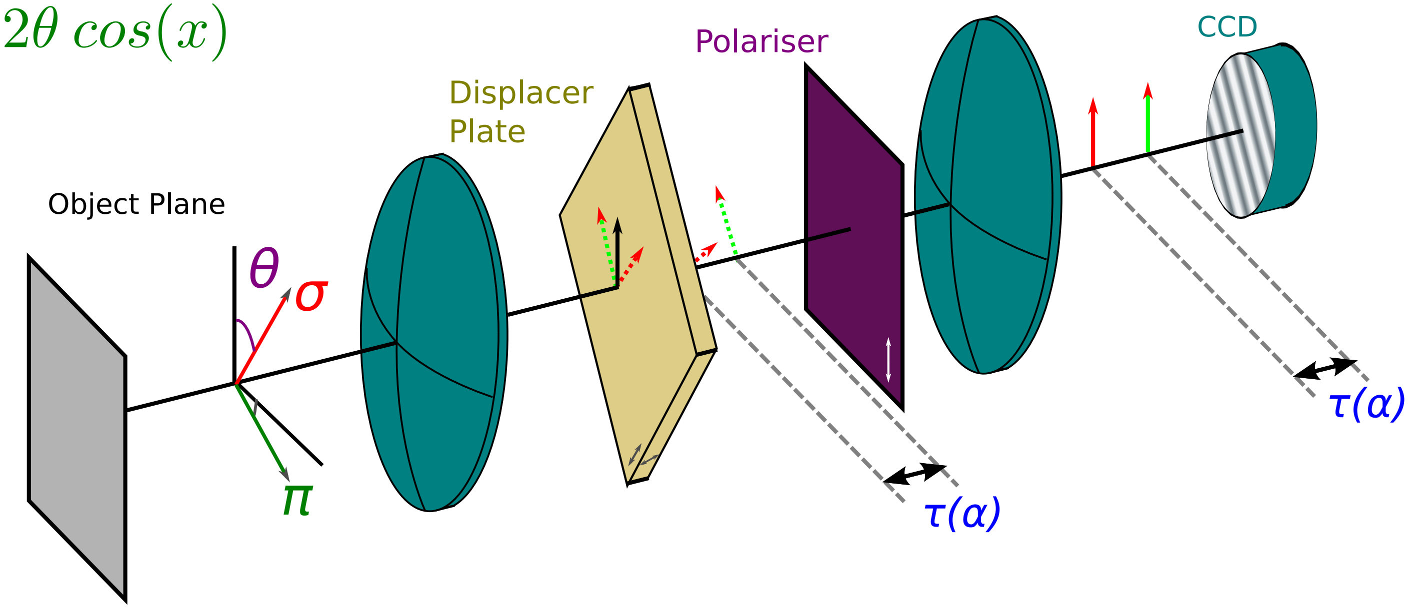


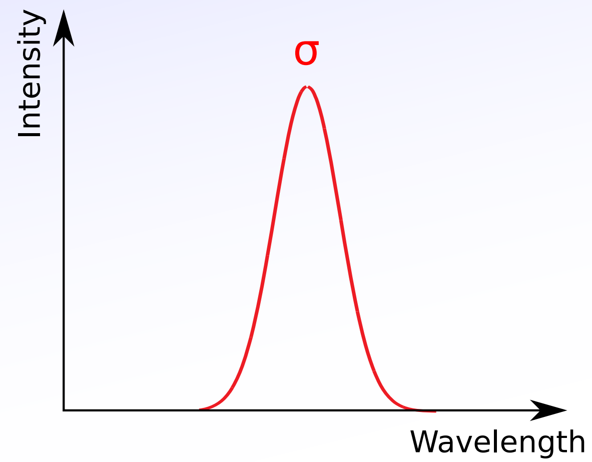
Oscillation amplitude proportional to polarisation angle.

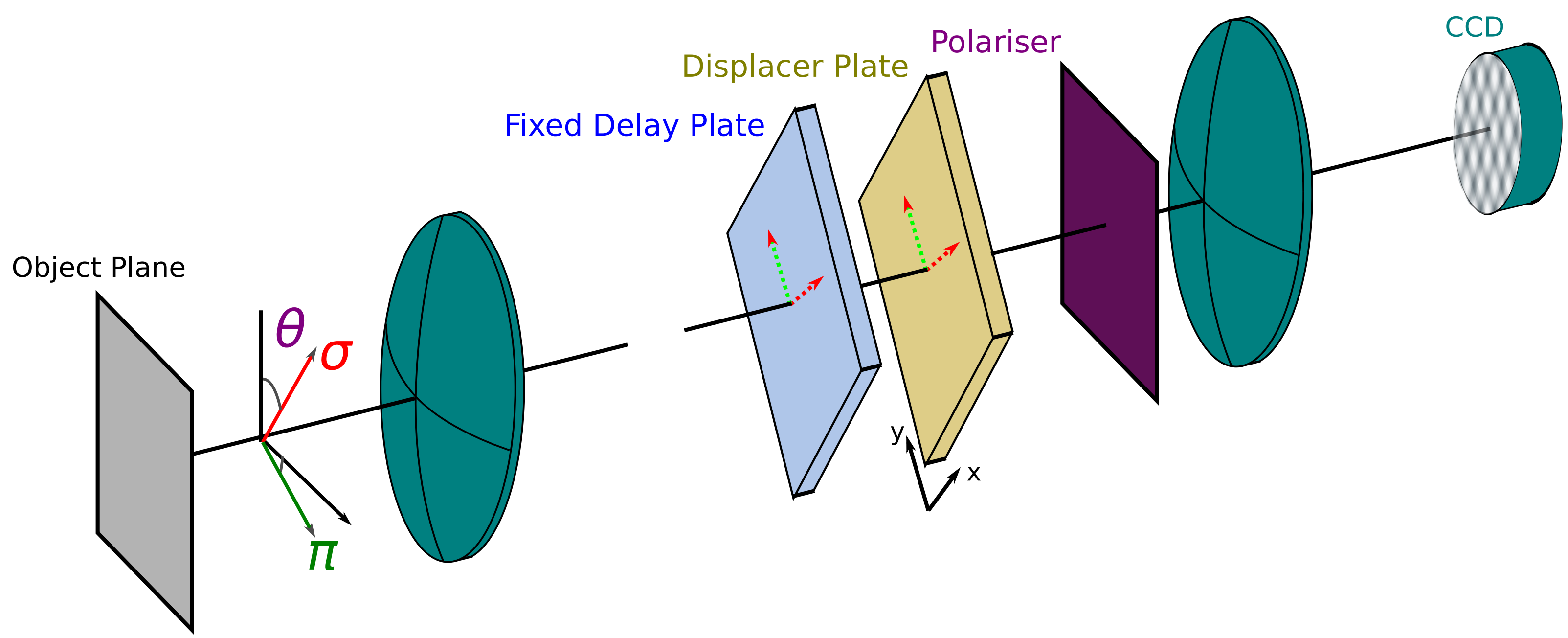
$$I \propto 1 + cos2\theta \; cos(x) - cos2\theta \; cos(x)$$

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



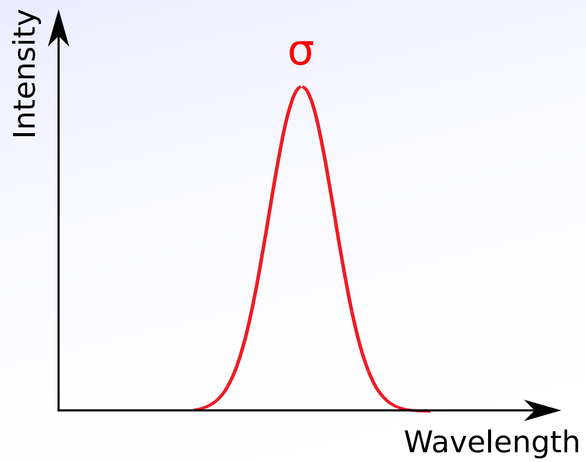
Spectral Coherence

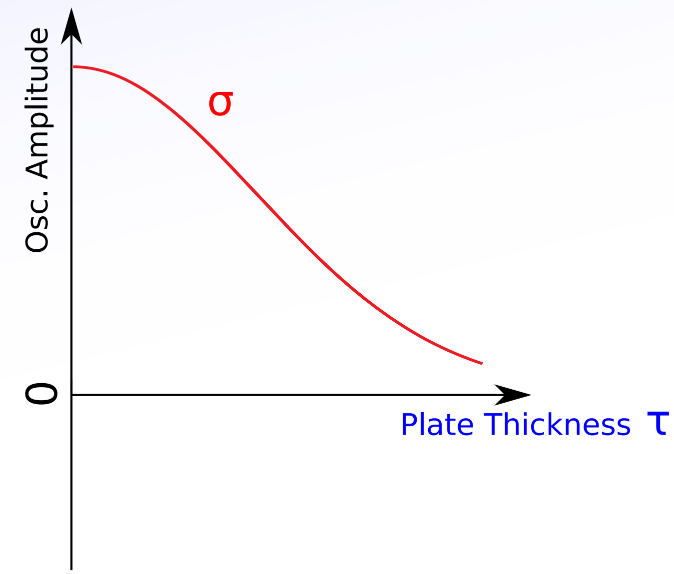


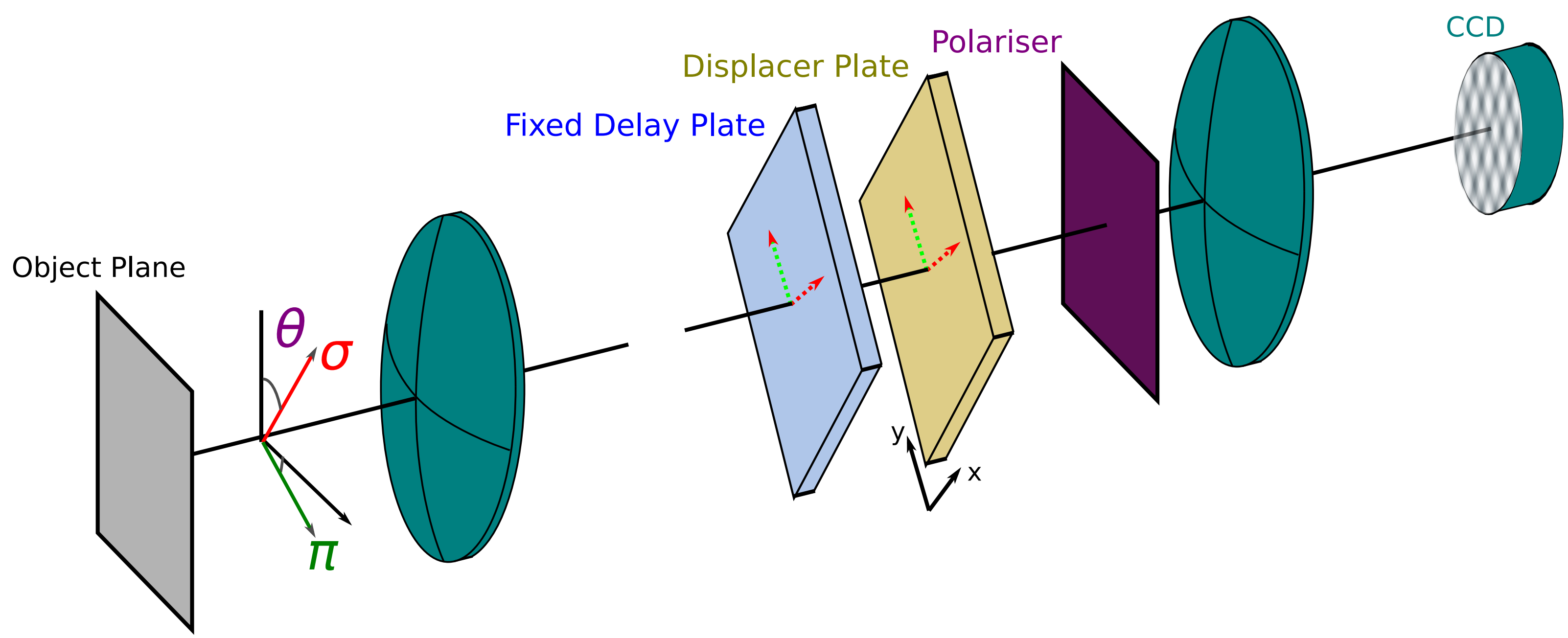


Spectral Coherence

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







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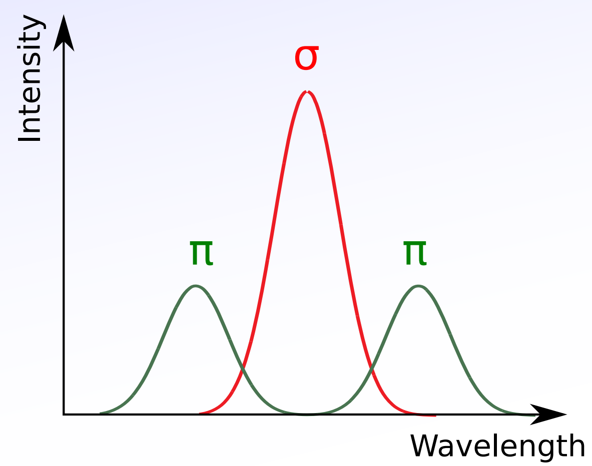
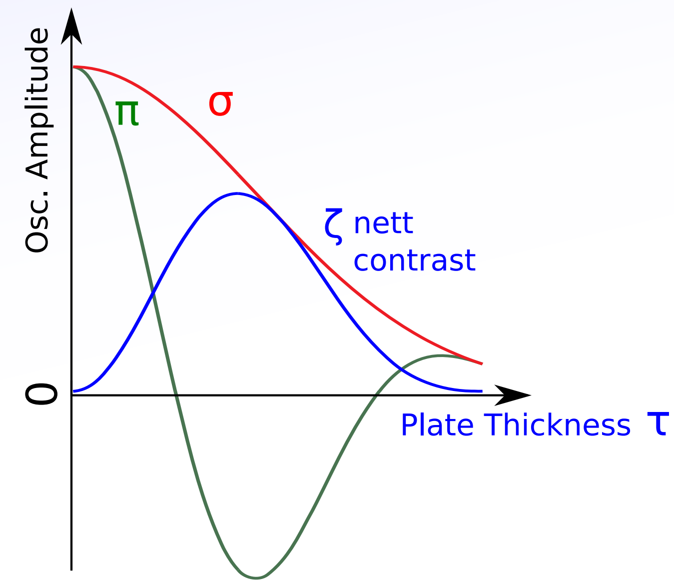
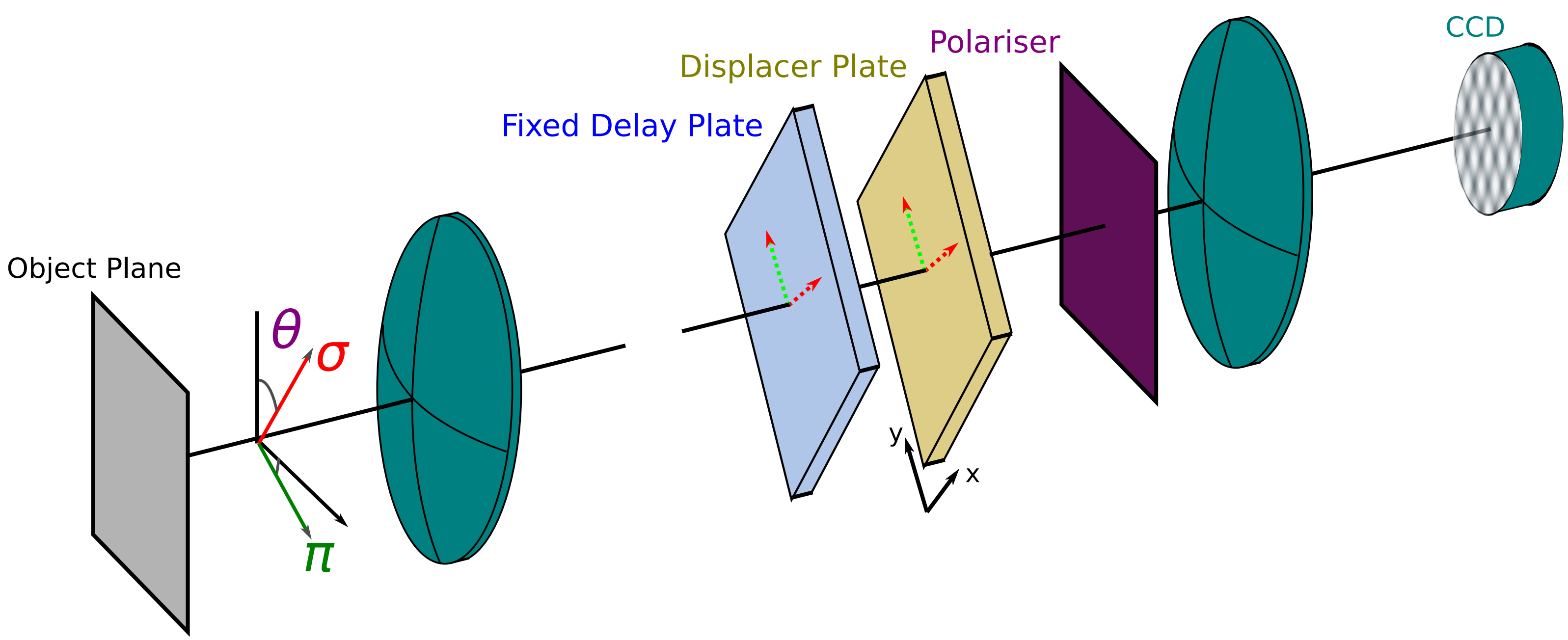
For a specific τ, the phase of the π wings is 180° from σ. This cancels the 180° from the opposite polarisation, and the patterns add.







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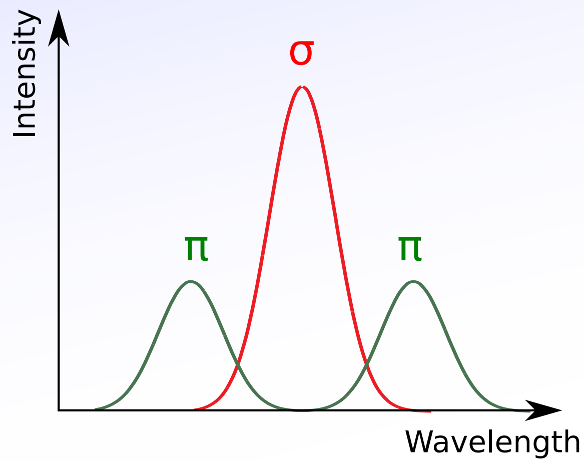
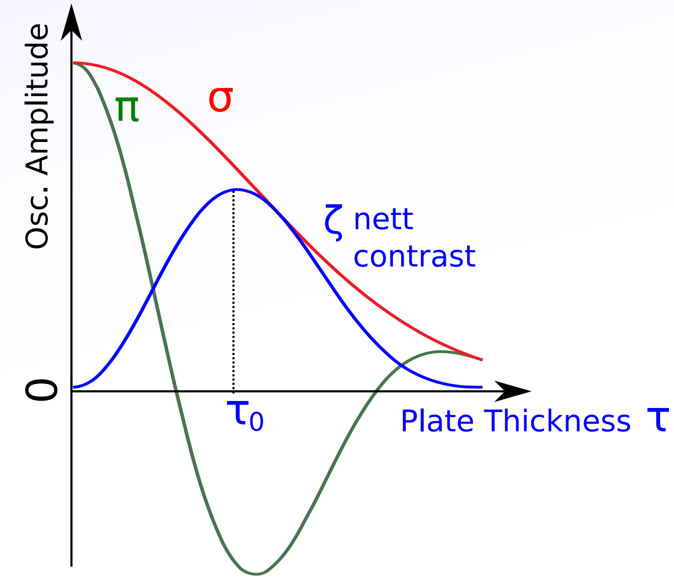
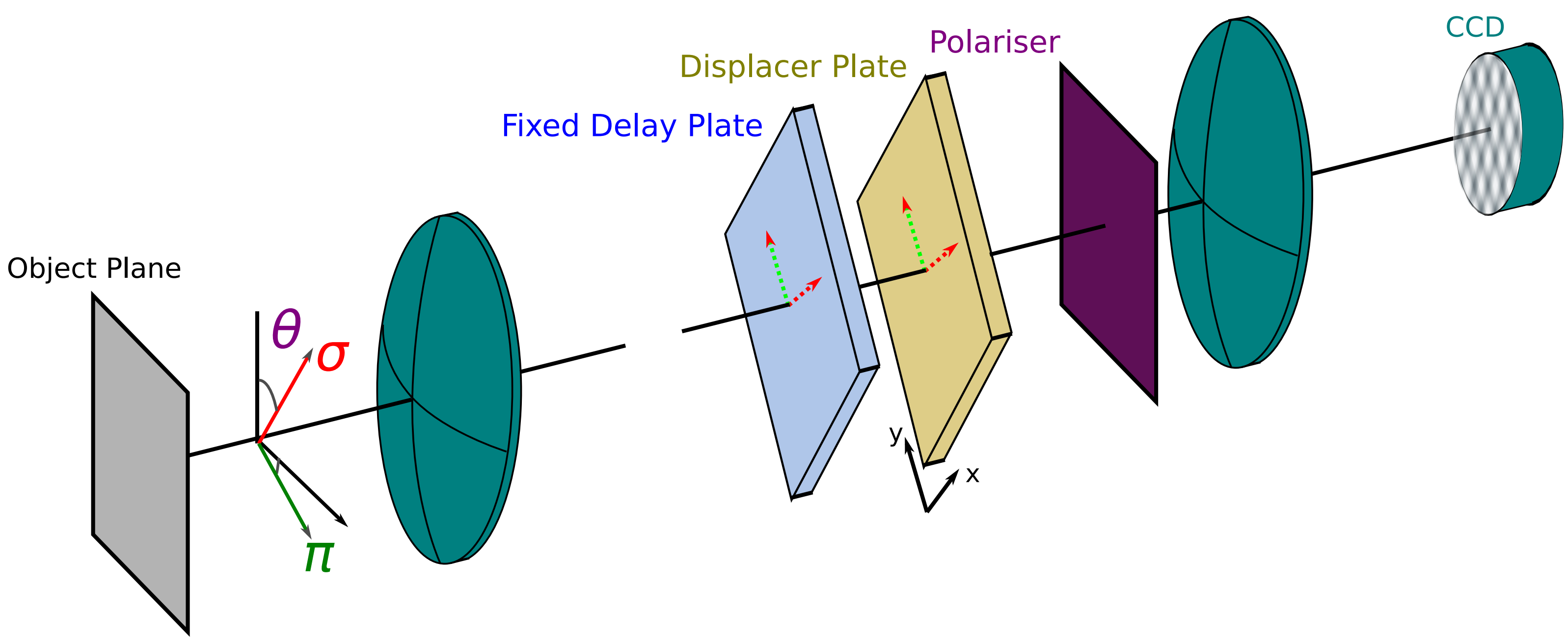
Add a delay plate to introduce the best τ_0 - where π and σ combine constructively.







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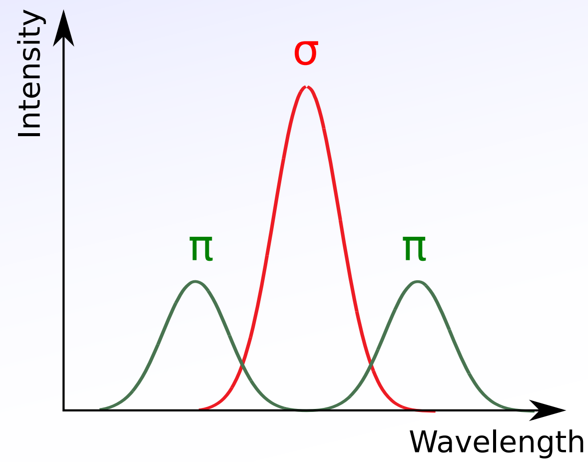

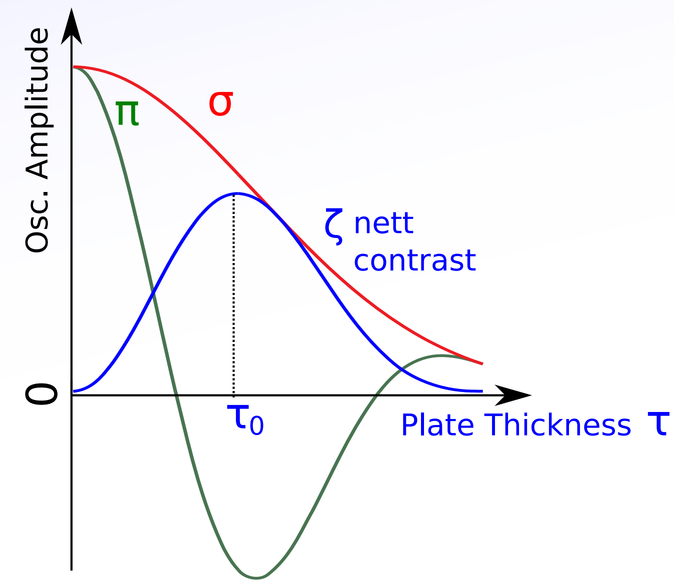

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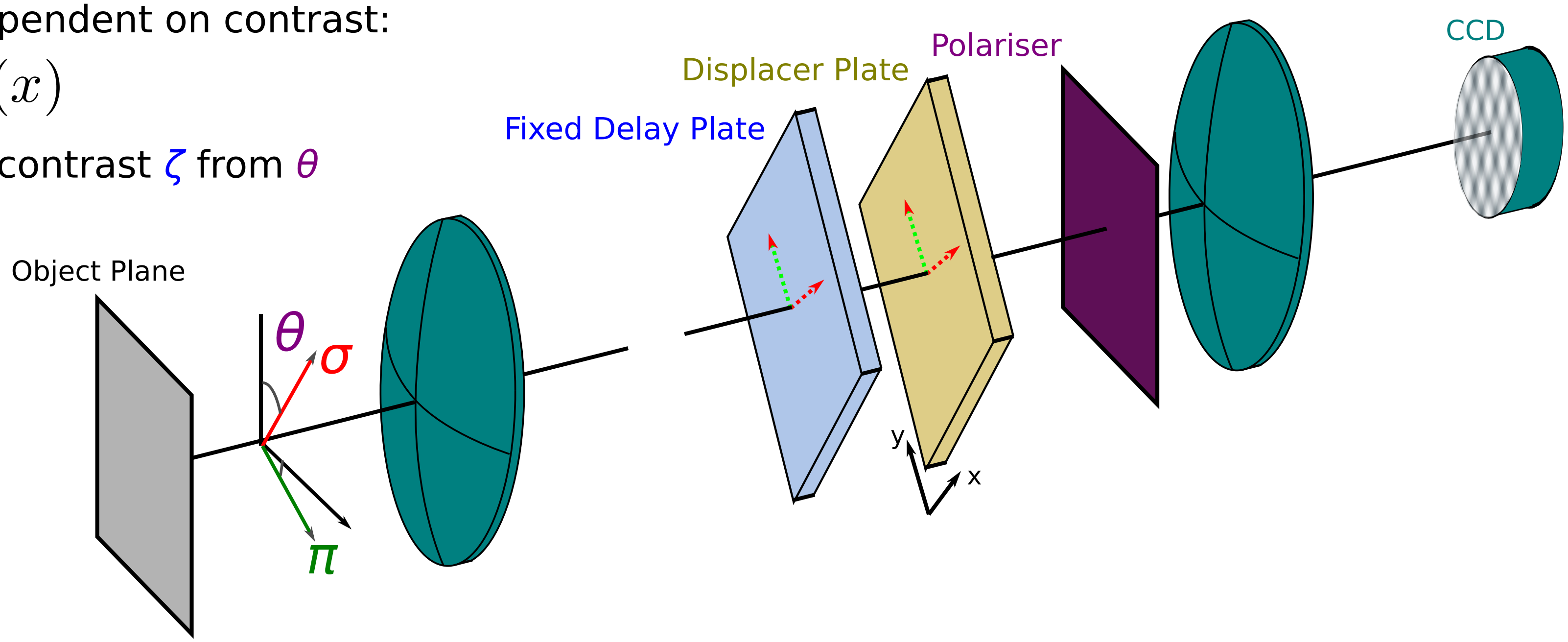
$$I \propto 1 + \zeta \; cos 2\theta \; cos(x)$$

Need to separate spectral contrast ζ from θ



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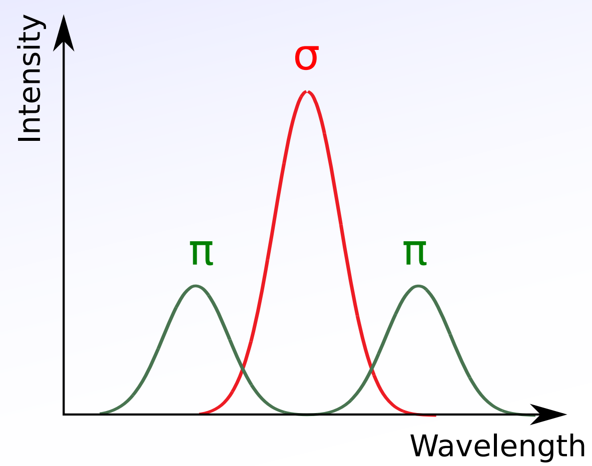

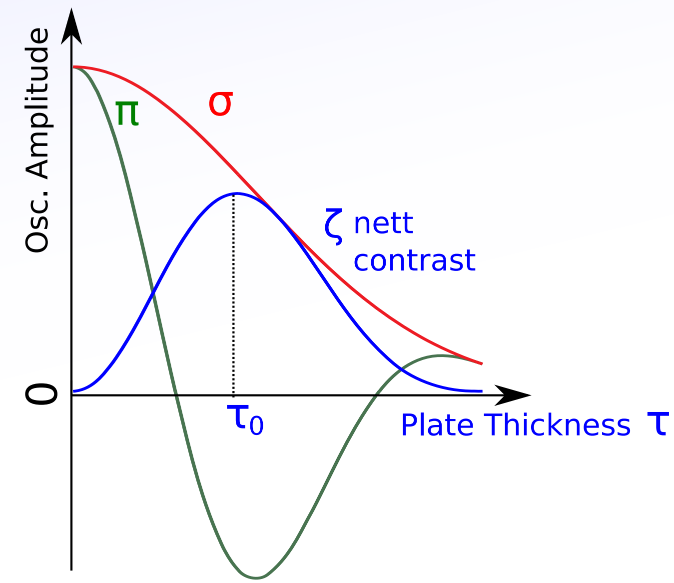

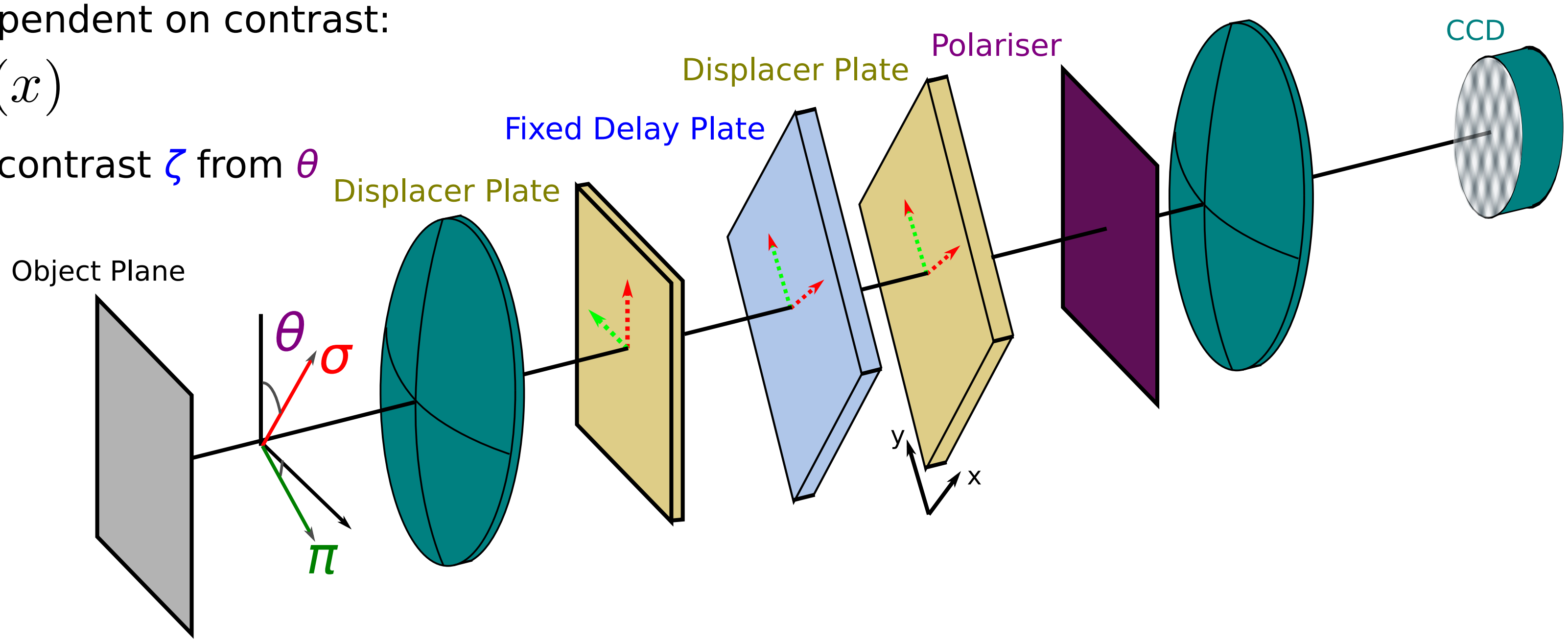

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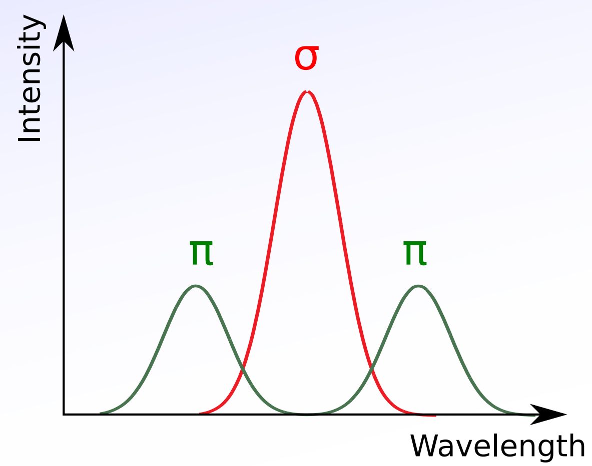

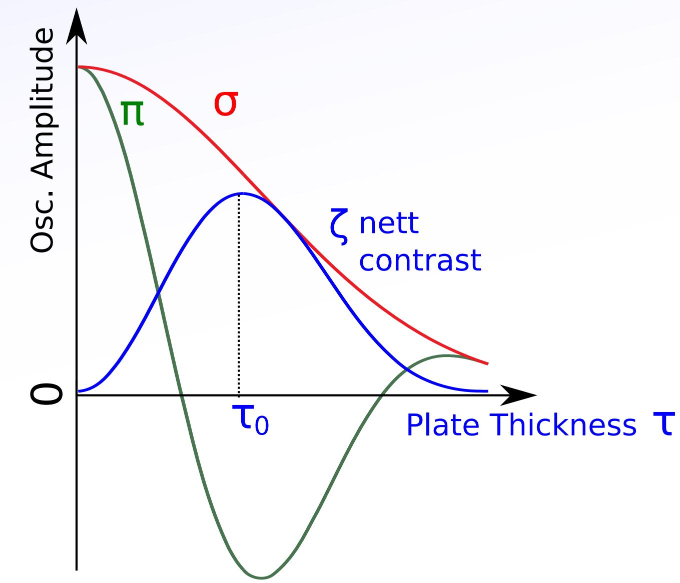

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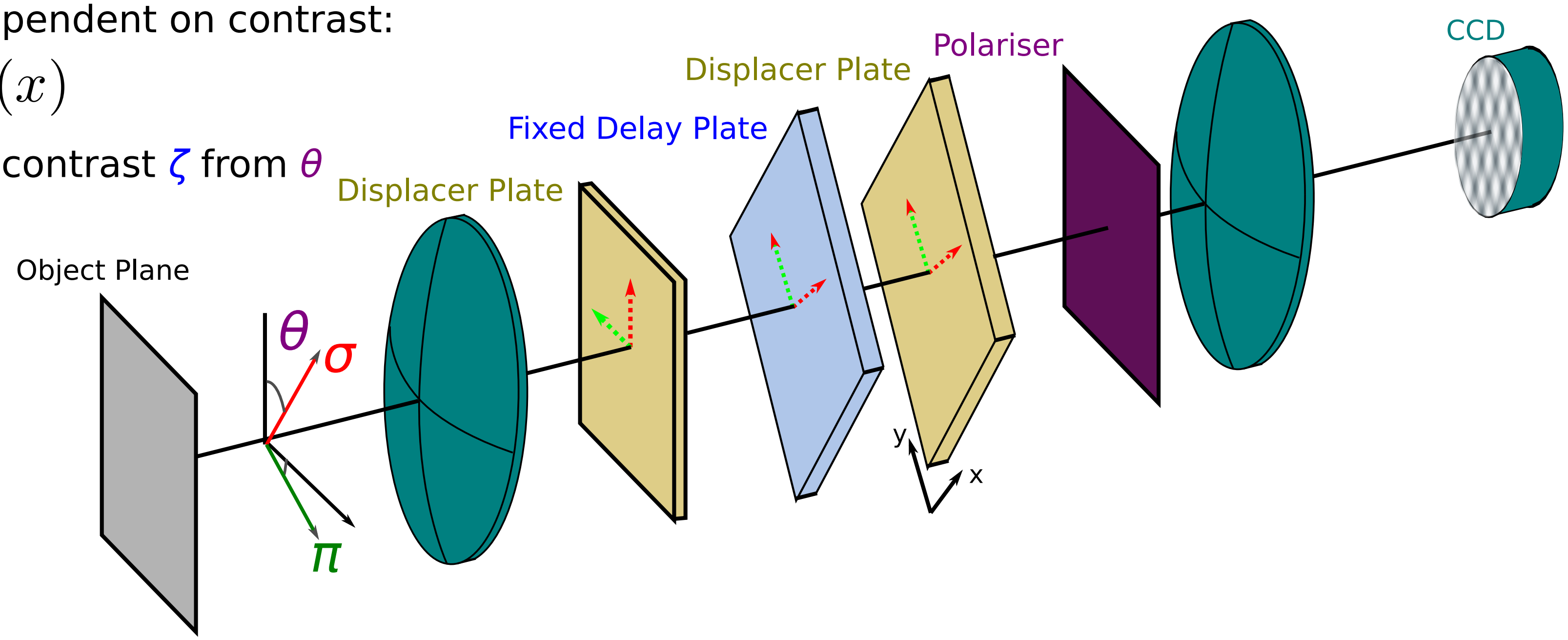
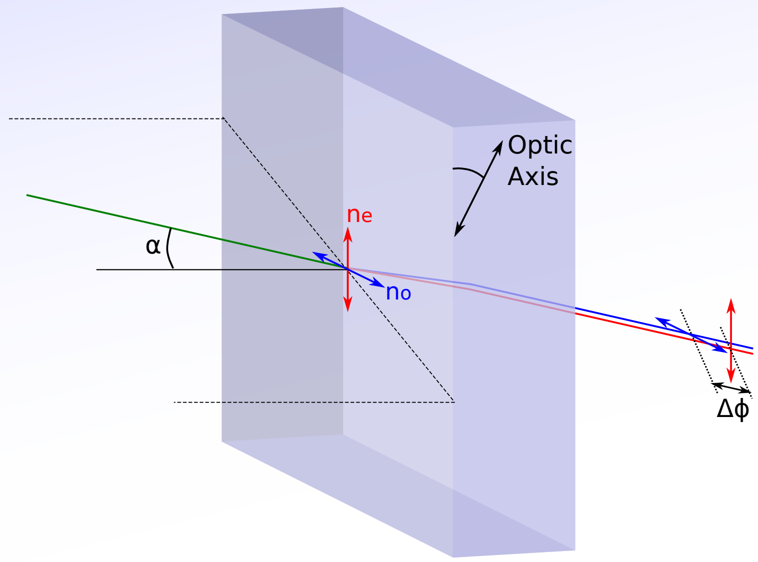


add another displacer at 45°. Combined effect adds 2 extra terms:

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

Concept Tests: Tilted Waveplates

The displacer plates are uniaxial crystals cut at 45° to their optic axis:



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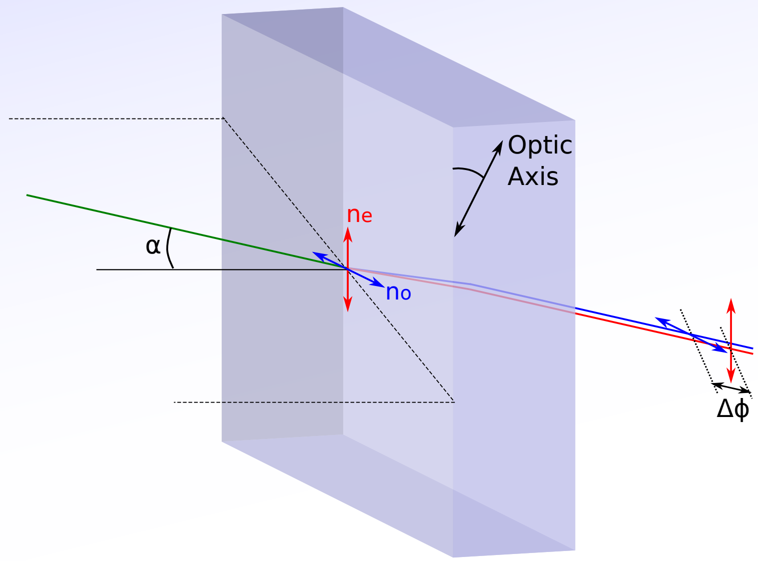
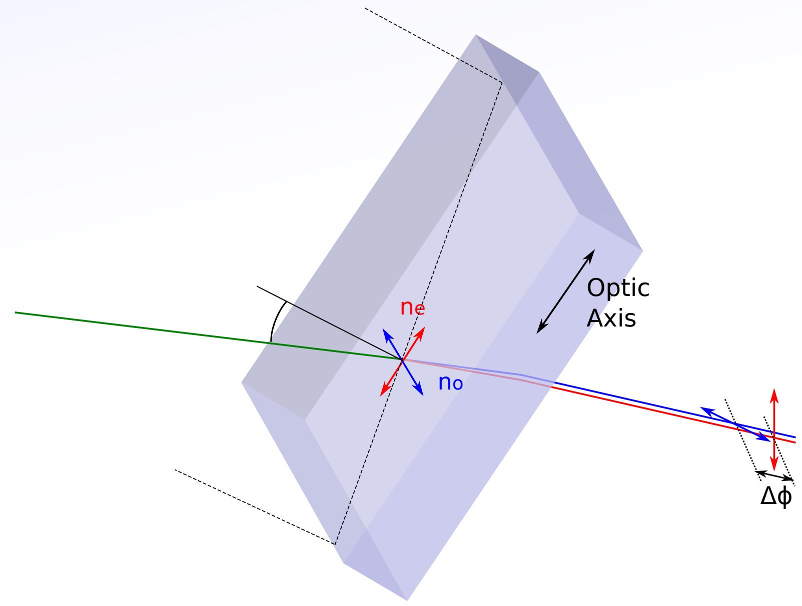


Before these arrive from Australia (today?), I have temporarily used tilted wave plates:



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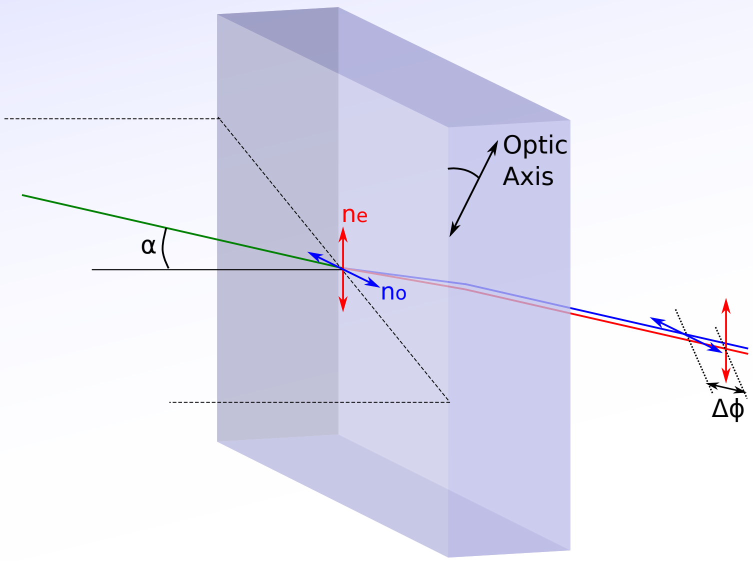

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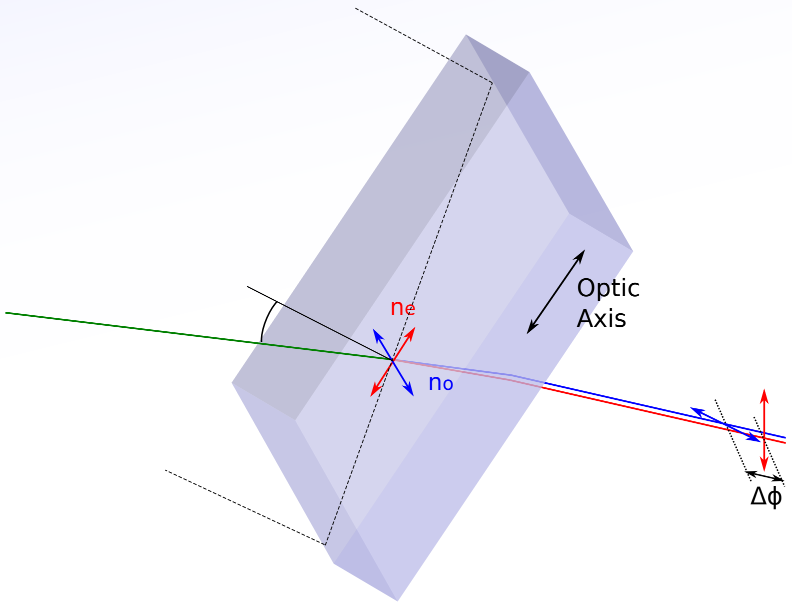
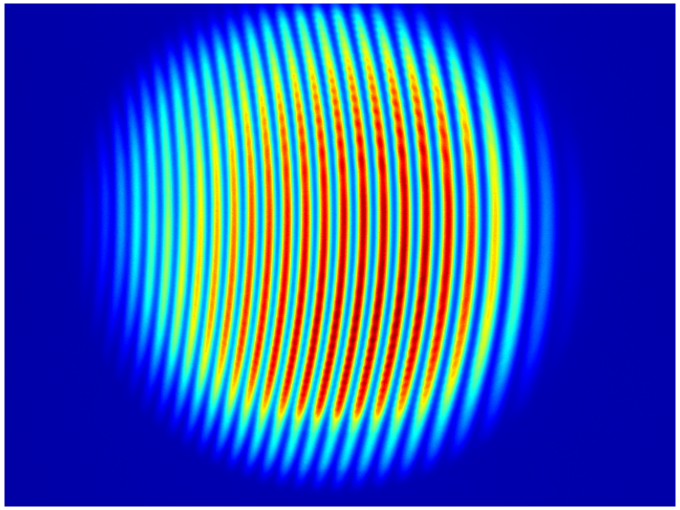


Delay pattern is a bit non-linear but, it still works well enough:



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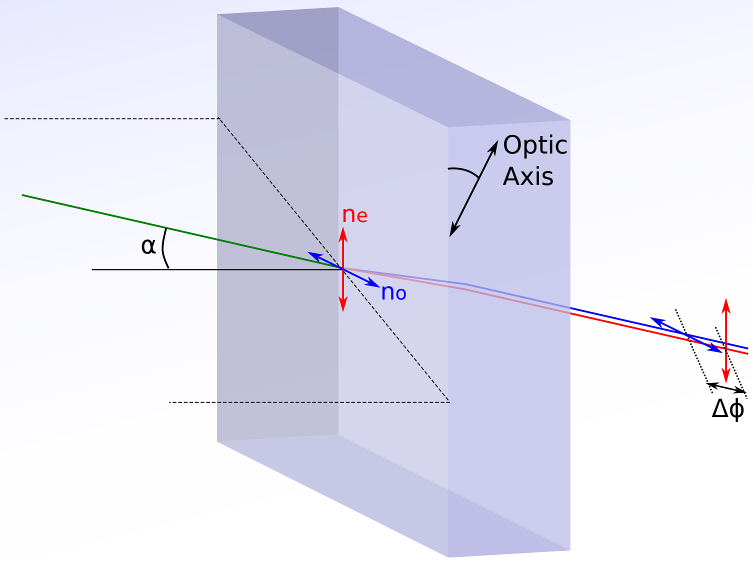

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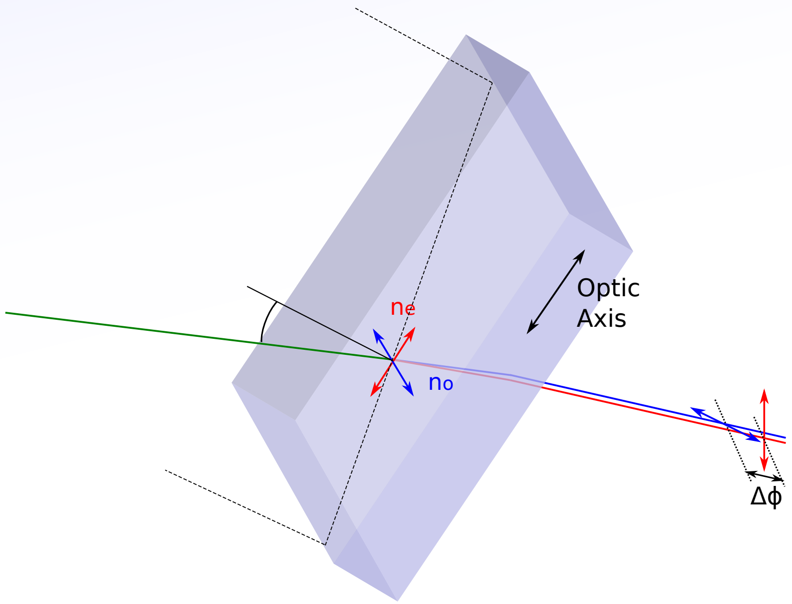

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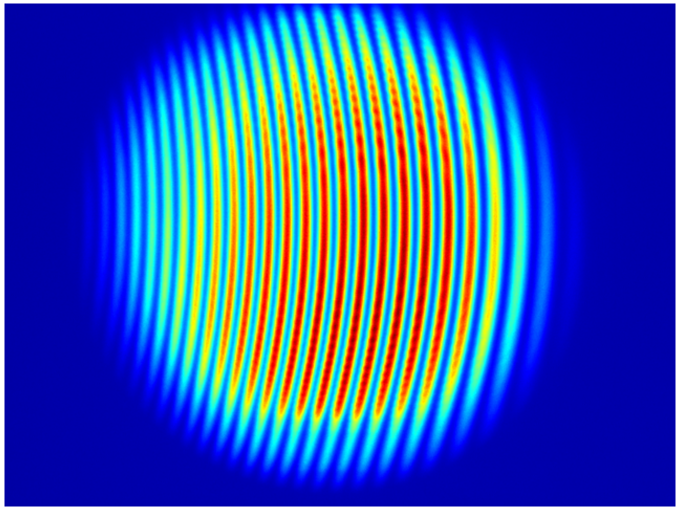
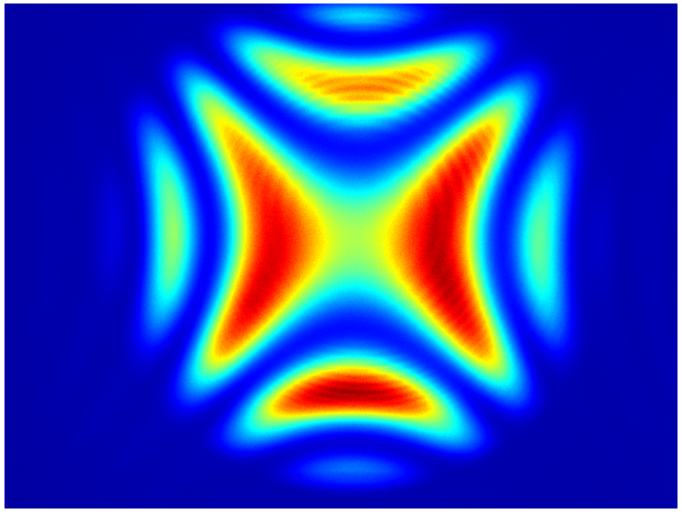
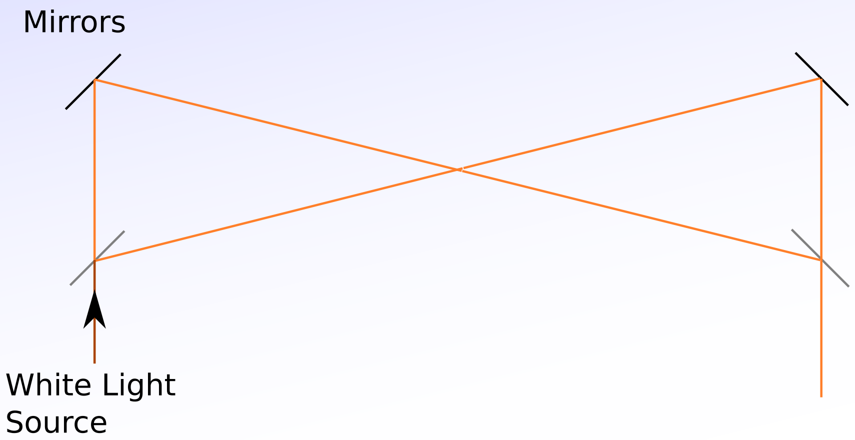


Incidentally, this happens a little with a flat waveplate and high field of view:



Concept Tests: Simulated Spectrum

A way to simulate a known spectrum,
with the same problem:



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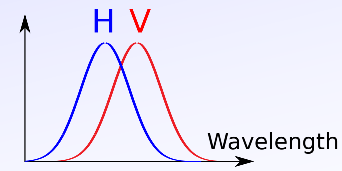

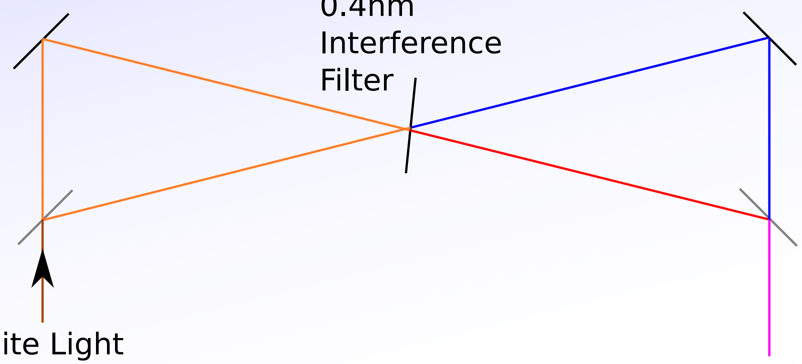

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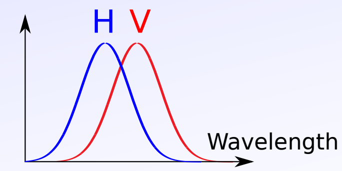

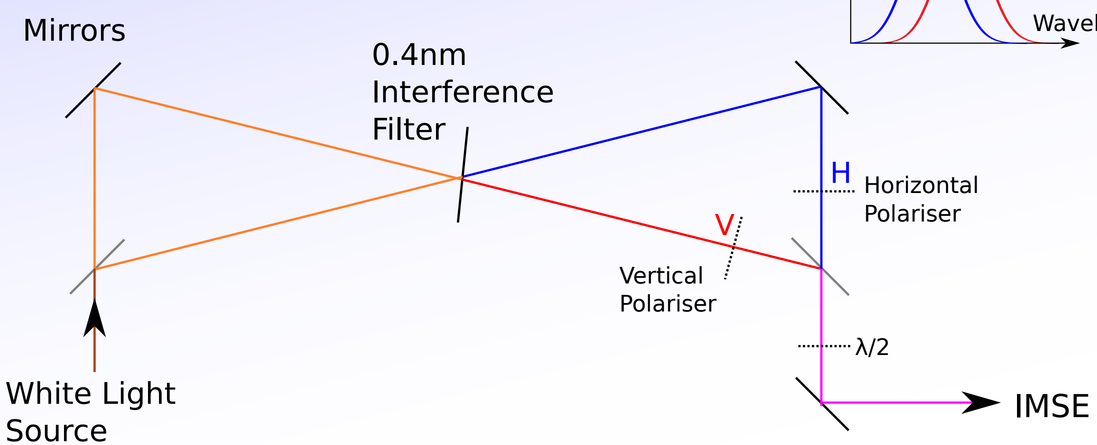

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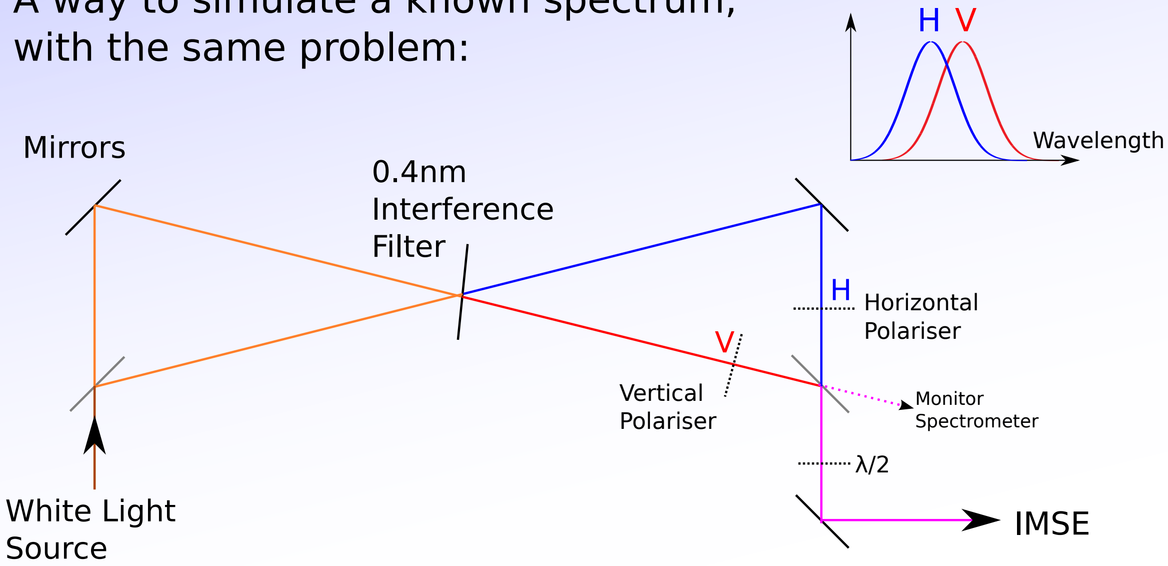

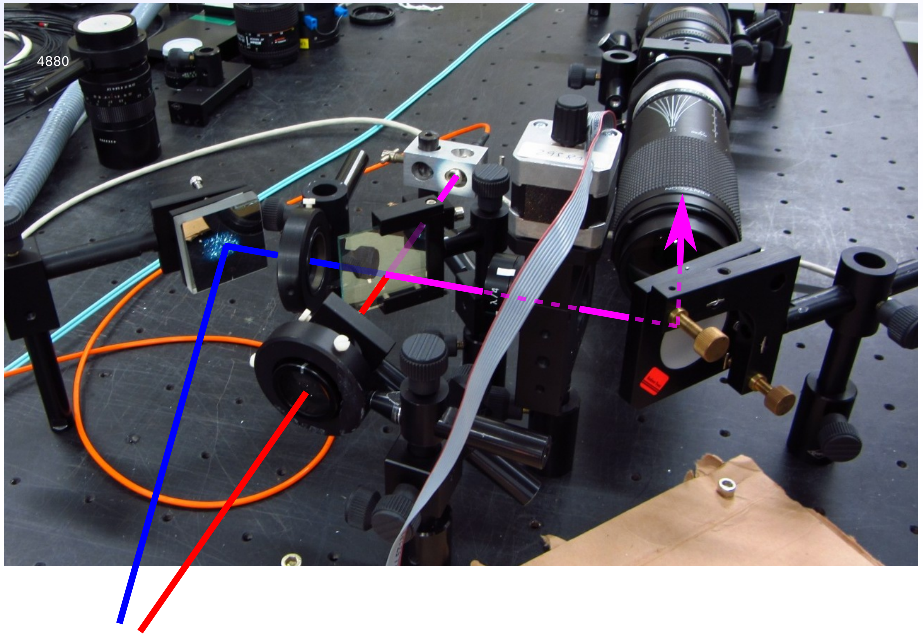

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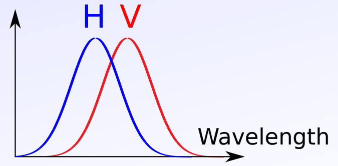
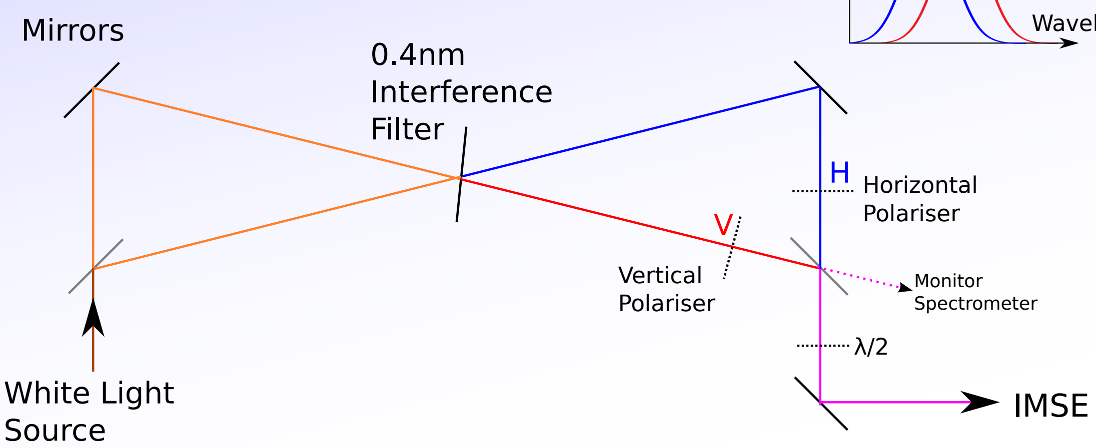
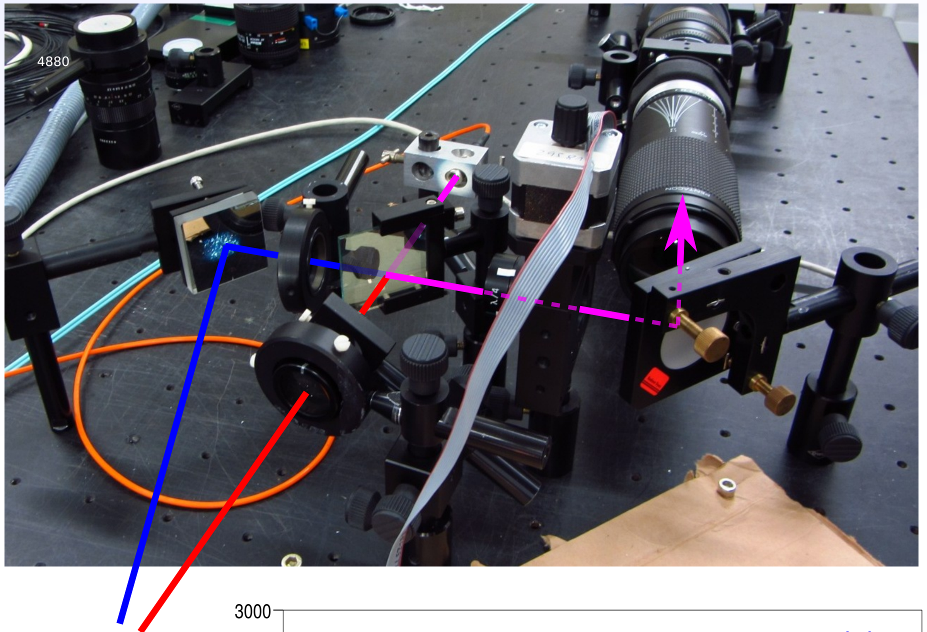
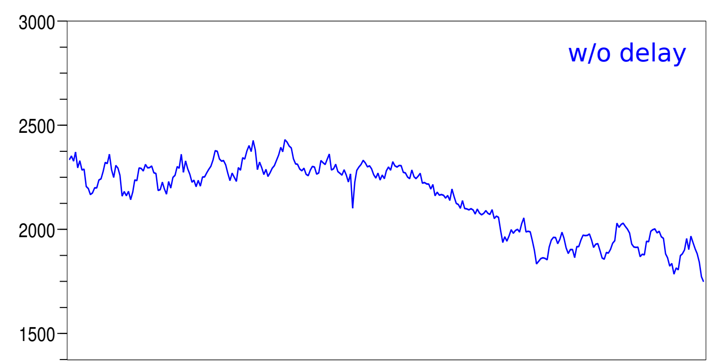
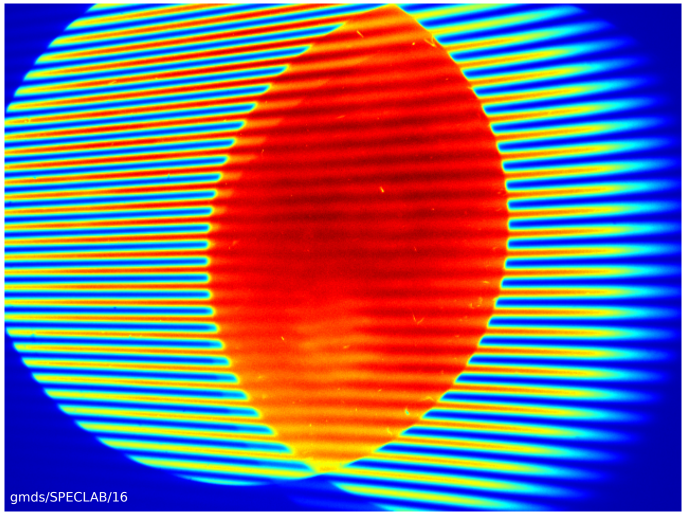






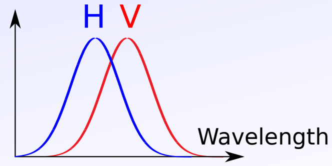


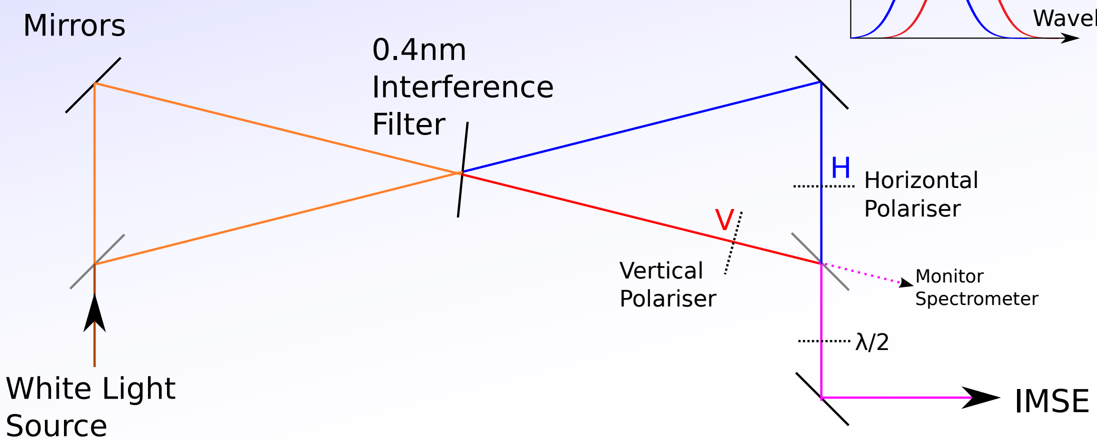
With just one tilted plate and no net delay, separating the beams slightly we can see where the V and H polarisations cancel (well, almost):

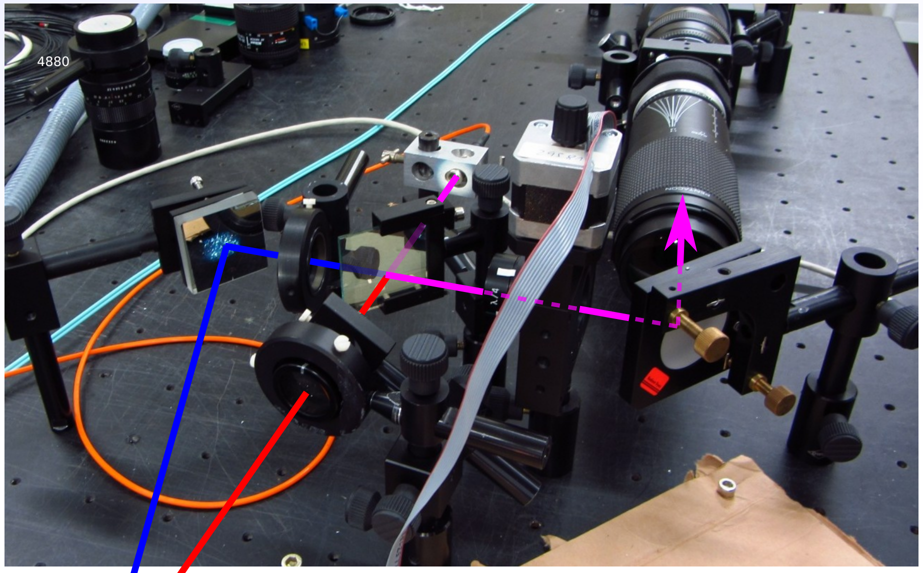


Concept Tests: Simulated Spectrum

A way to simulate a known spectrum, with the same problem:







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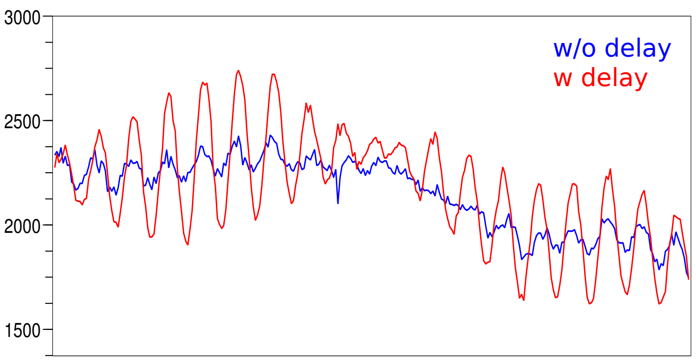
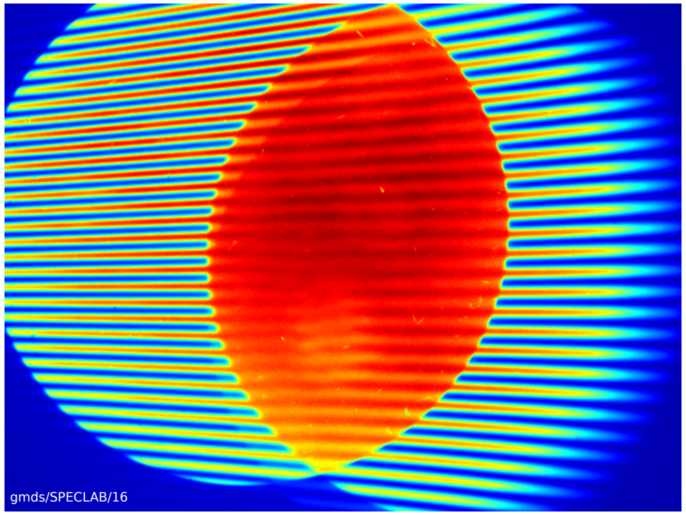
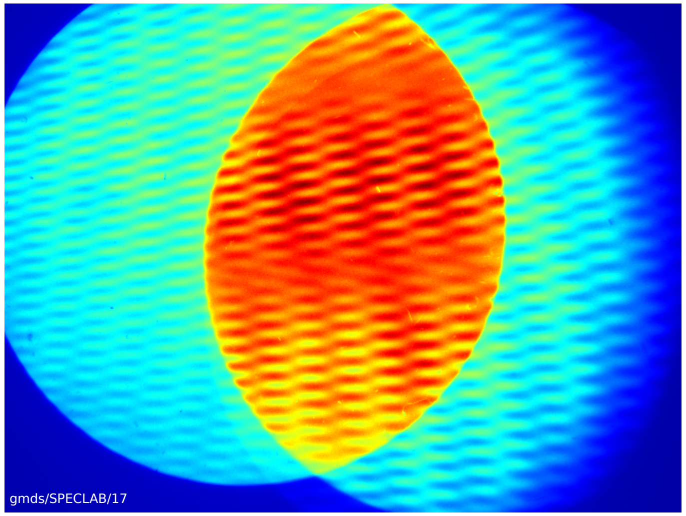
Adding both displacer plates and a small net delay:







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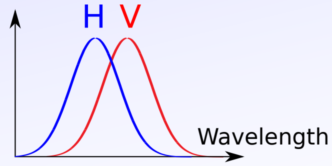

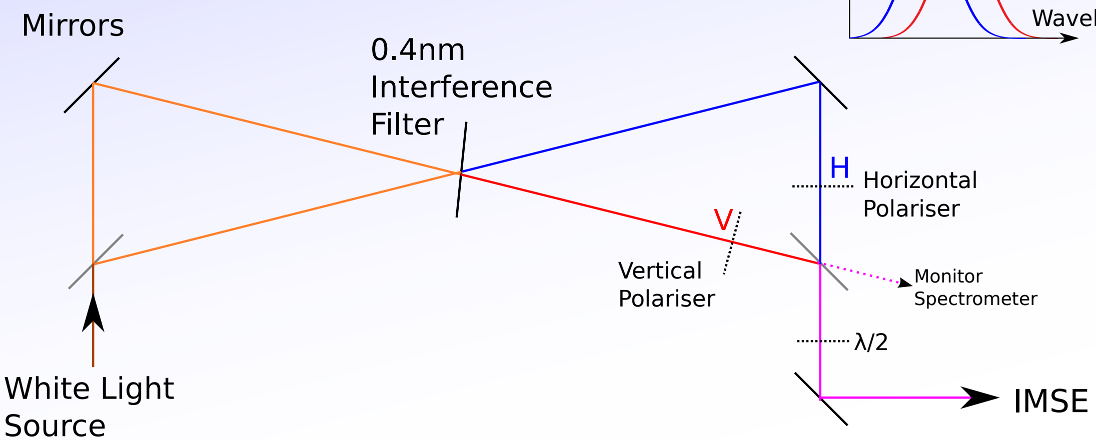

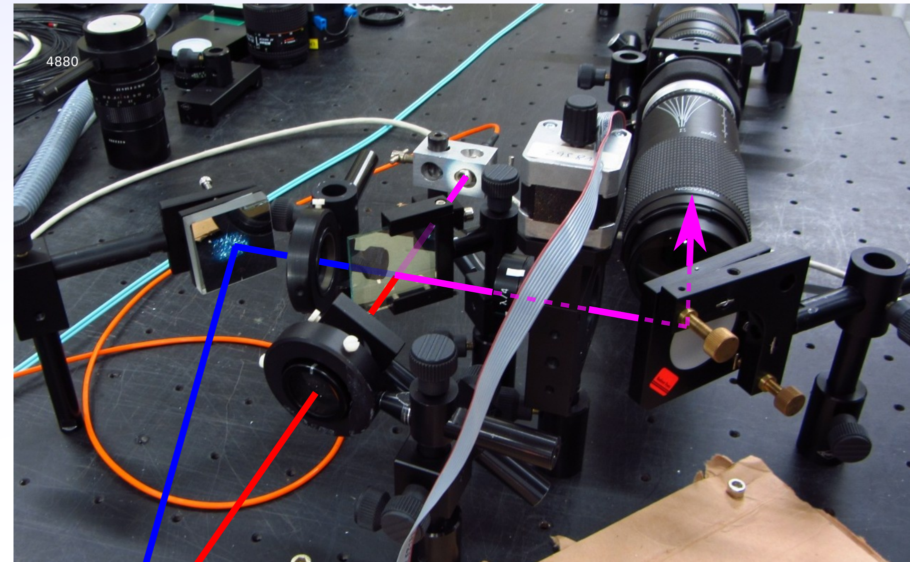

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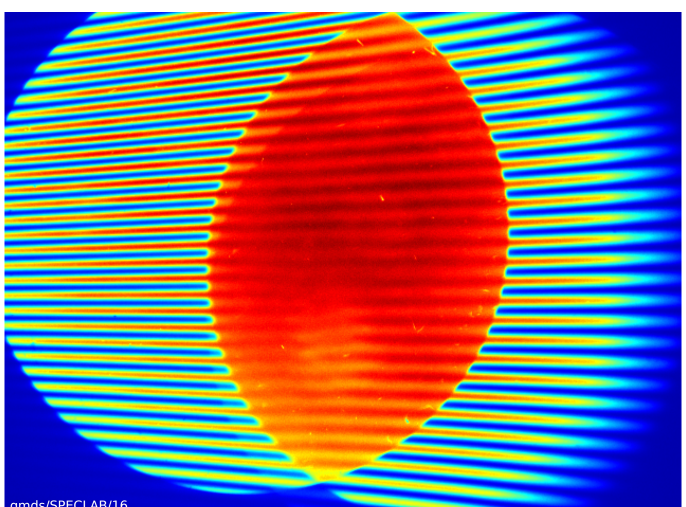

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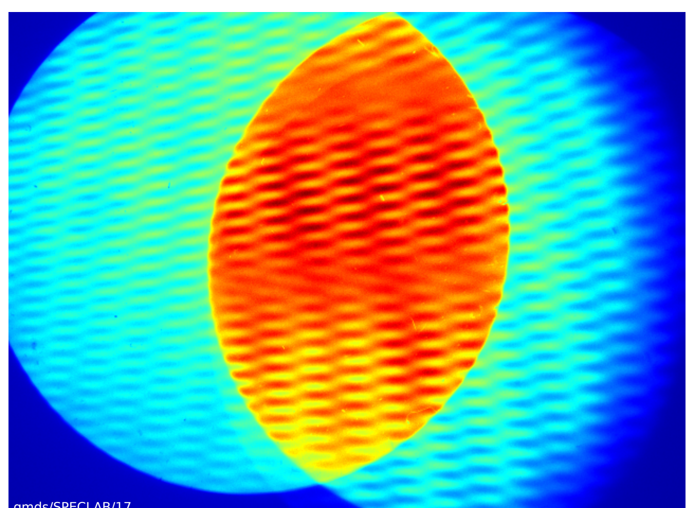

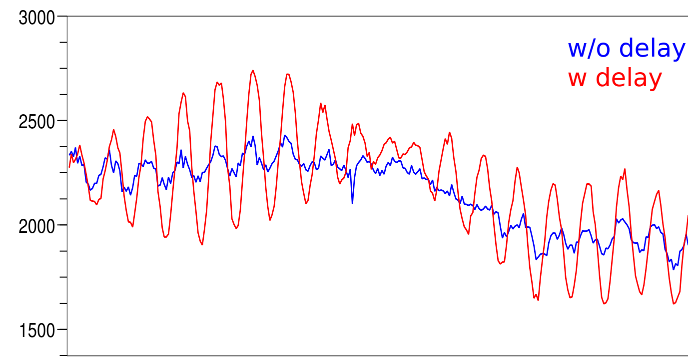

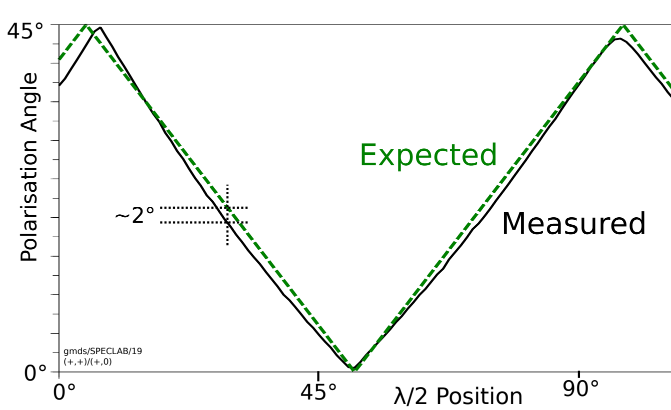

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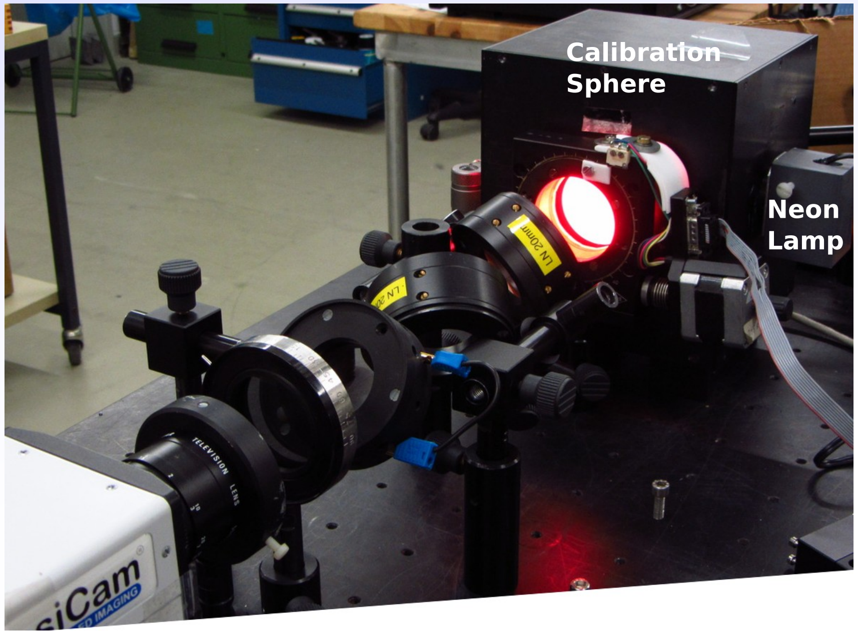

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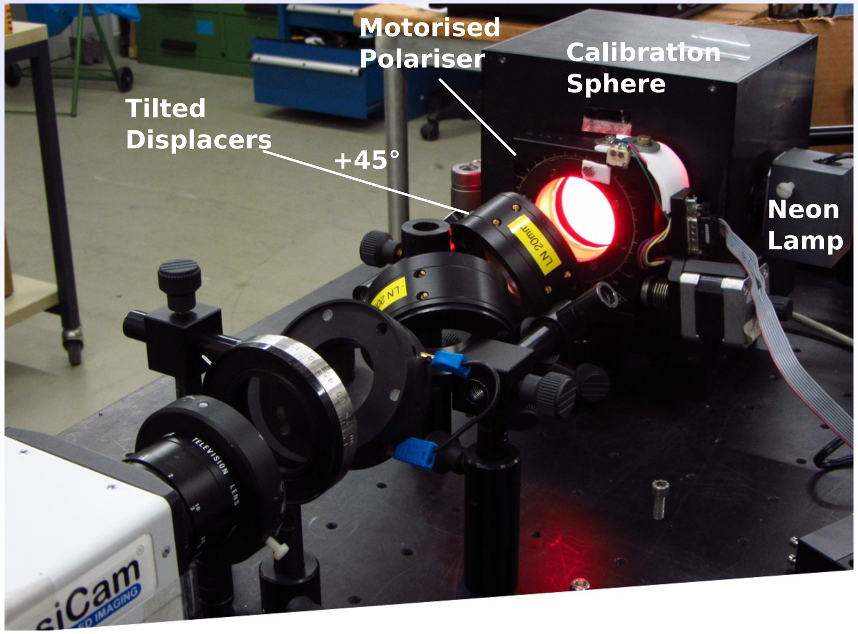

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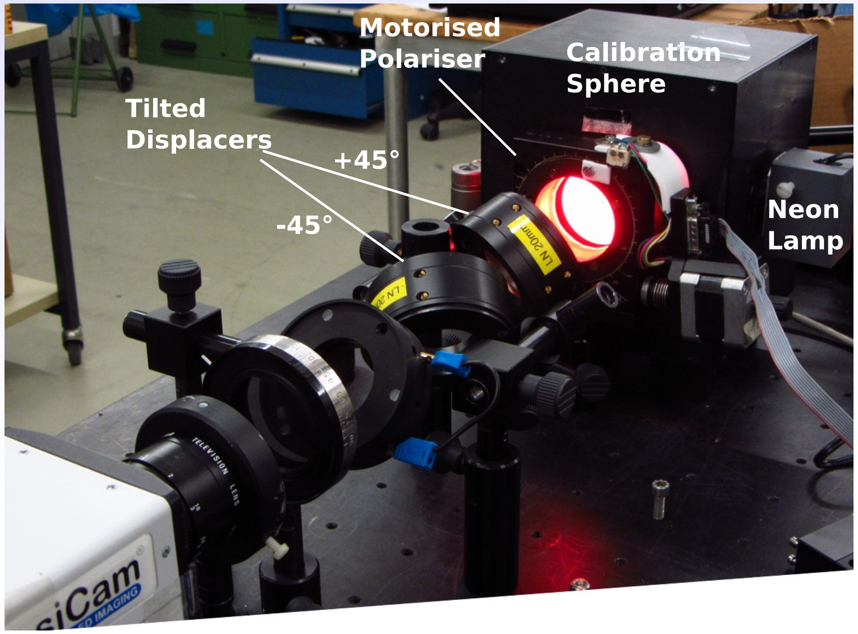

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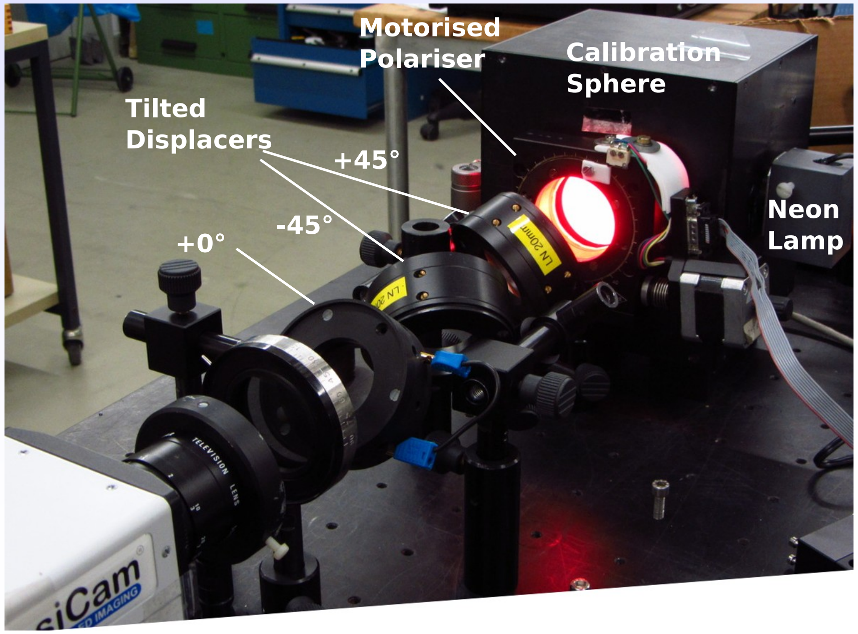

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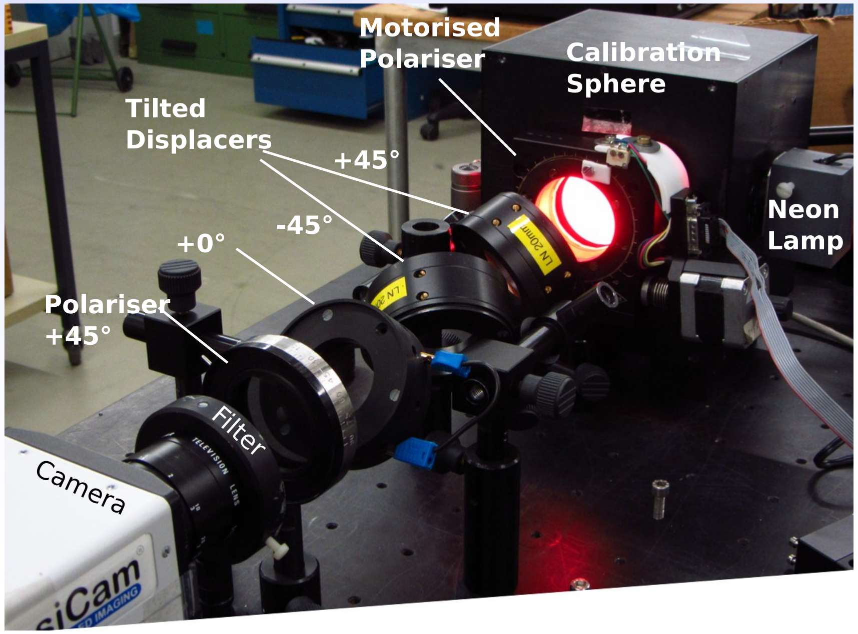
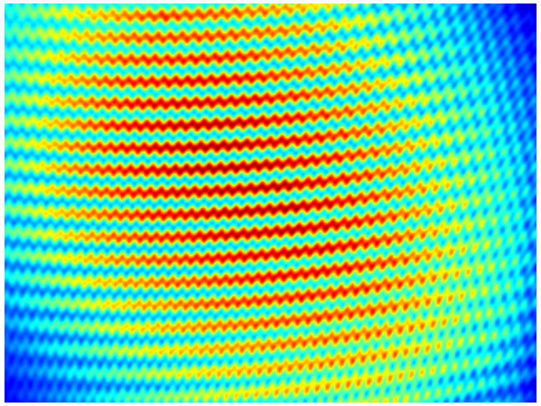


Image:



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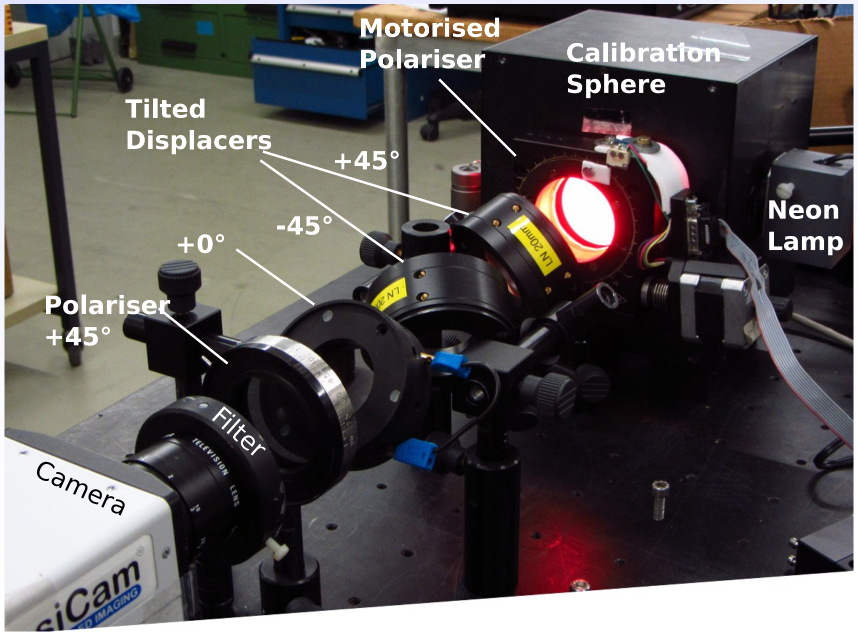

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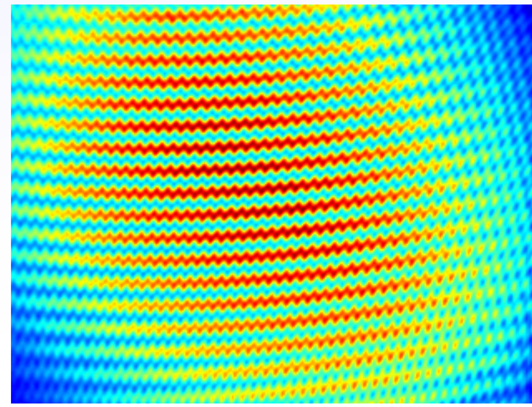
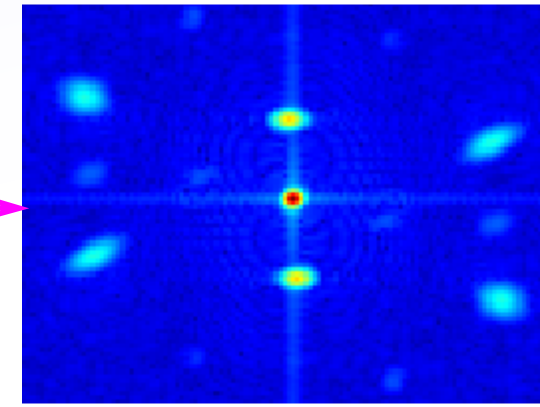


FFT:



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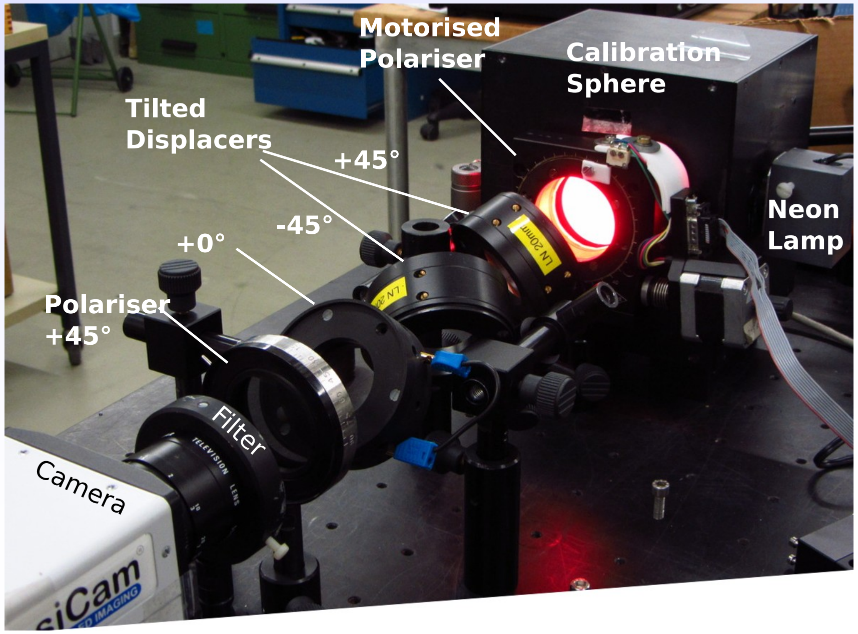

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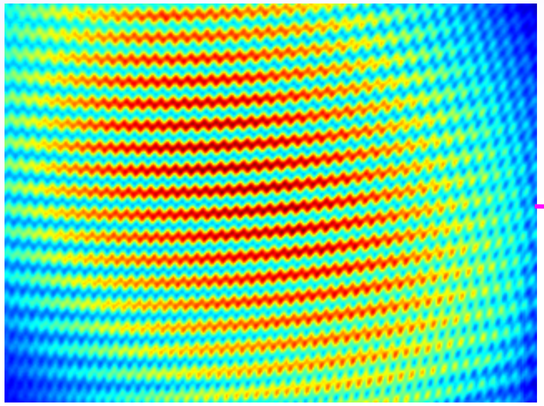

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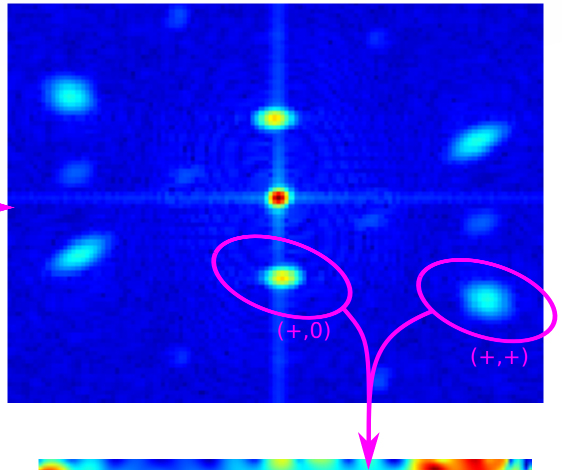

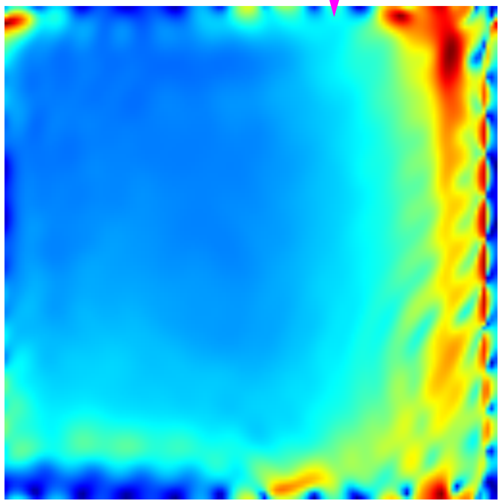

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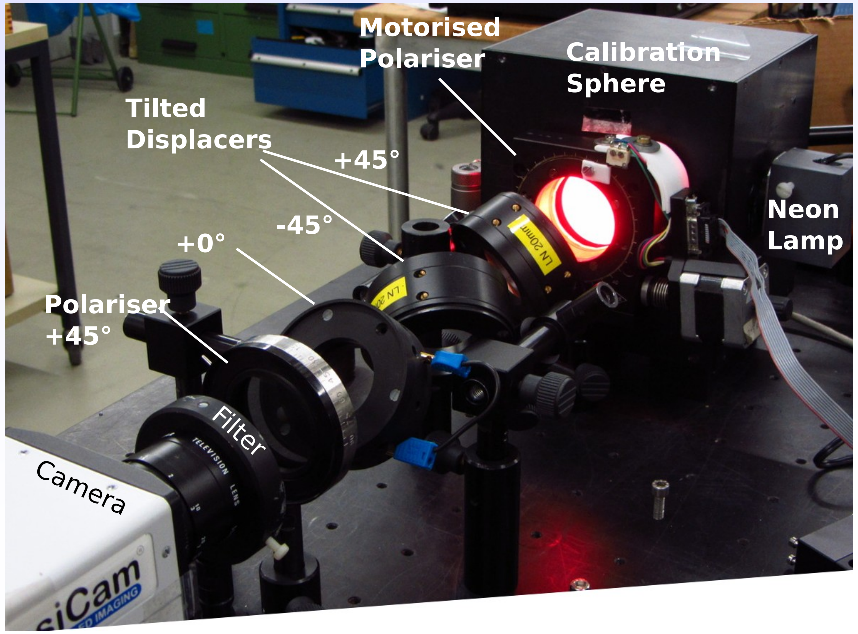

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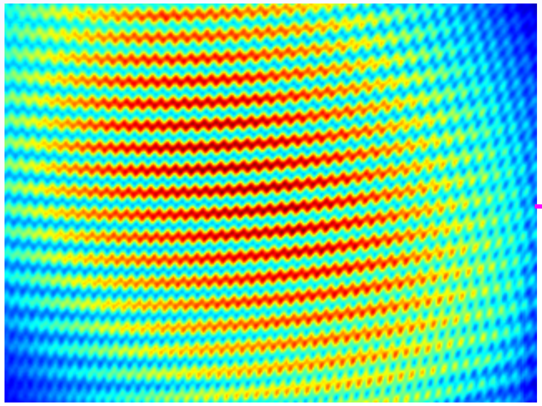

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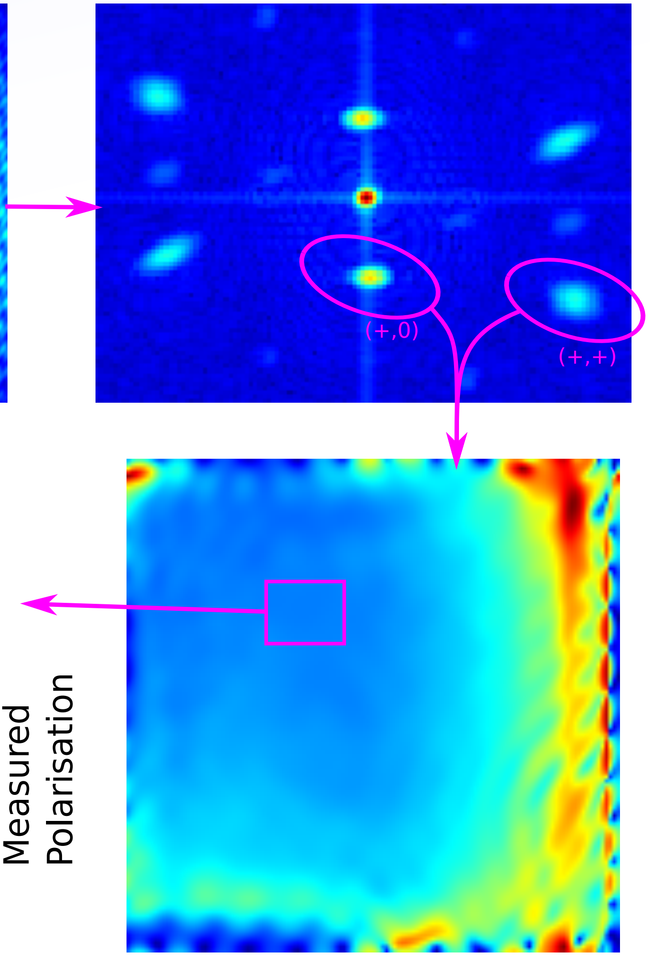

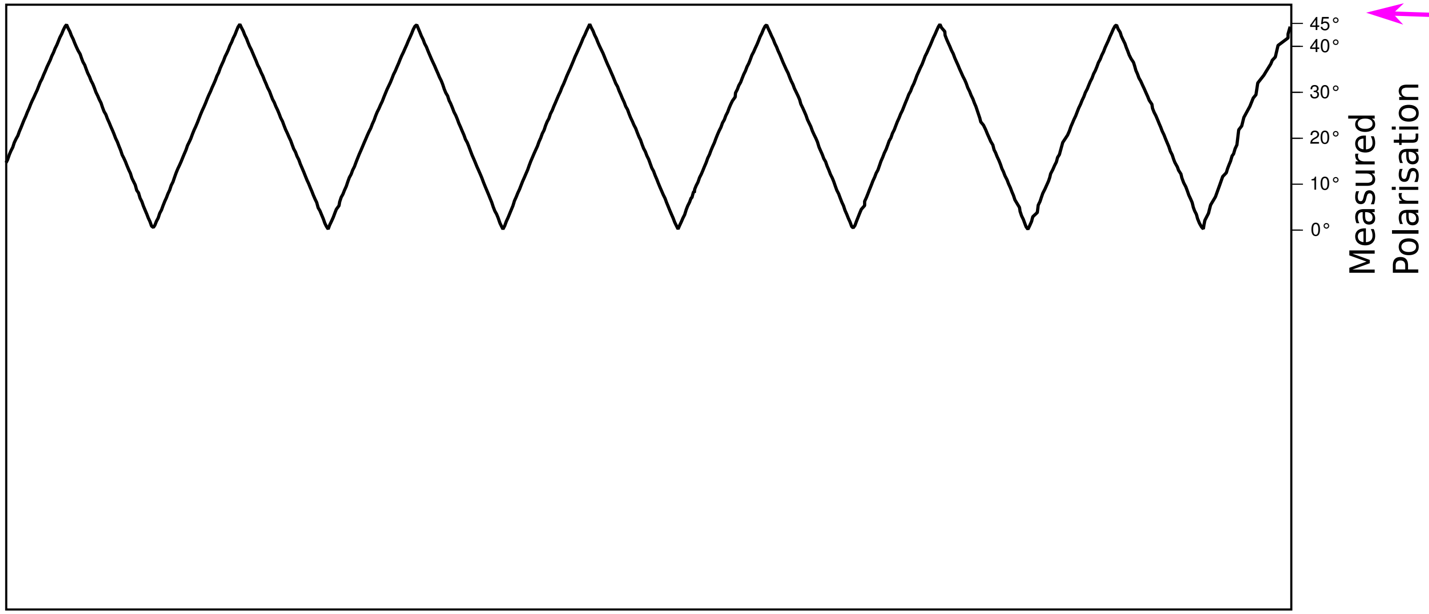

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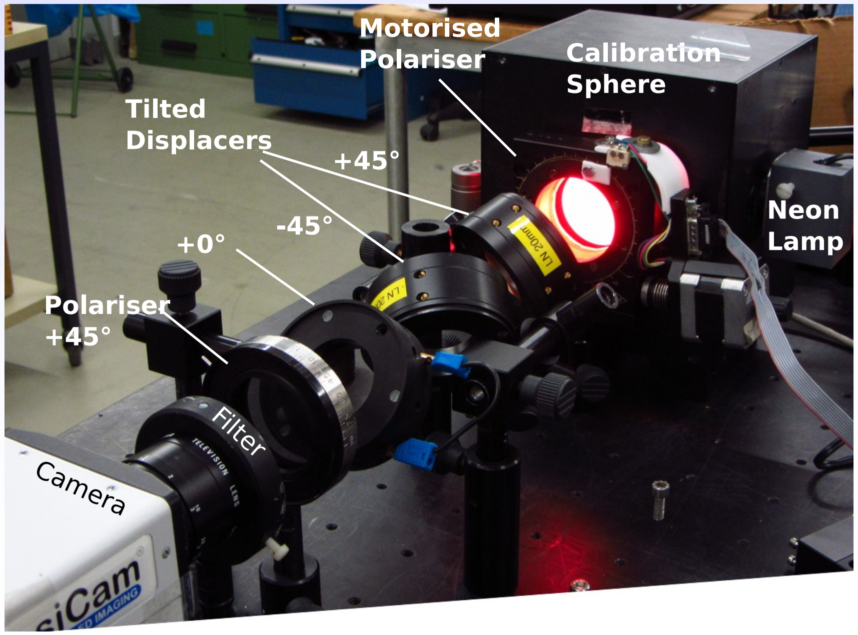

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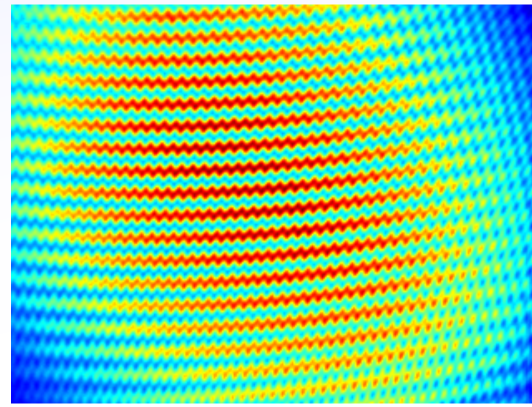

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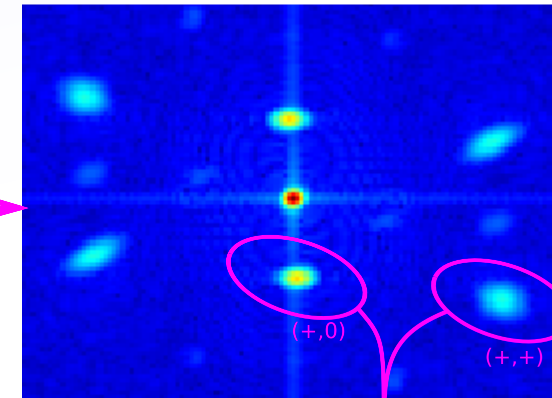

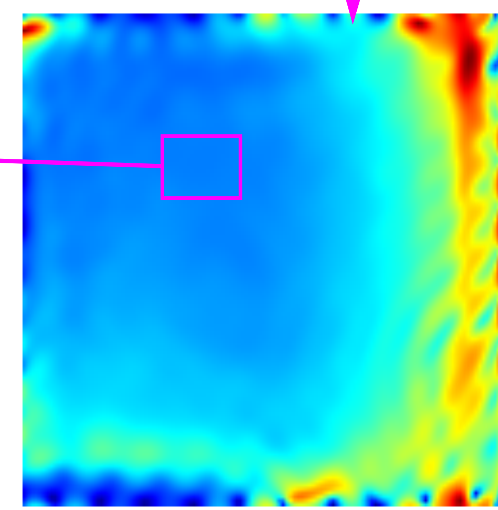

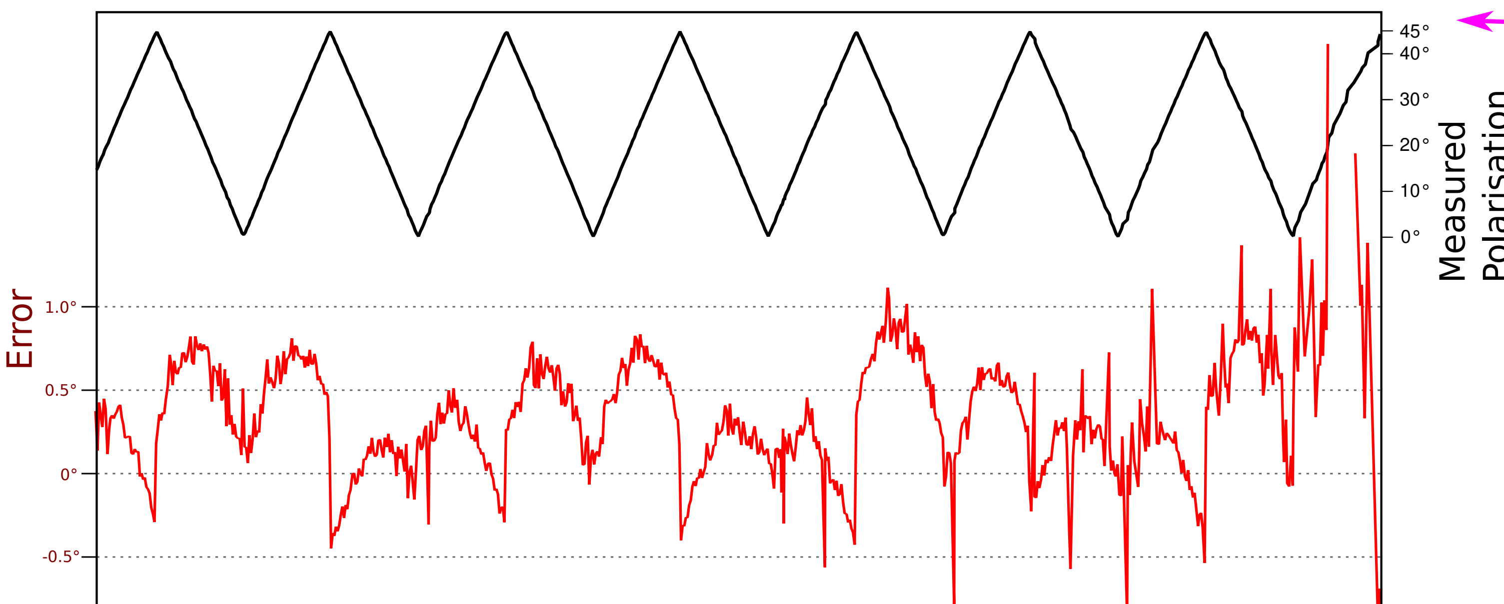

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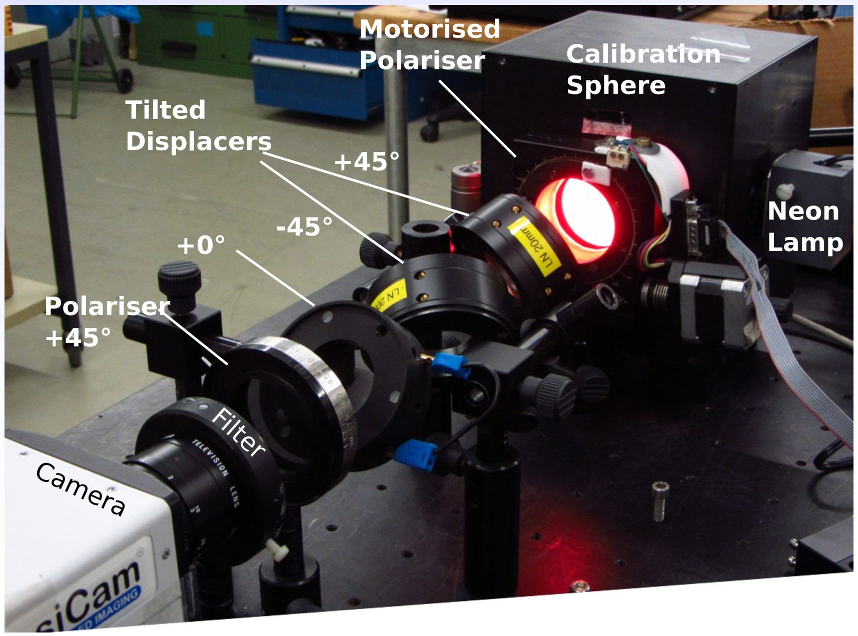

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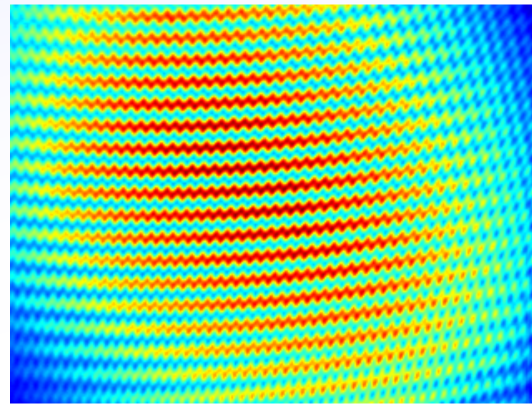

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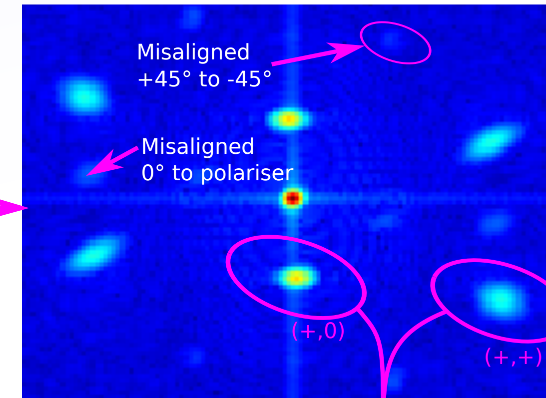
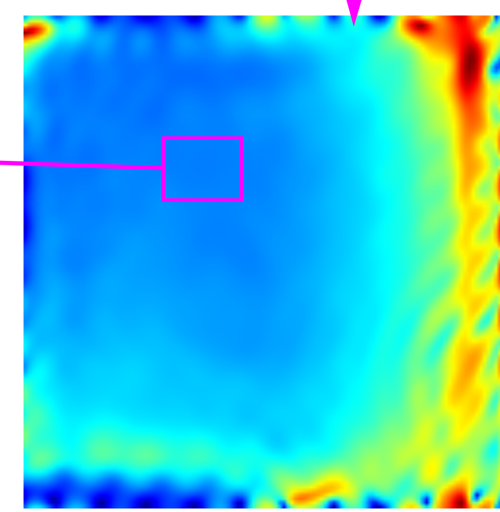
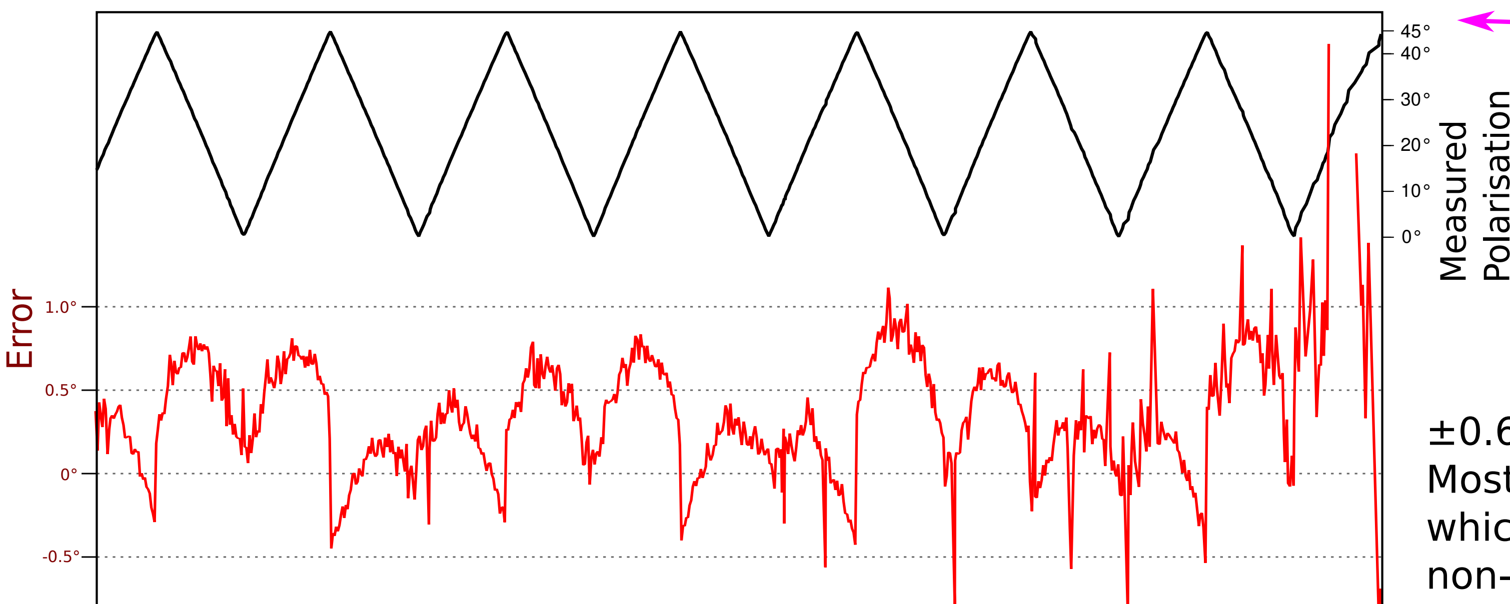
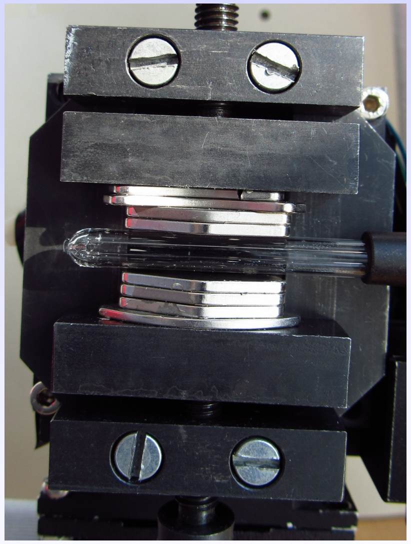


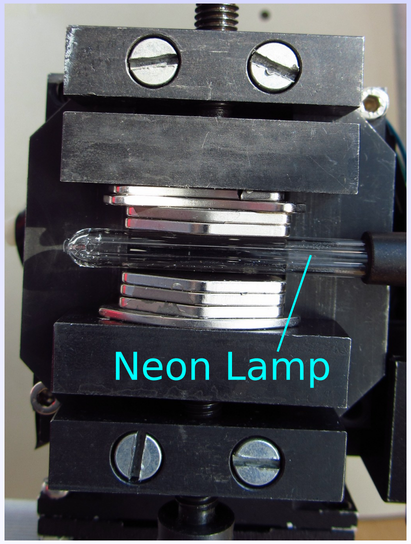




±0.6° is still 3x too much.
Most is from misalignment (I think) which will be easier with the non-tilted waveplates.

HDD Magnets Zeeman Lamp





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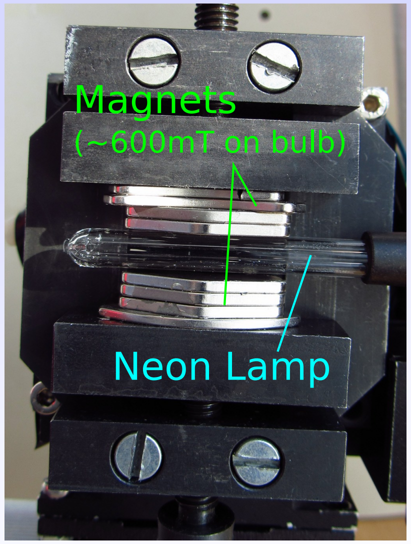

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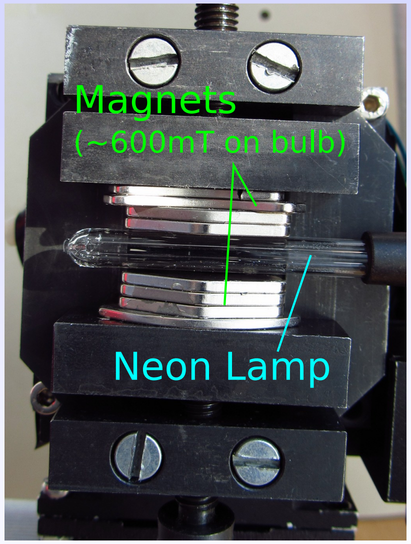
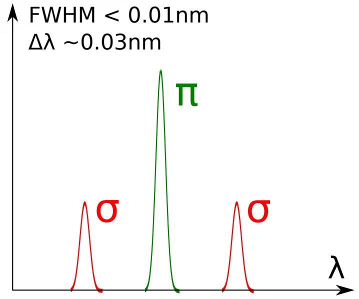


With 600mT of hard disk magnets across the bulb, the 720nm neon line is Zeeman split by about ±0.03nm. As with MSE, light is net unpolarised so we need to exploit the coherence.



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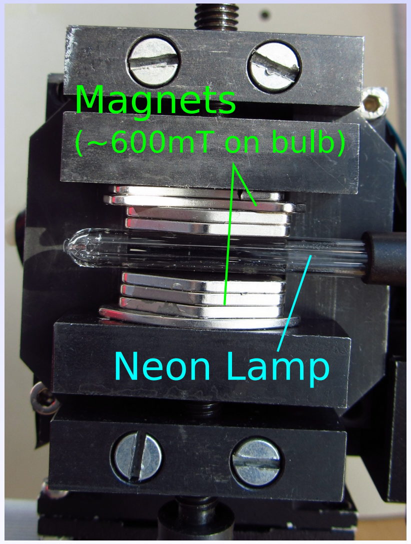

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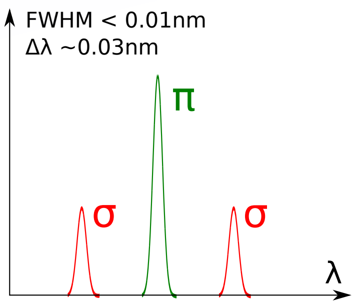

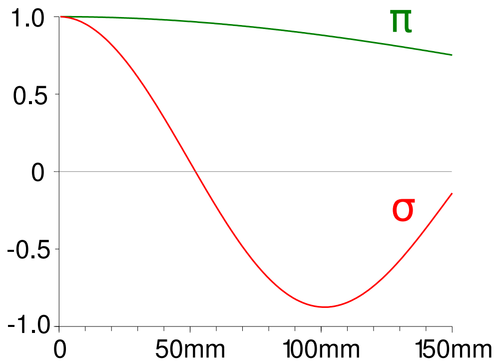

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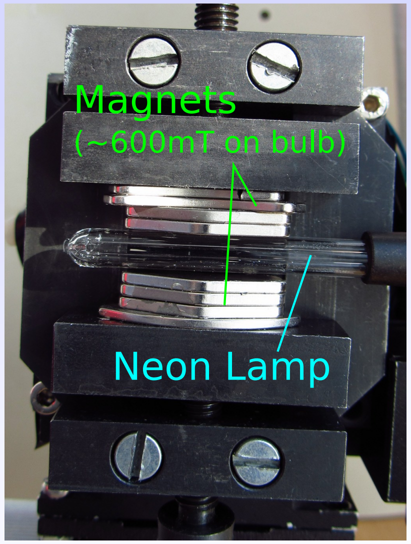

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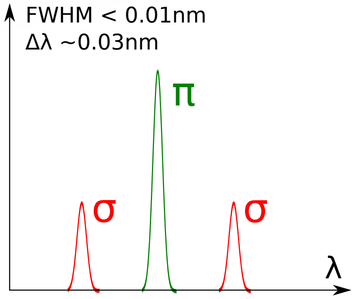

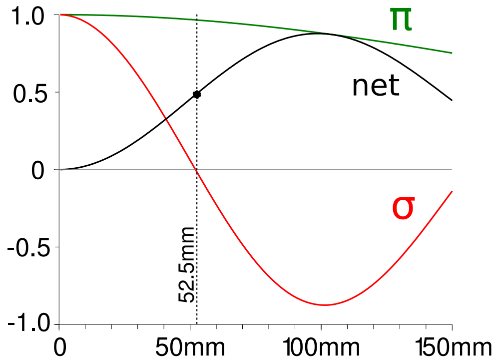

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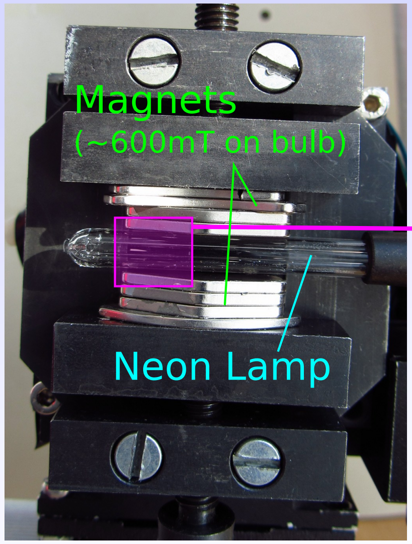

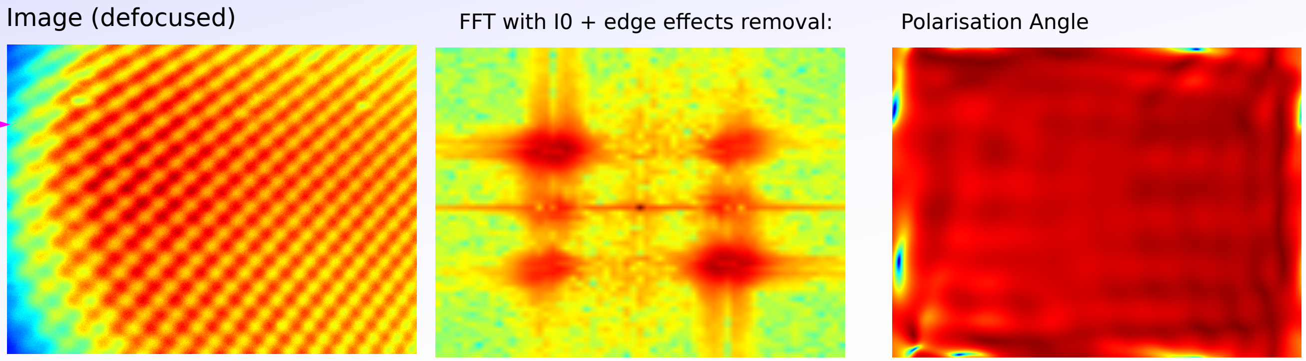

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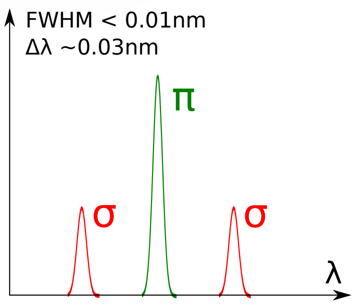

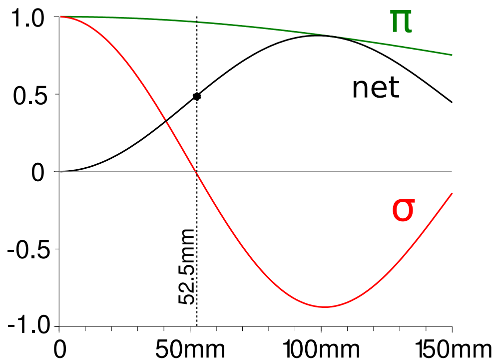

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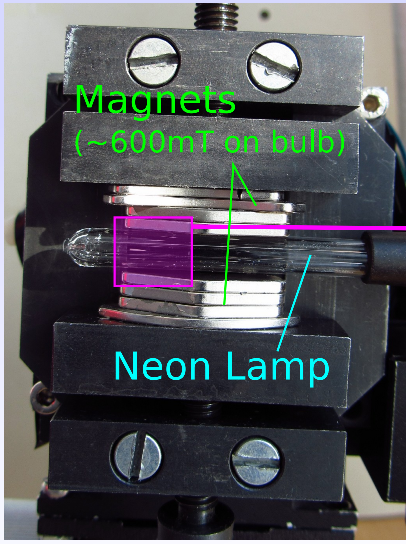
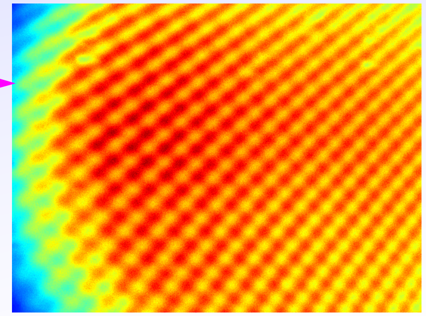
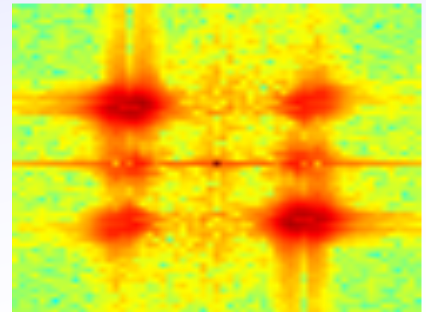


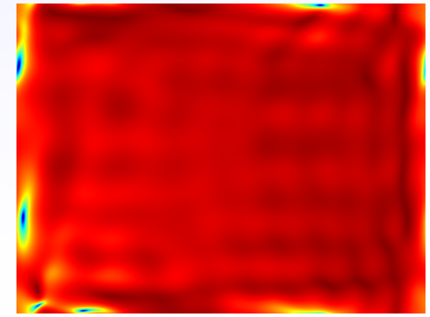
Image (defocused)



FFT with I0 + edge effects removal:



Polarisation Angle



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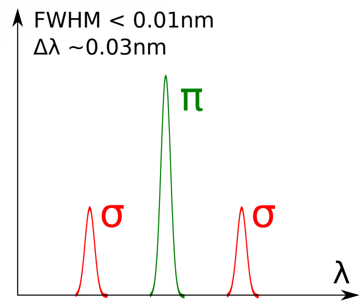

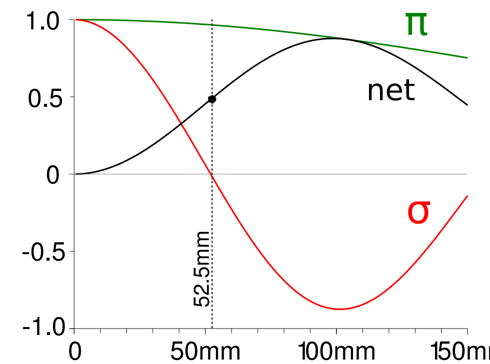

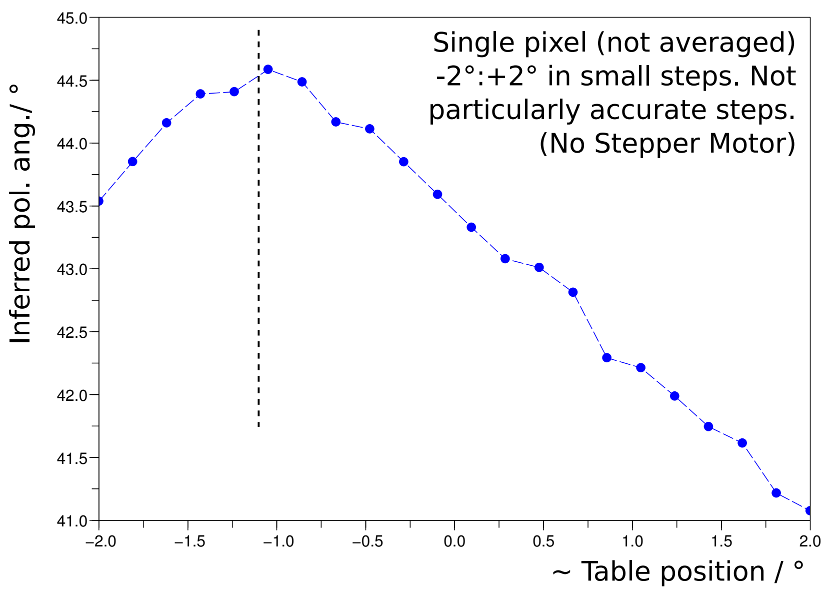

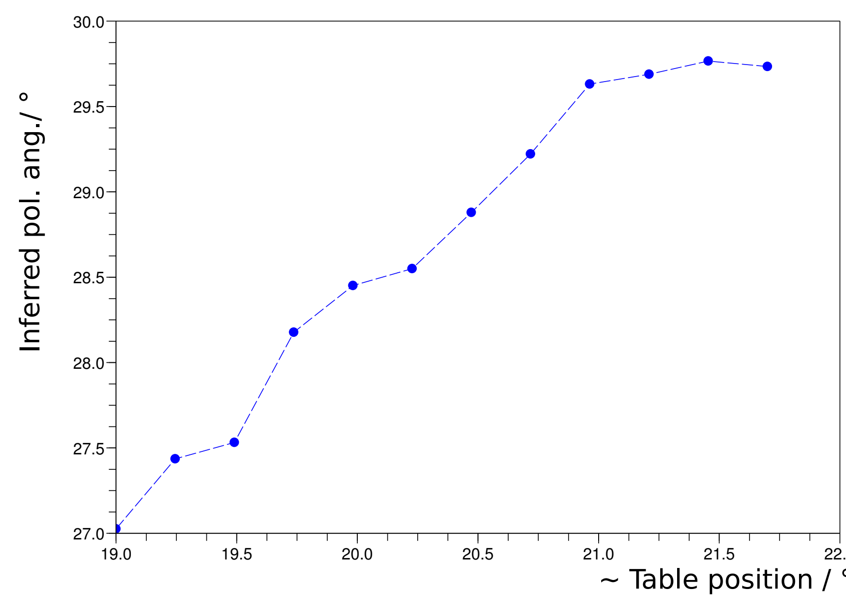

IMSE Optics Design

The AUG IMSE system will couple to the existing MSE optics:
The design requires knowing the image that the existing optics will give, and how to optimally couple to it.

Developed a 3D ray tracer:
- Arbitrary multi-path ray trees.
- Models of basic camera lenses
 (Canon, Nikon, Schneider).
- Aspheric surfaces.
- Optimisation of all properties
- Polarisation state tracking.
- PSF and Imaging characterisation.
- Incoherent and/or coherent polarisation addition.
- 3D VRML output for rays, objects and polarisations
 (display e.g. in Sergei's 'wendel' program)
- Birefringent media (incl. E/O ray path splitting)

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The design requires knowing the image that the existing optics will give, and how to optimally couple to it.

Developed a 3D ray tracer:
- Arbitrary multi-path ray trees.
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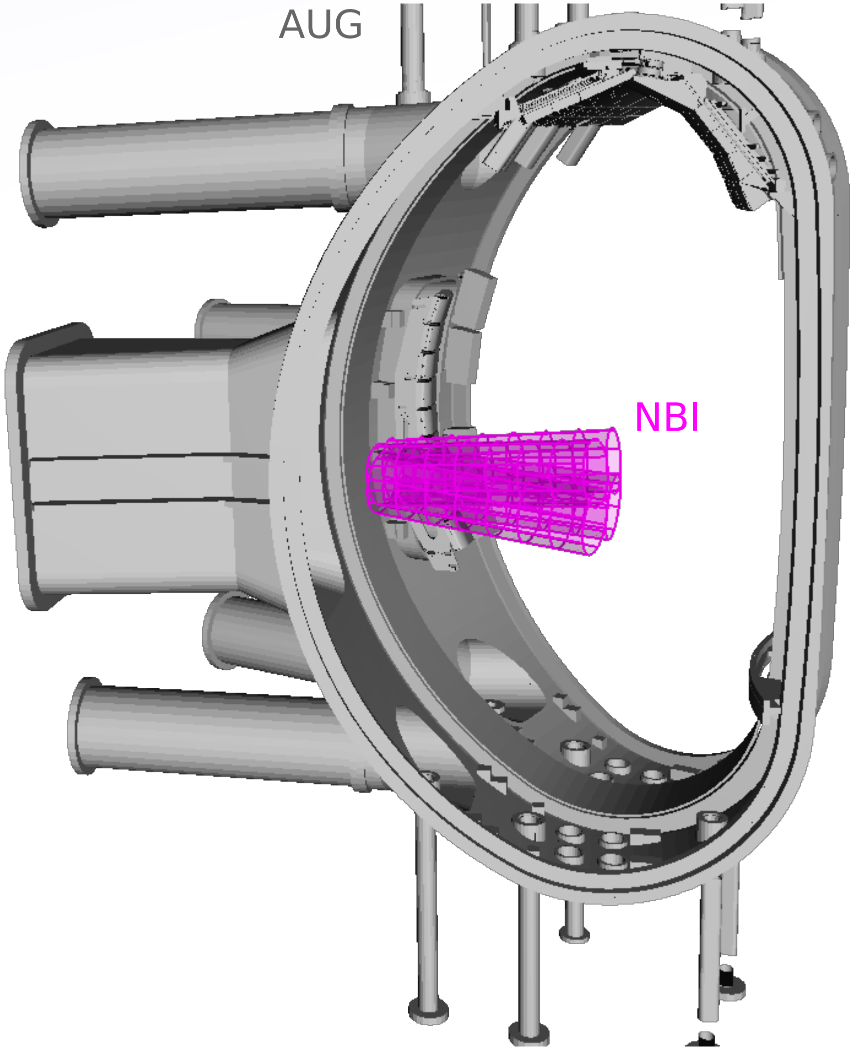
- Aspheric surfaces.
- Optimisation of all properties
- Polarisation state tracking.
- PSF and Imaging characterisation.
- Incoherent and/or coherent polarisation addition.
- 3D VRML output for rays, objects and polarisations (display e.g. in Sergei's 'wendel' program)
- Birefringent media (incl. E/O ray path splitting)



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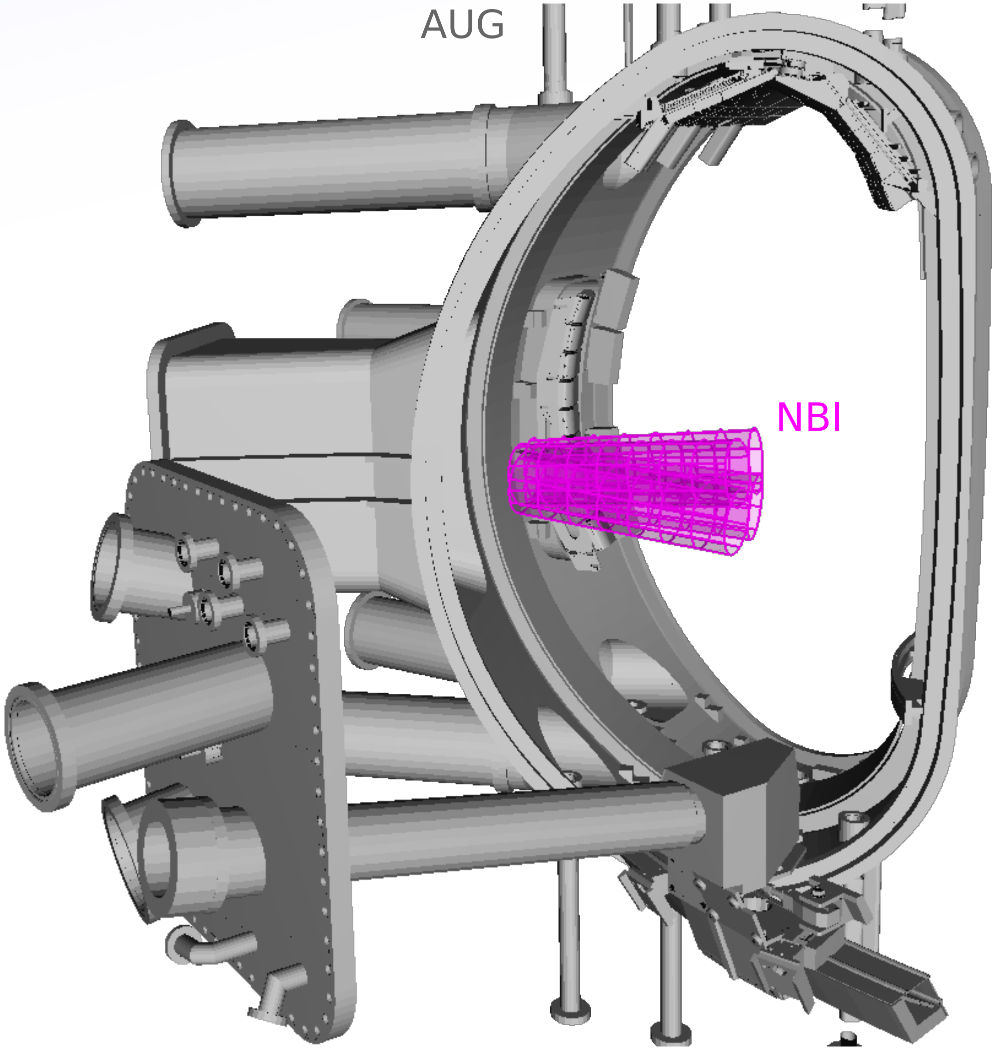

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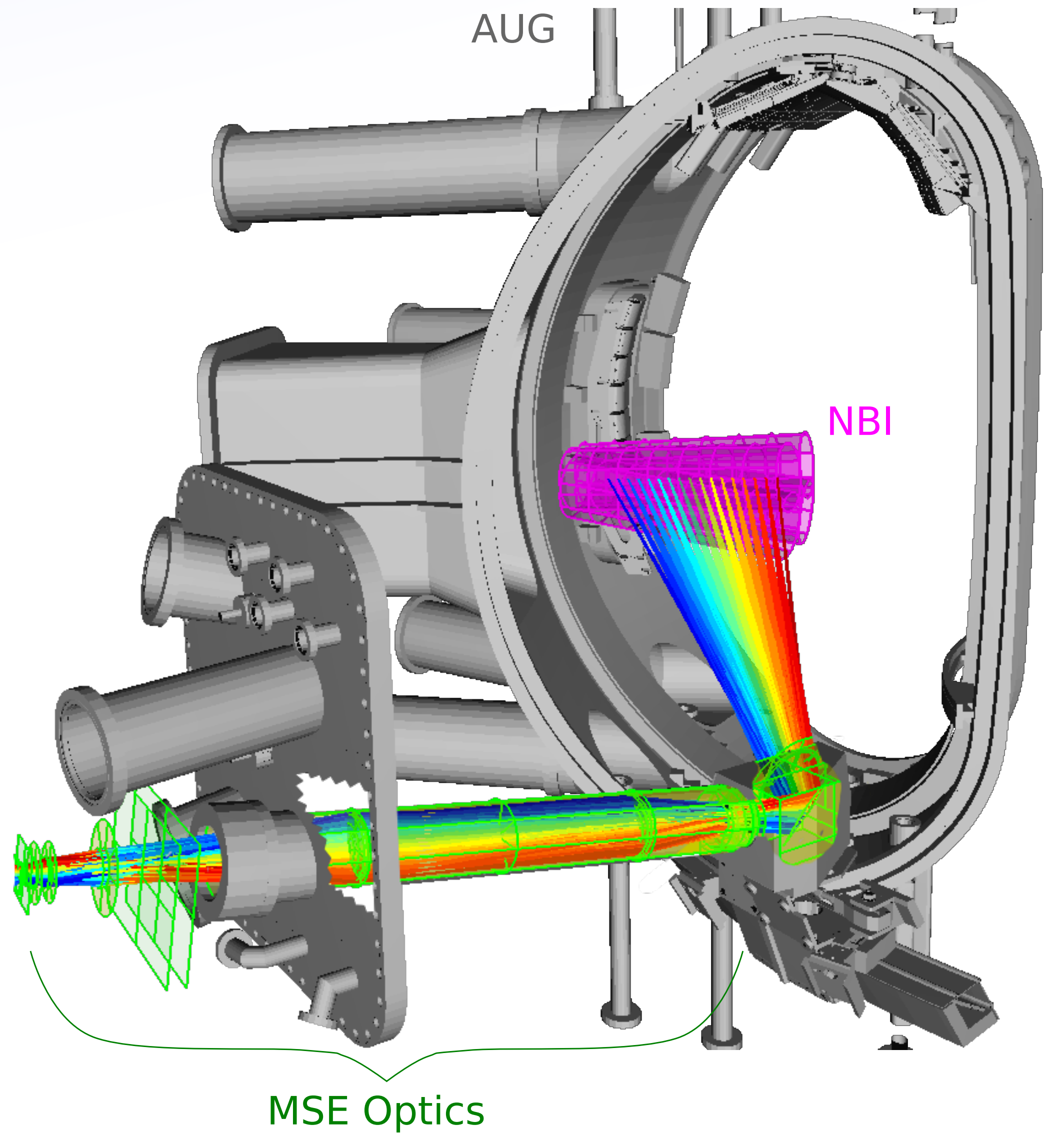

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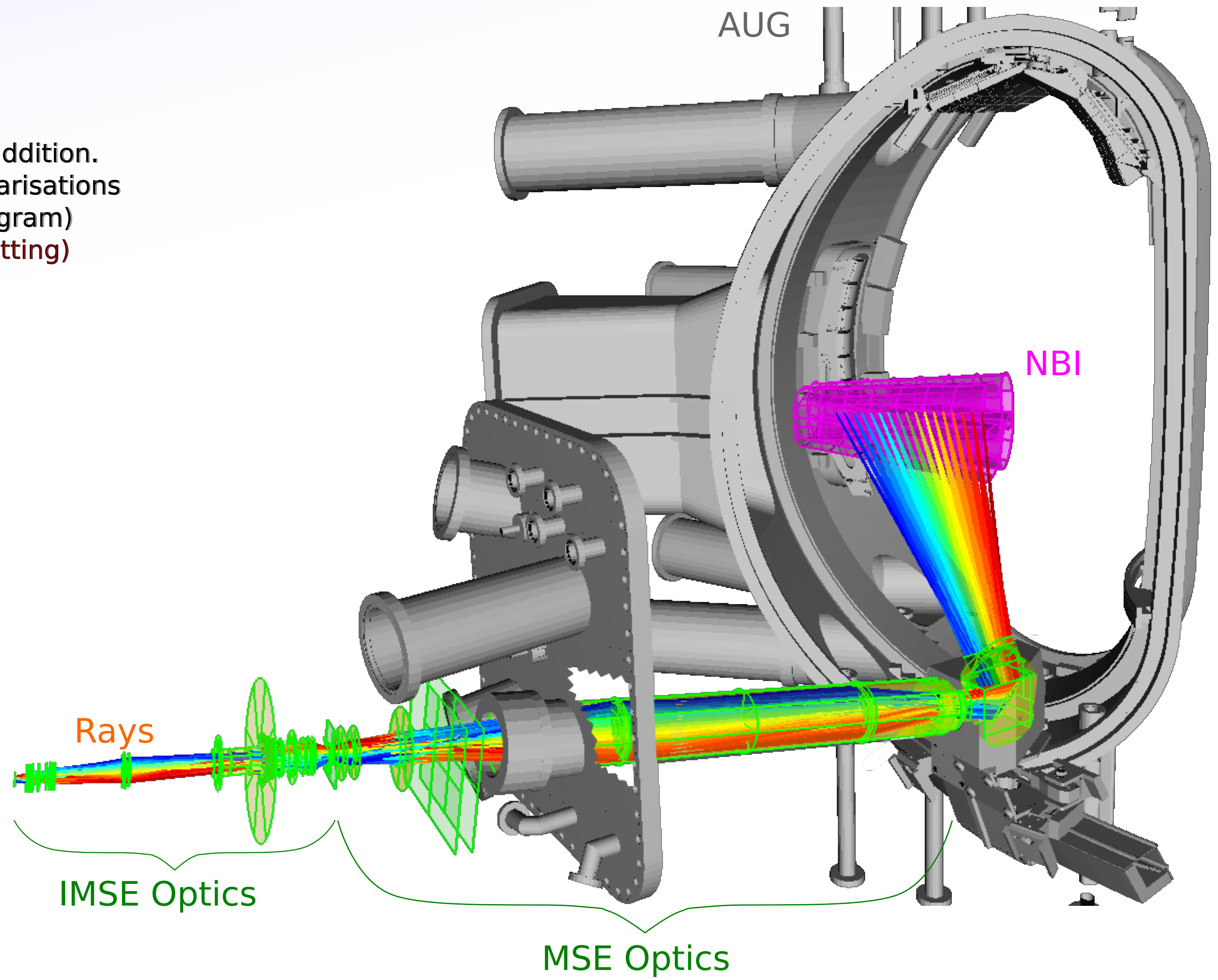

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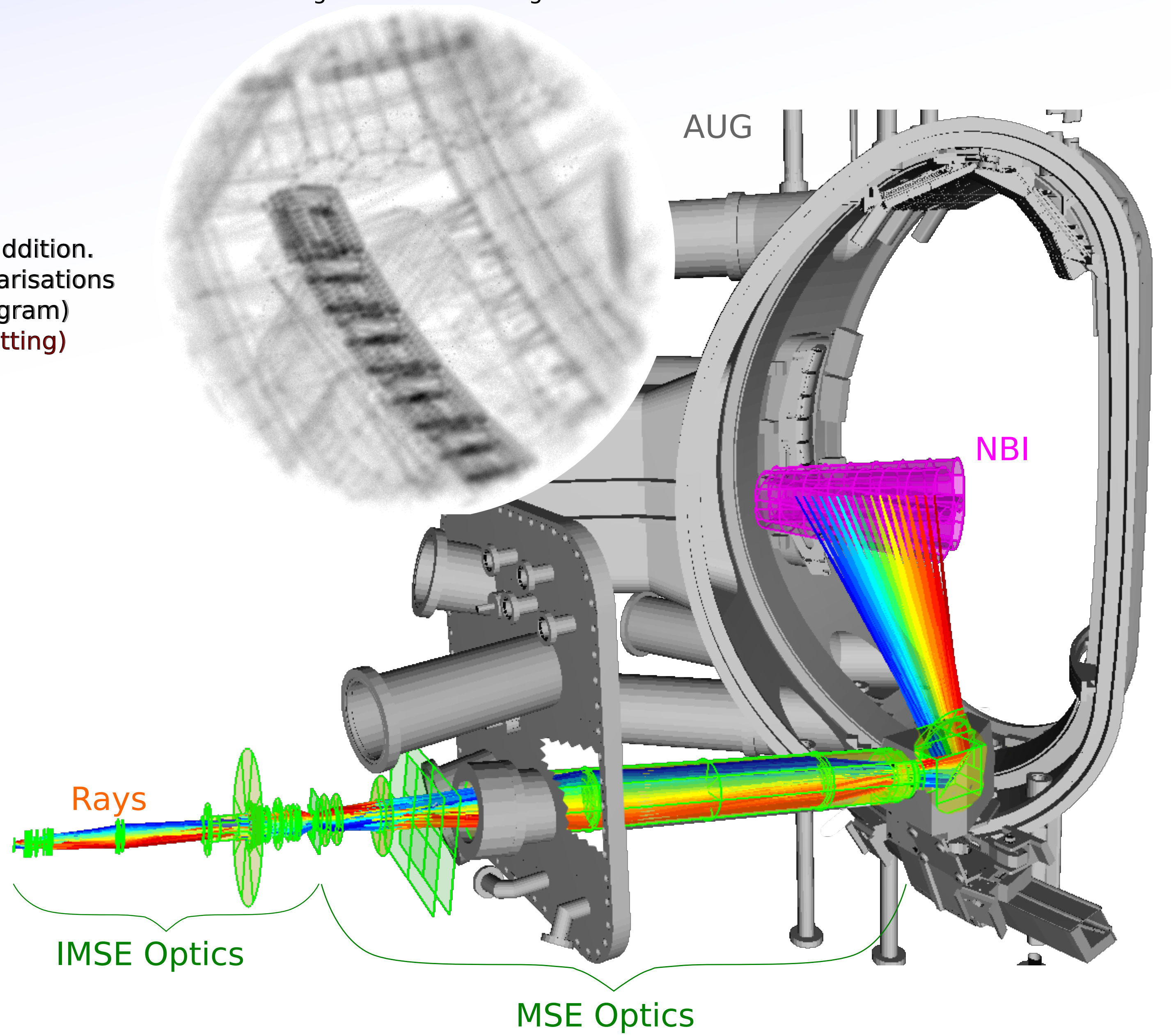
Rendering of beams + background



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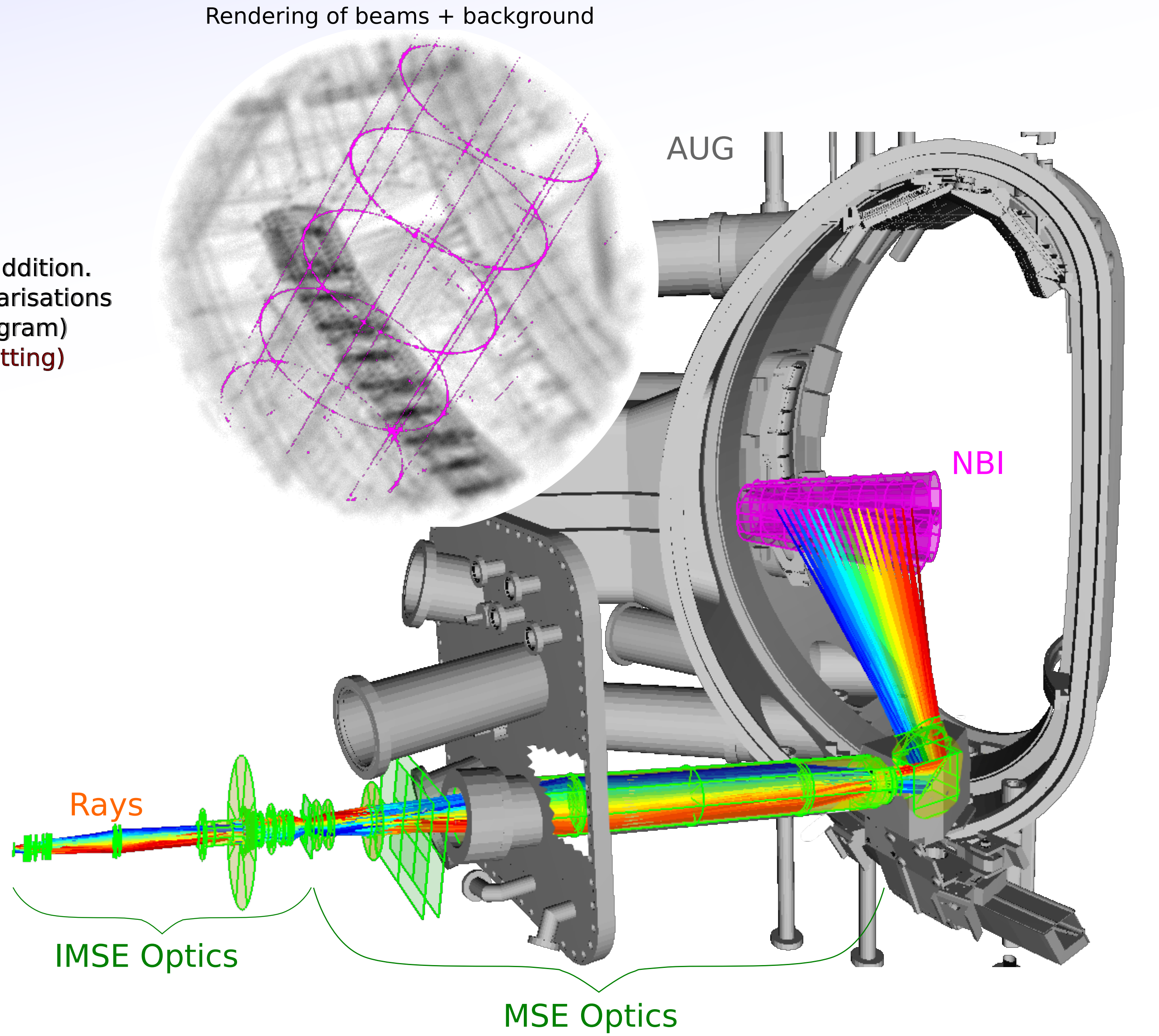

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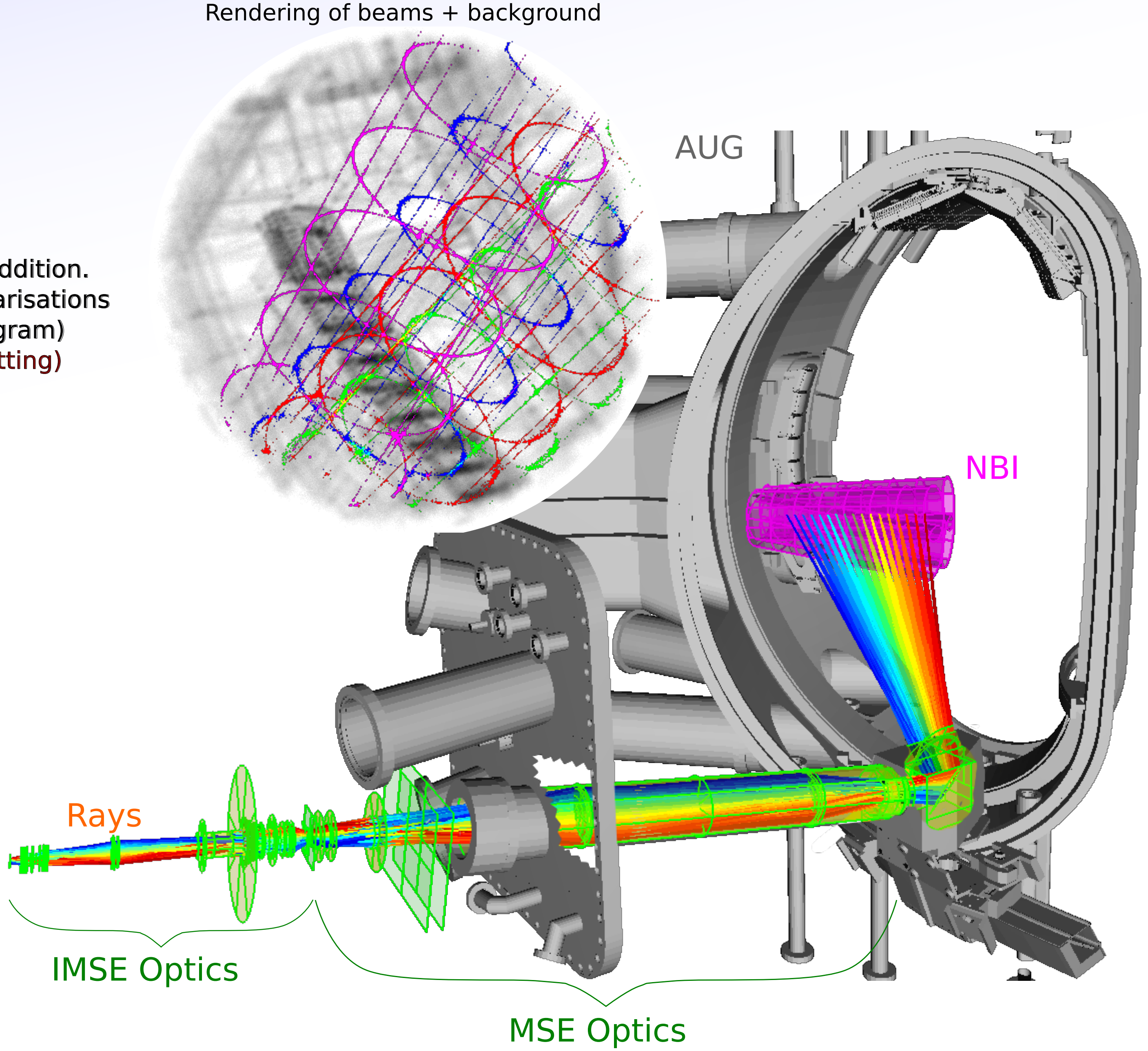

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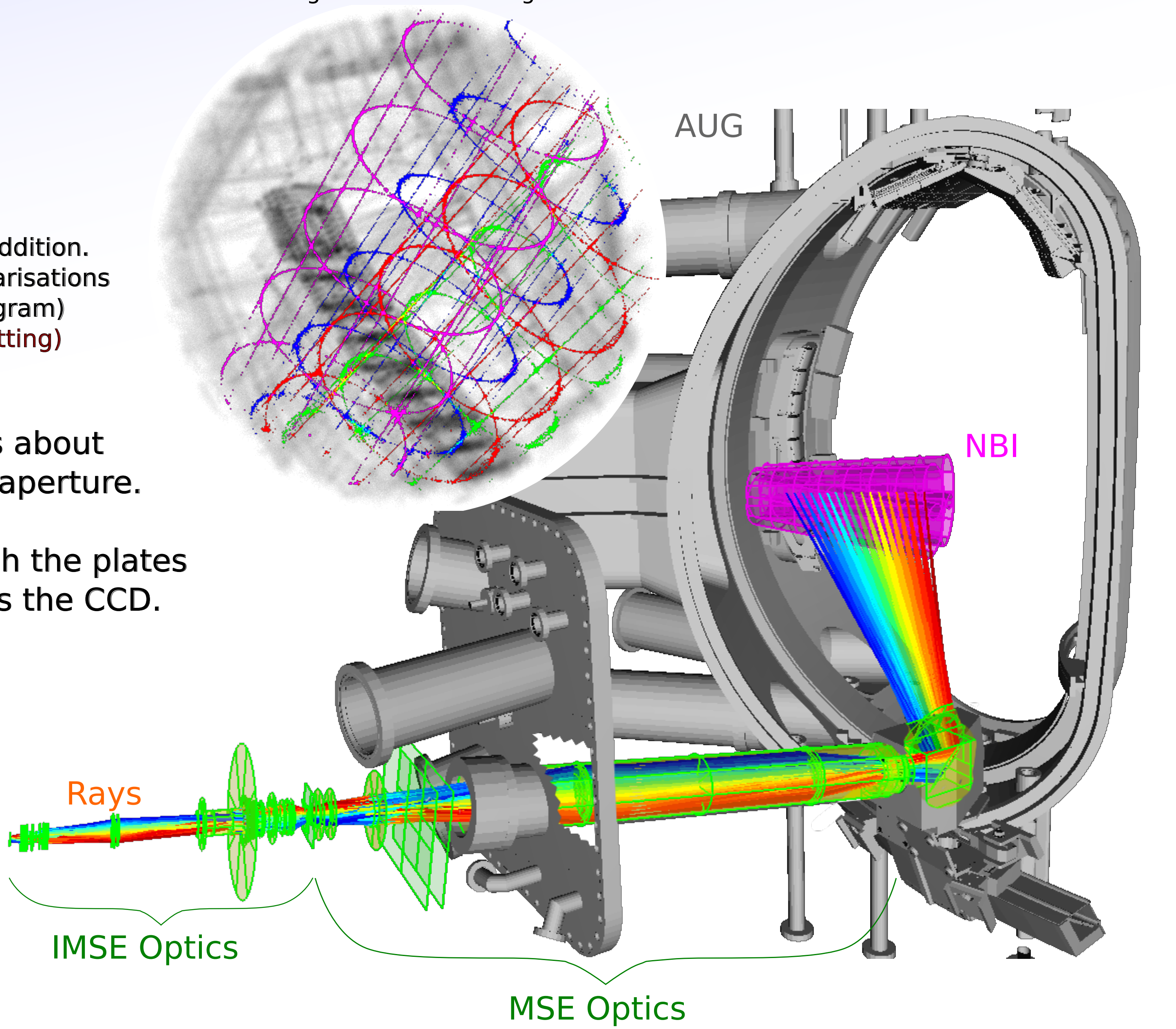
The ray tracer says:

Delivery to back of MSE system is about 7% of total light hitting the first aperture.

For the first IMSE design (for which the plates were ordered) only 0.6% reaches the CCD.

Rendering of beams + background



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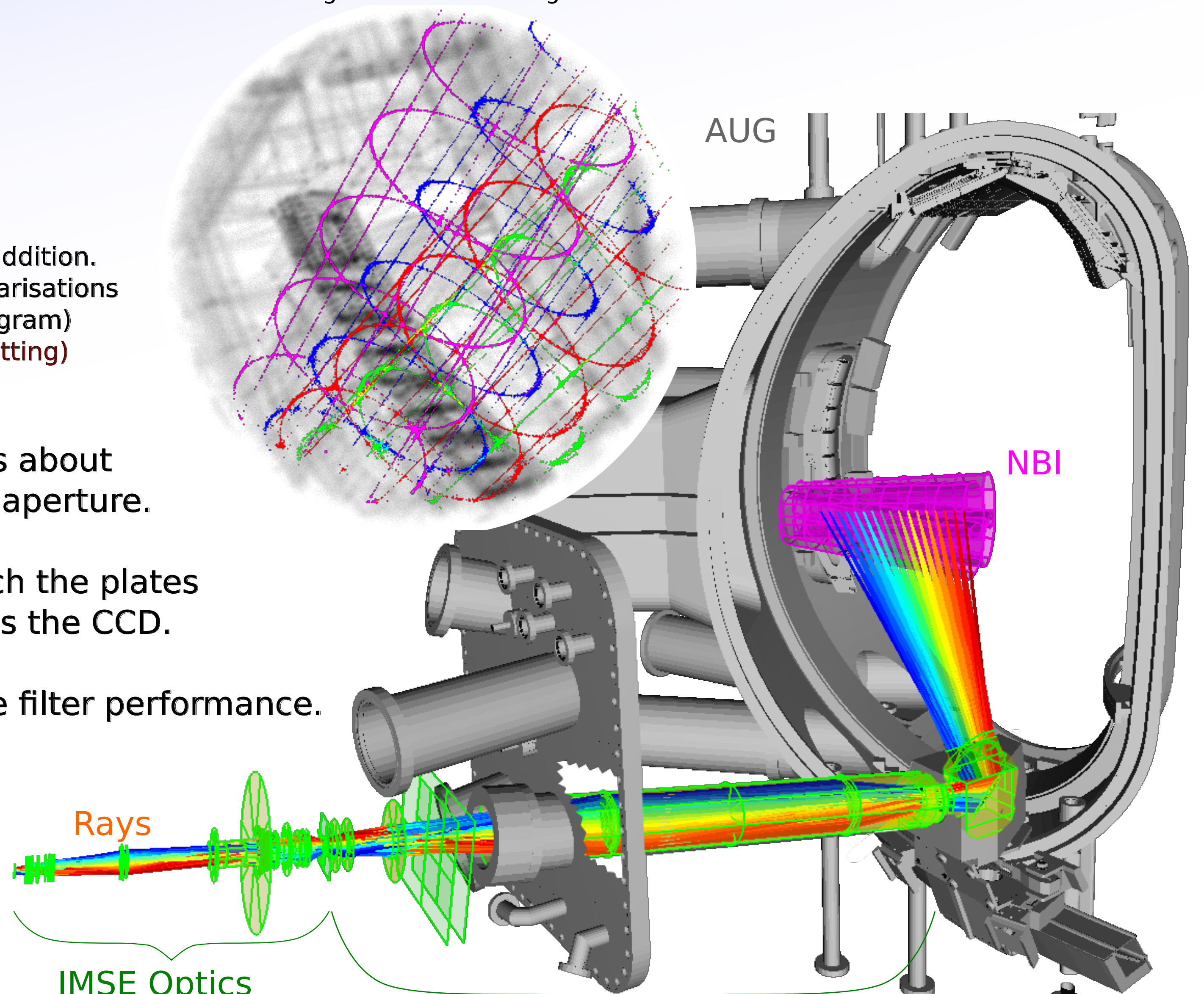

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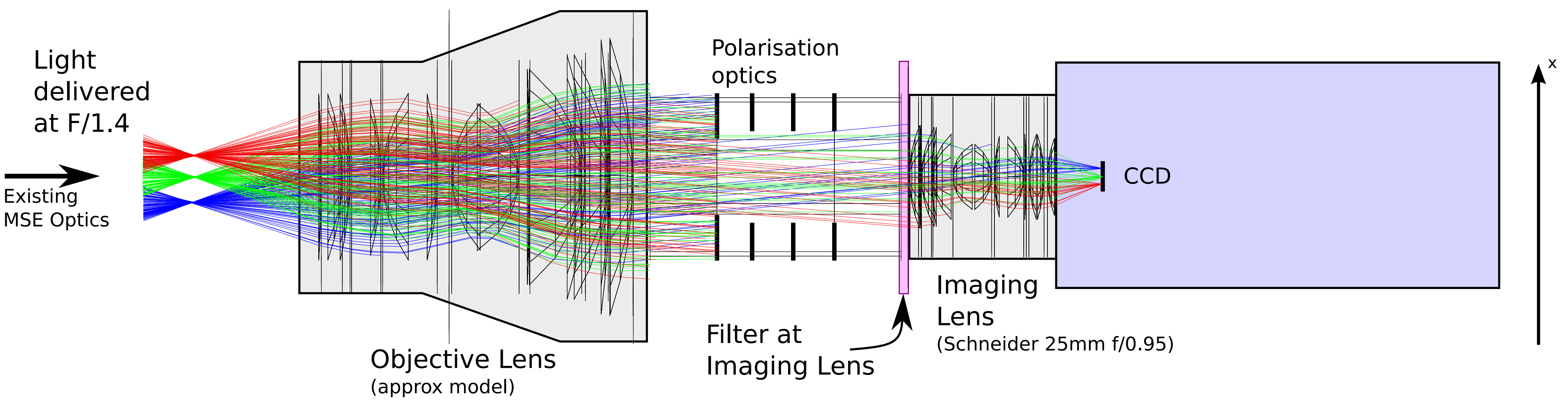
More is possible, but it effects the filter performance.

Need to balance:

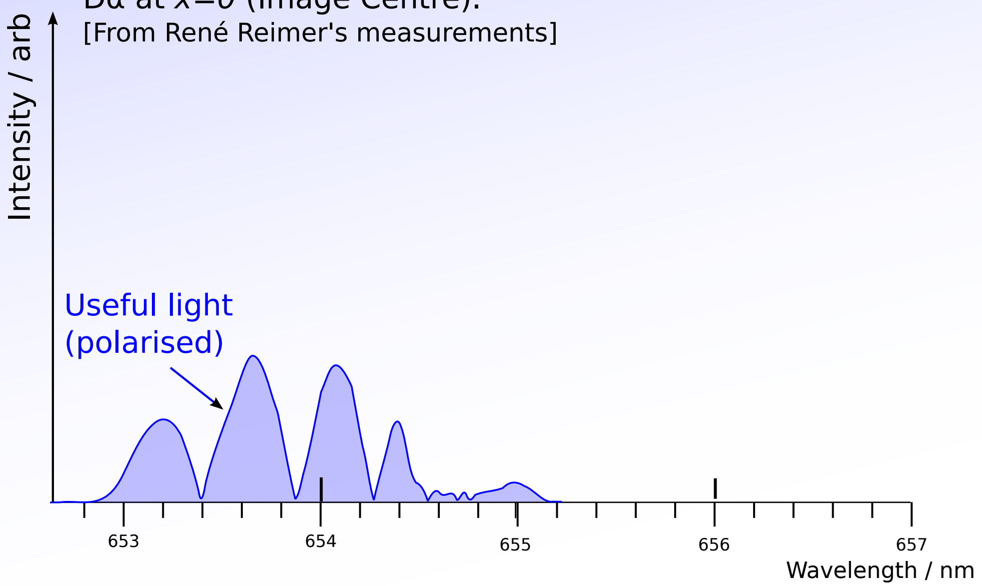
Throughput
Filter shift
Vignetting
Fringe frequency / linearity
Fringe imaging quality
Flexibility
Optics size/cost

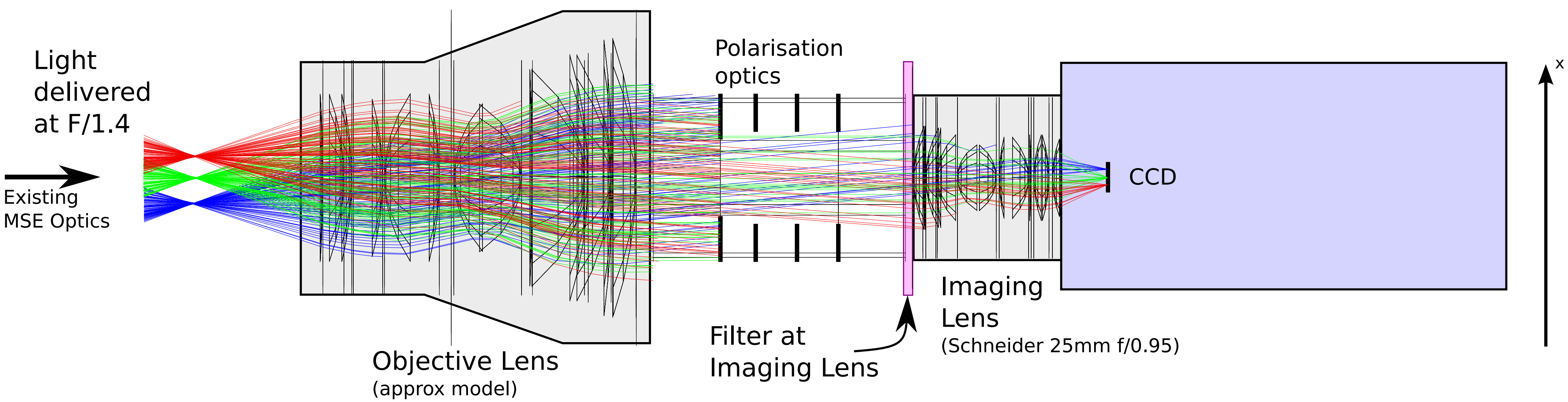
IMSE Design - Spectrum and Filter



IMSE Design - Spectrum and Filter

Spectrum including background
Dα at *x=0* (Image Centre).
[From René Reimer's measurements]





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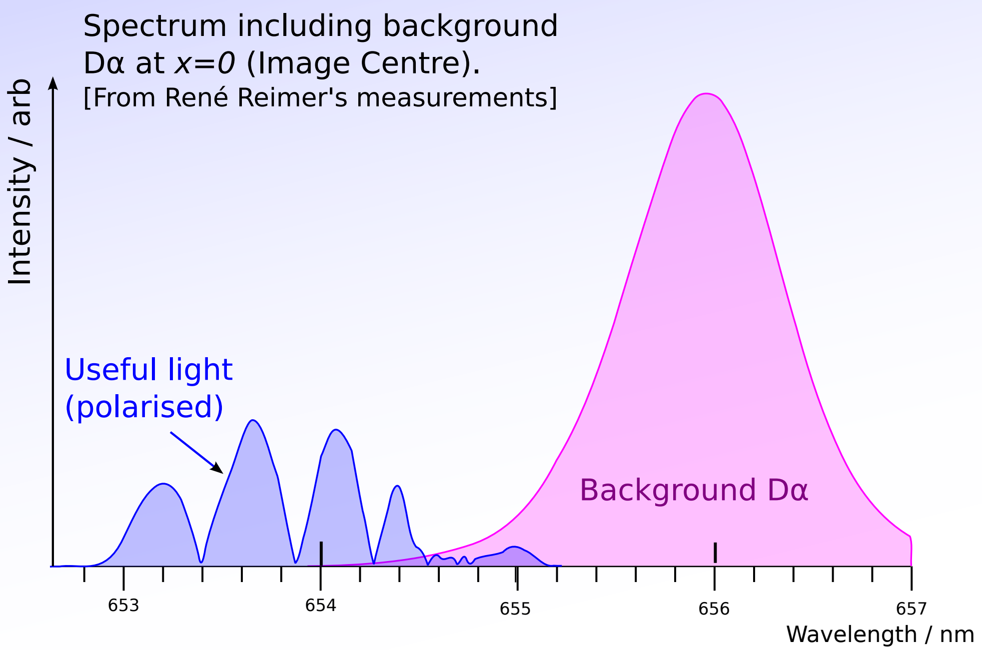

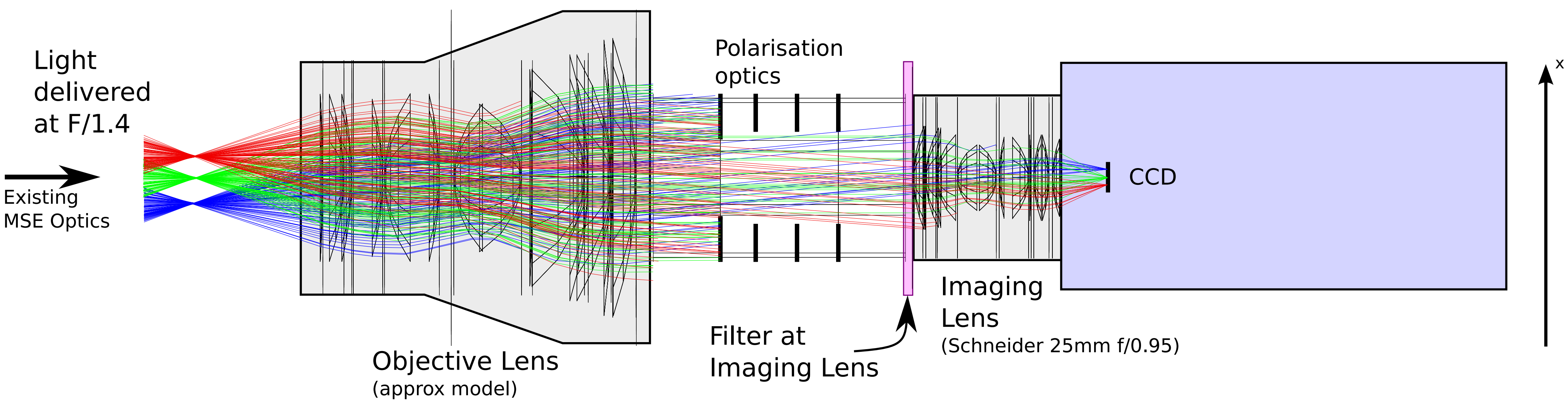

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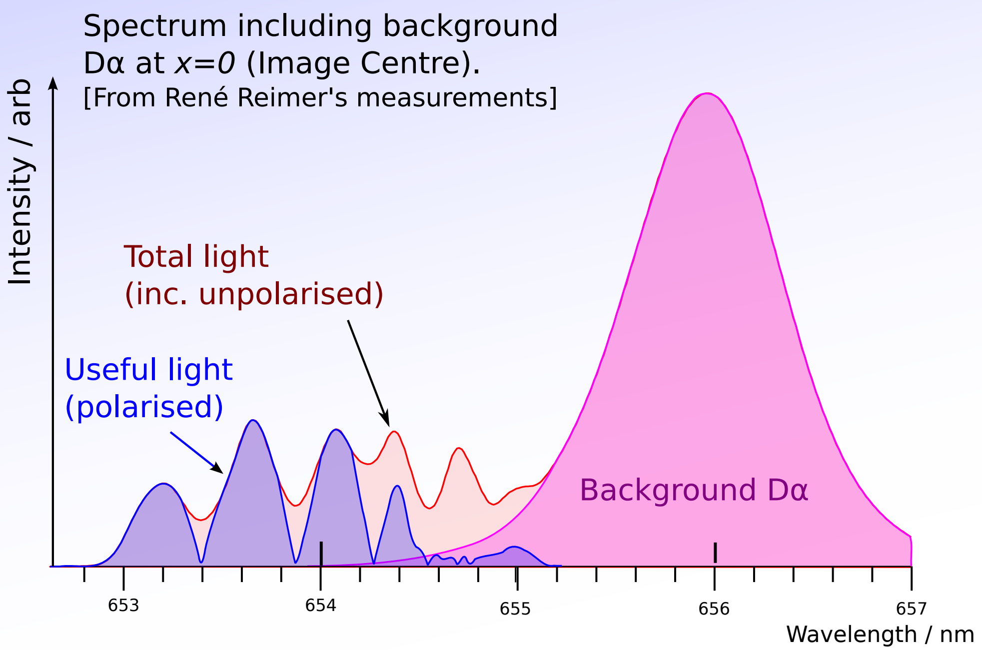

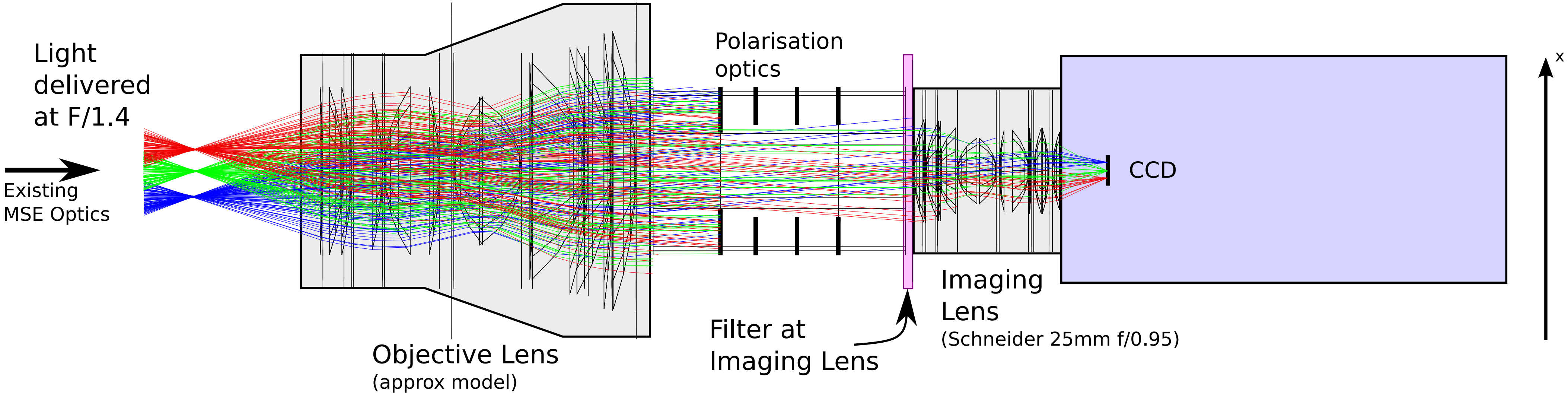

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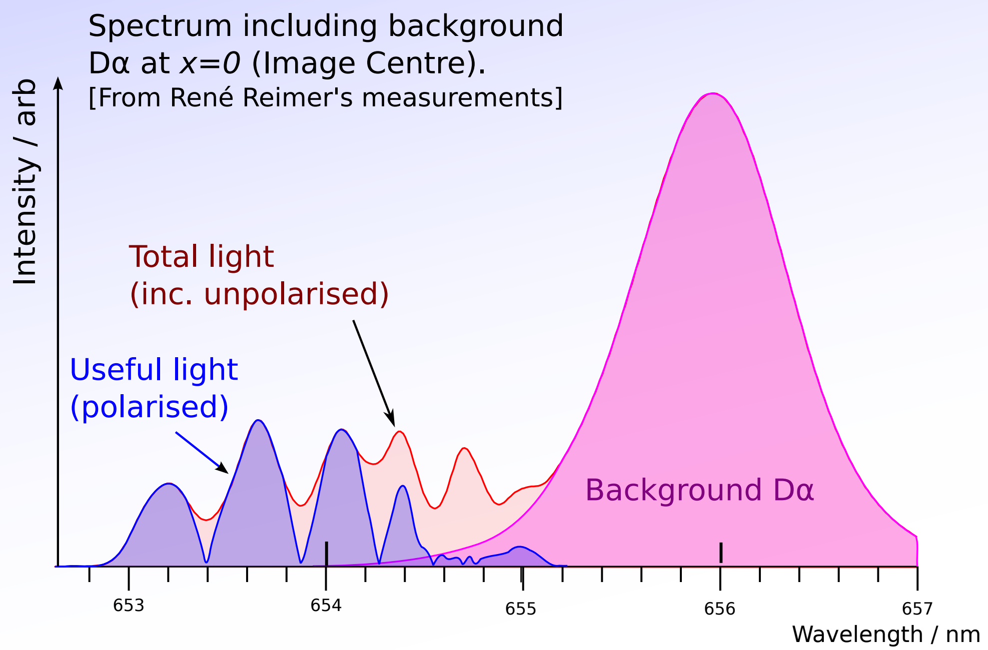

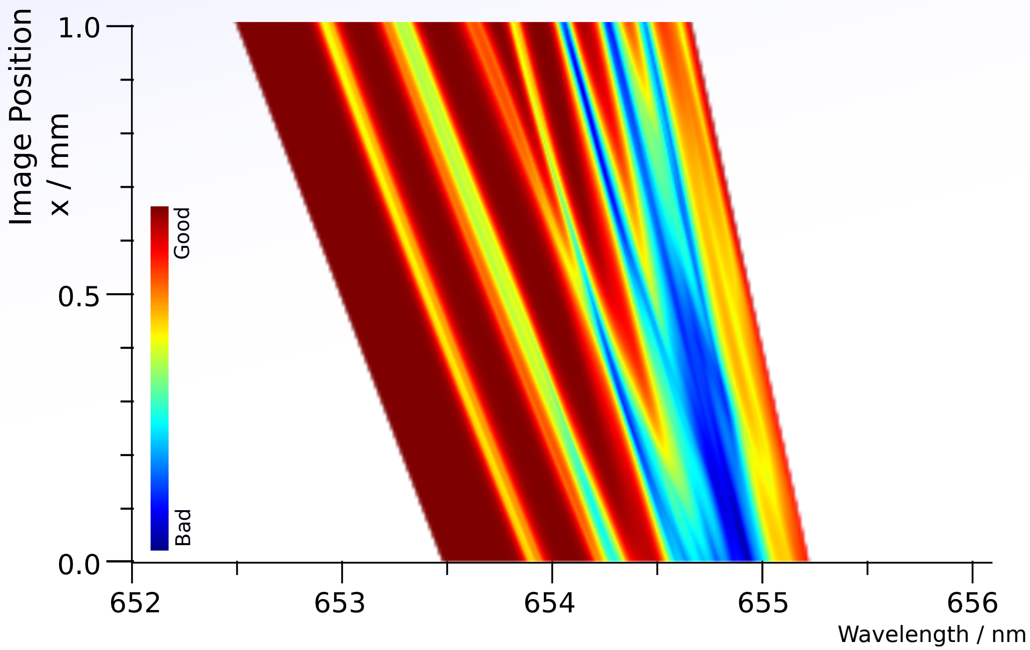

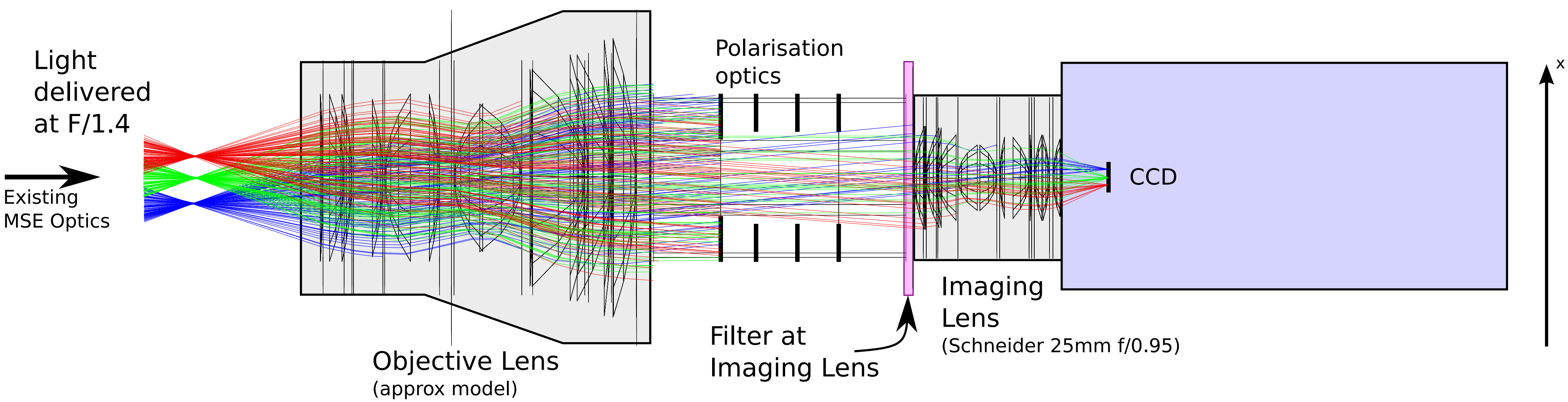

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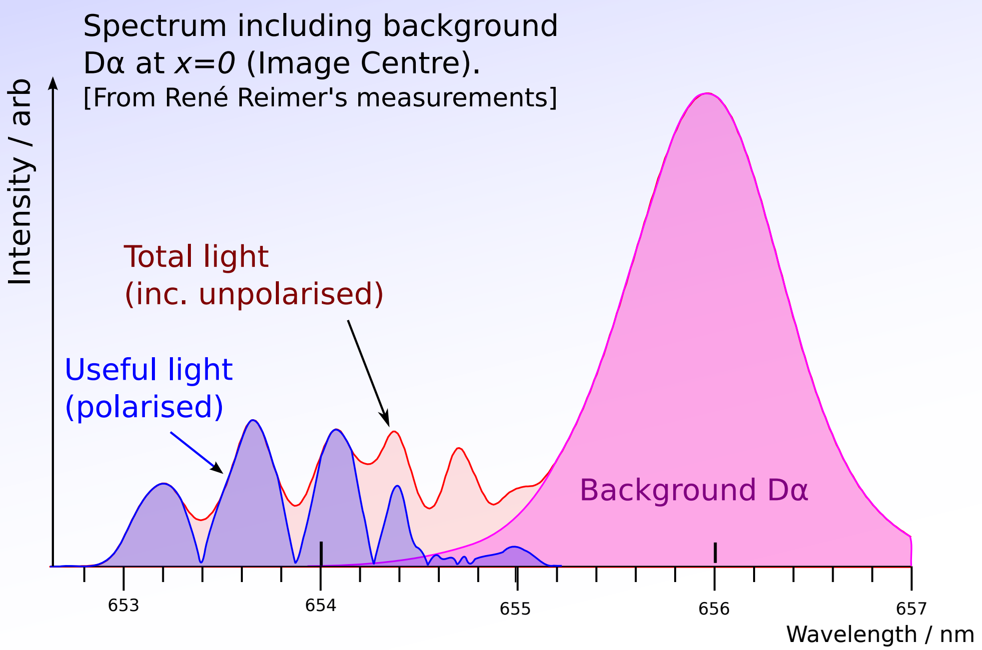

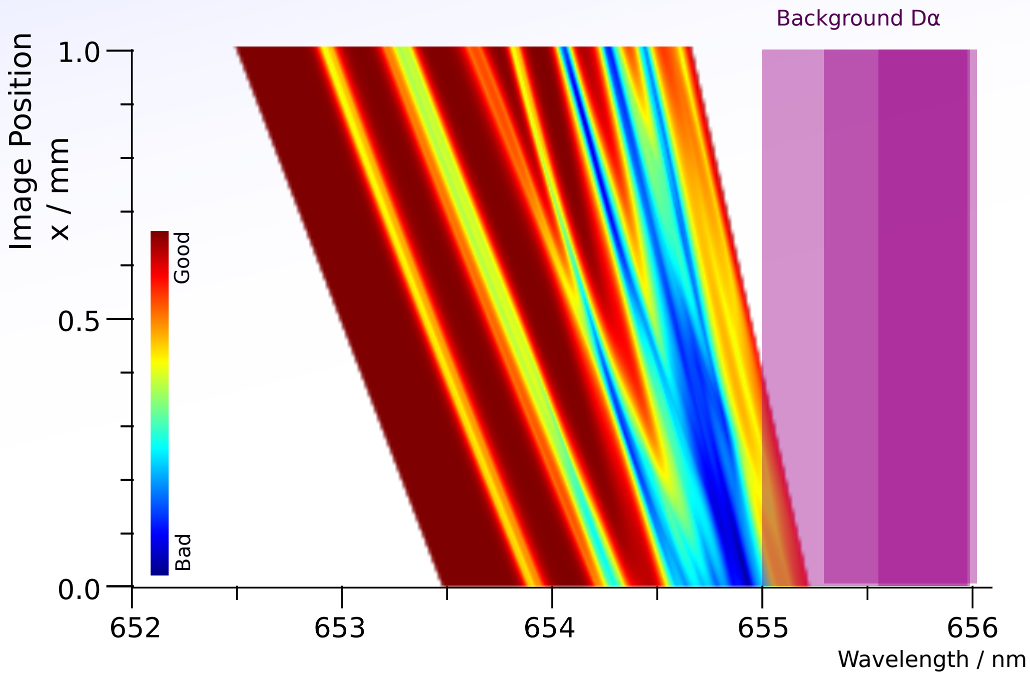

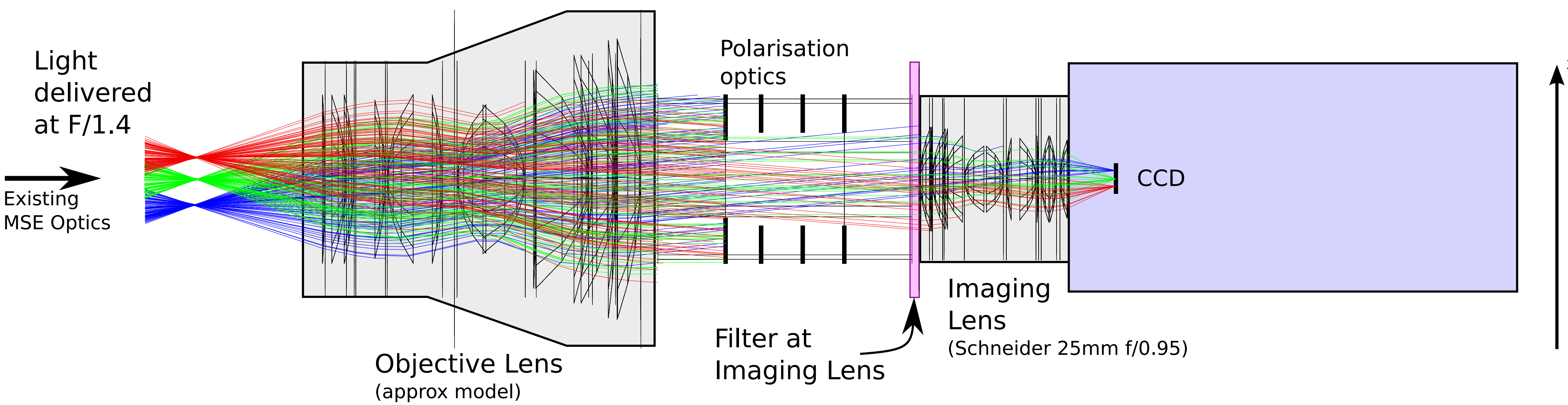

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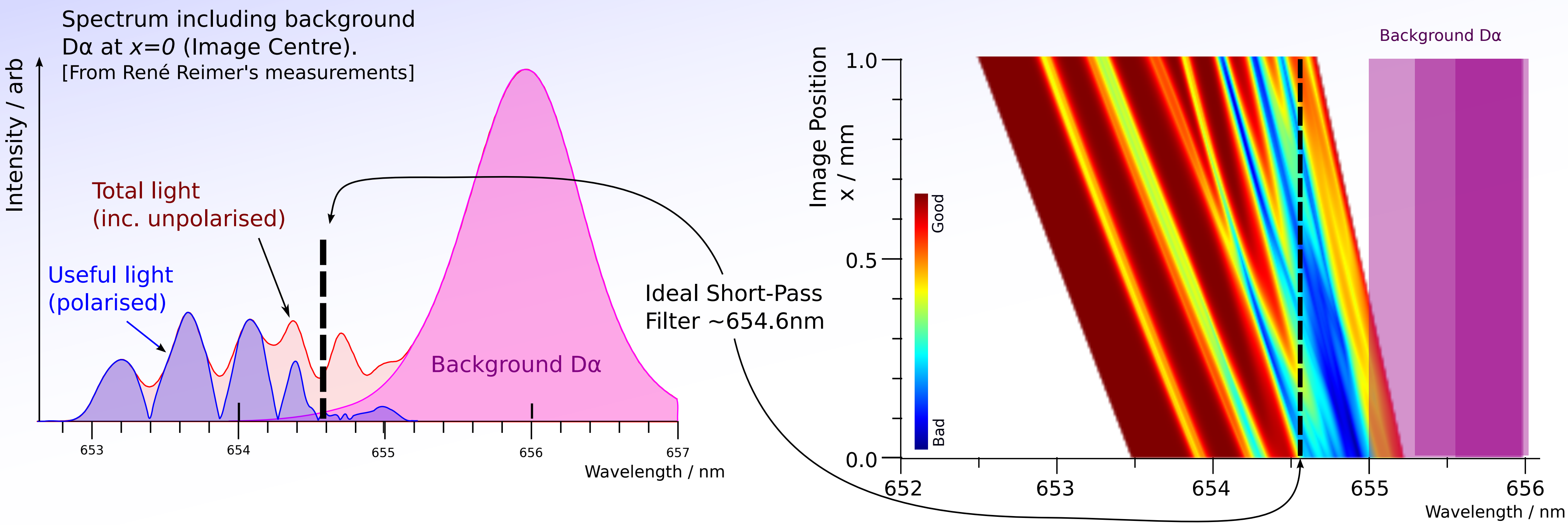

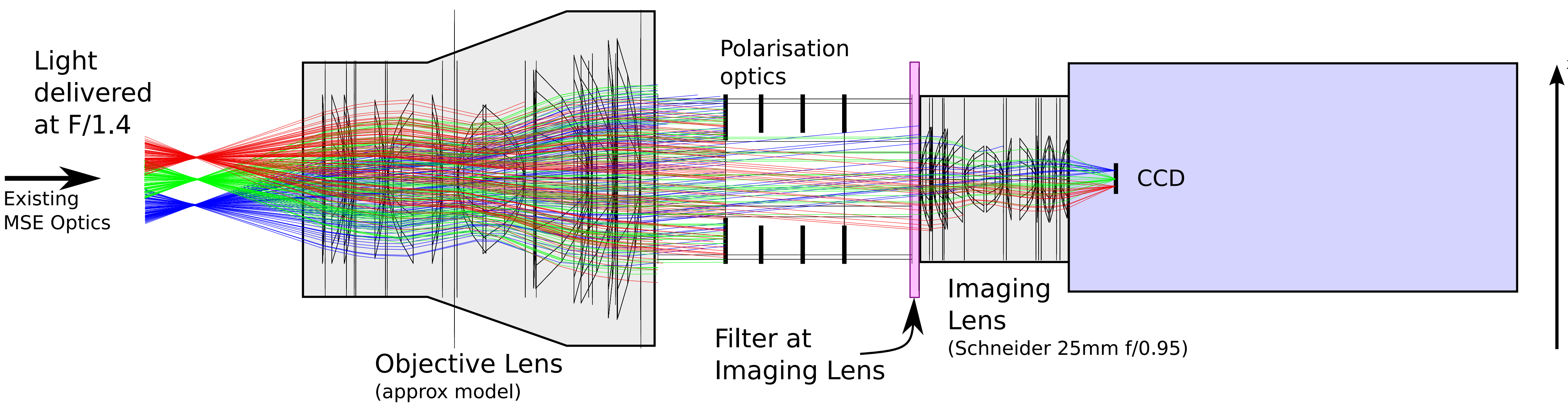

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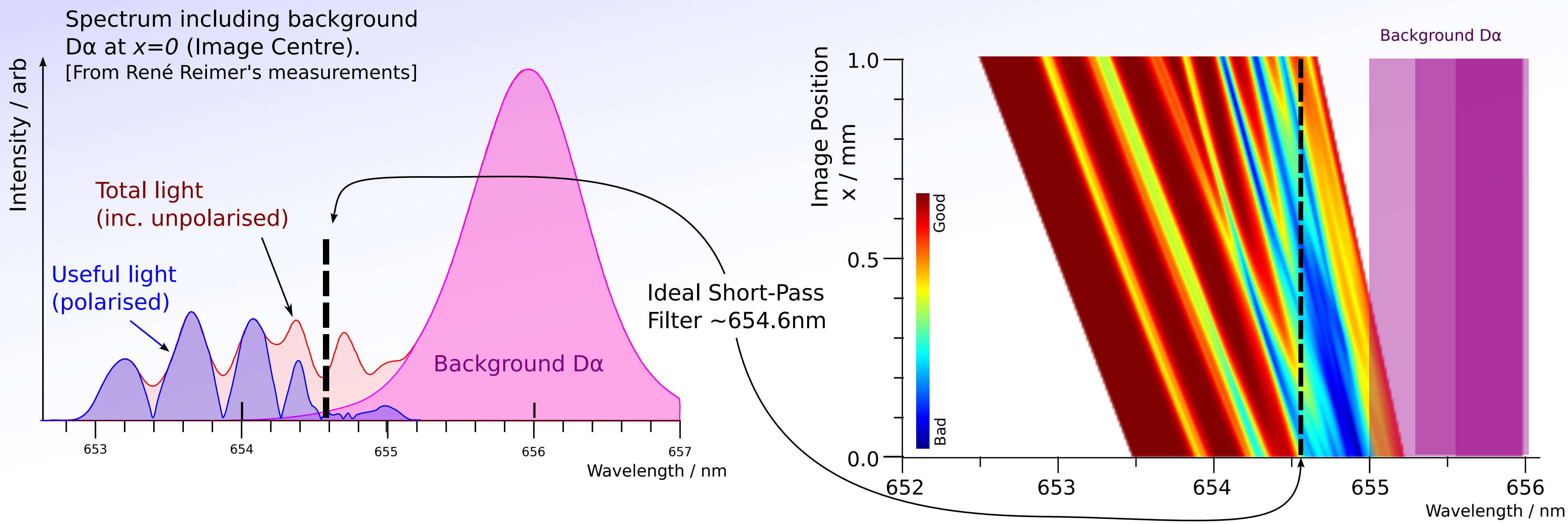
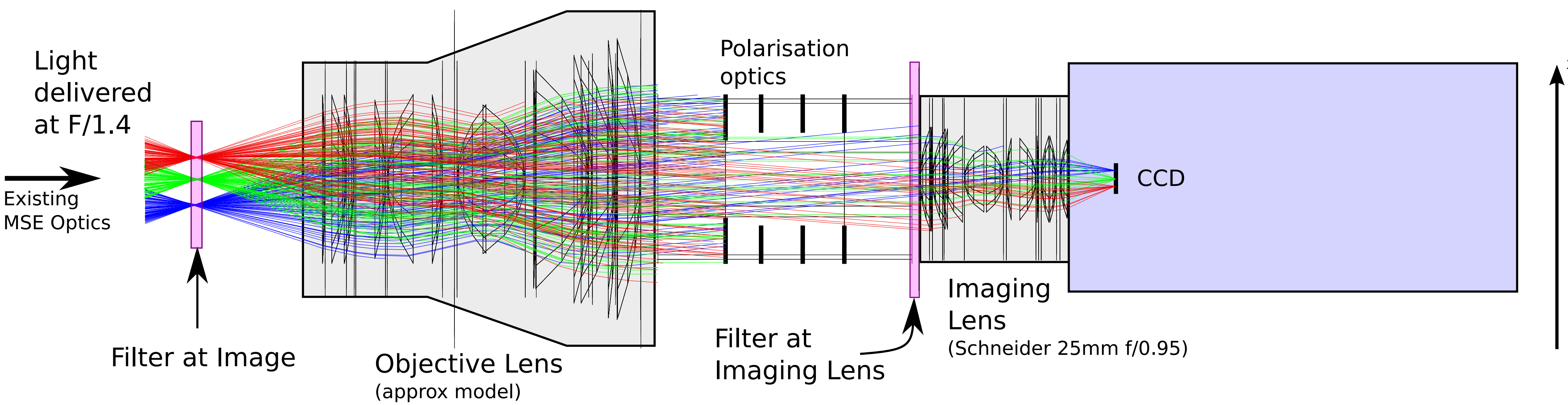
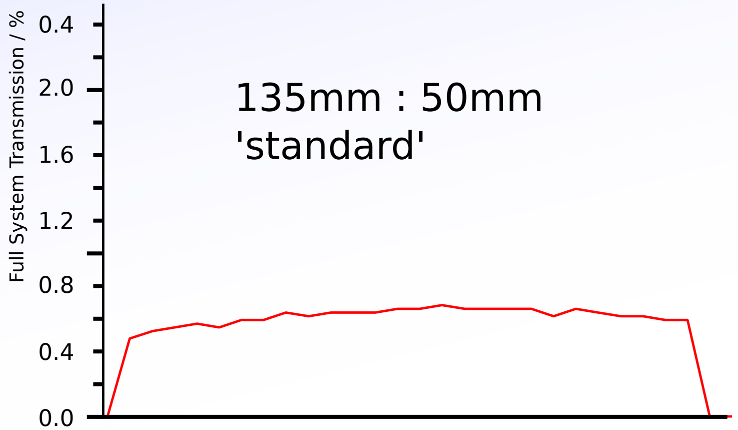


Filter can be placed at intermediate image plane, or on the front of the imaging lens (in the parallel rays):



IMSE Design - Throughput and filter shift.

For the 'standard' case, light throughput is only ~0.6% of MSE emission to mirror. Maximum possible is 7%.



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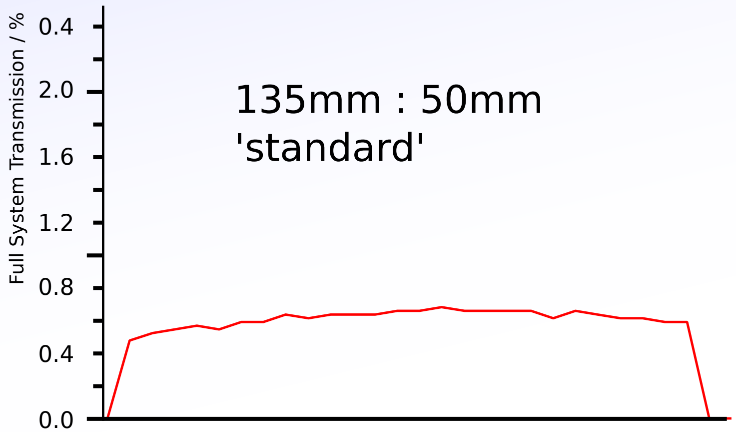
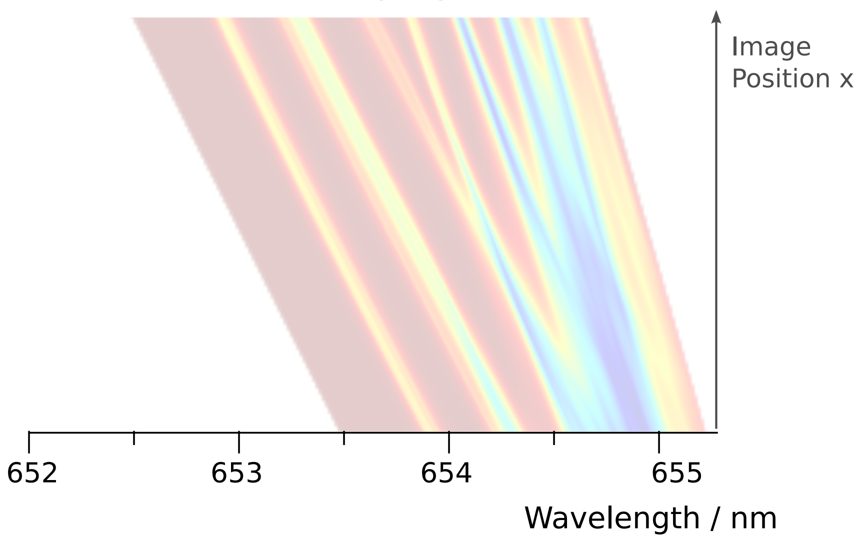


Some proportion of the light goes through the filter at a very steep angle and shifts the filter short-pass into the useful spectrum. The filter functions for different image positions calculated by the ray tracer are shown below.

Filter at imaging lens:



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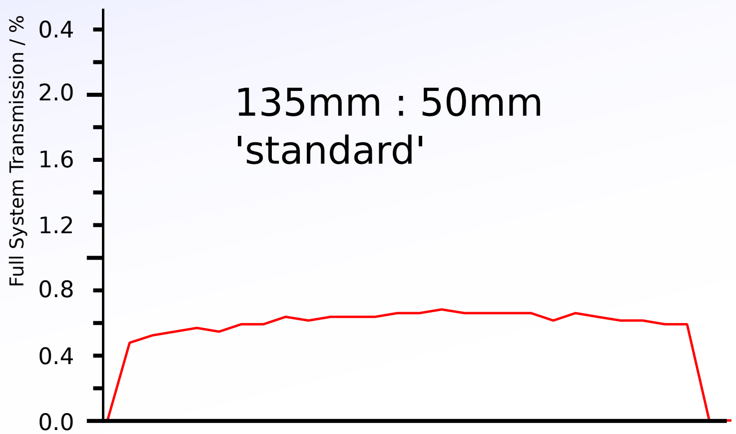

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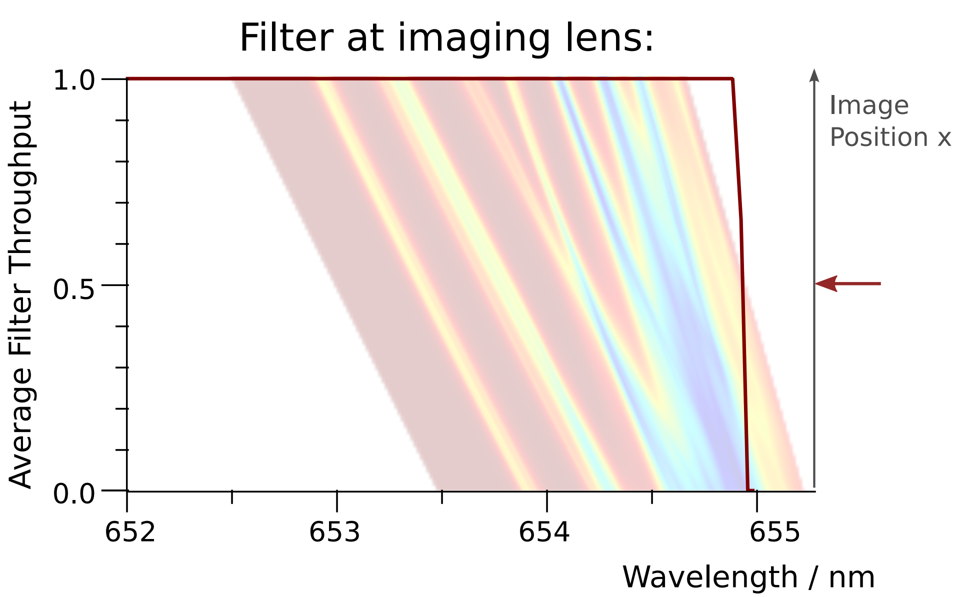

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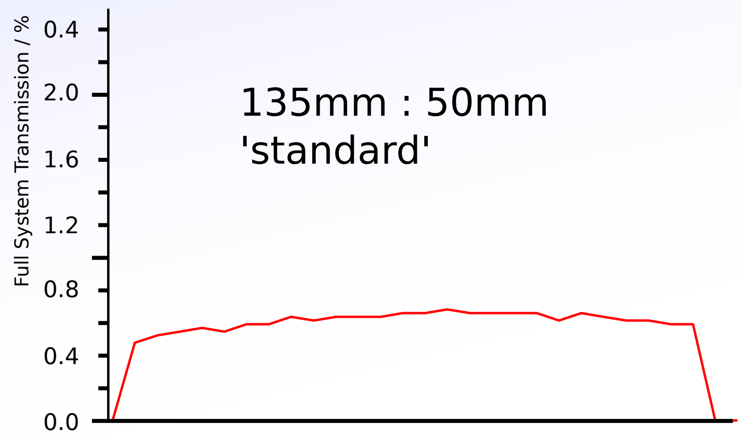

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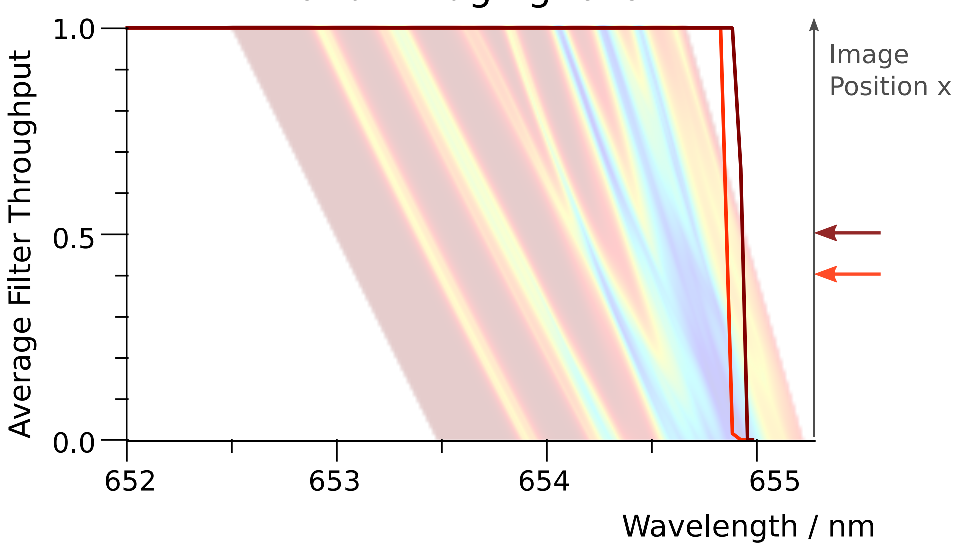

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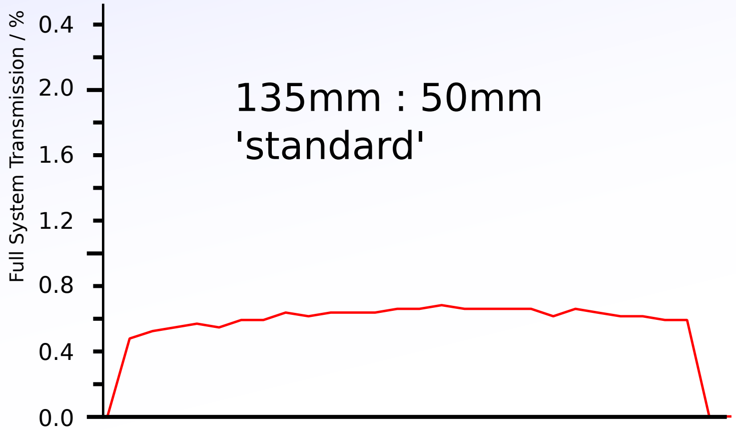

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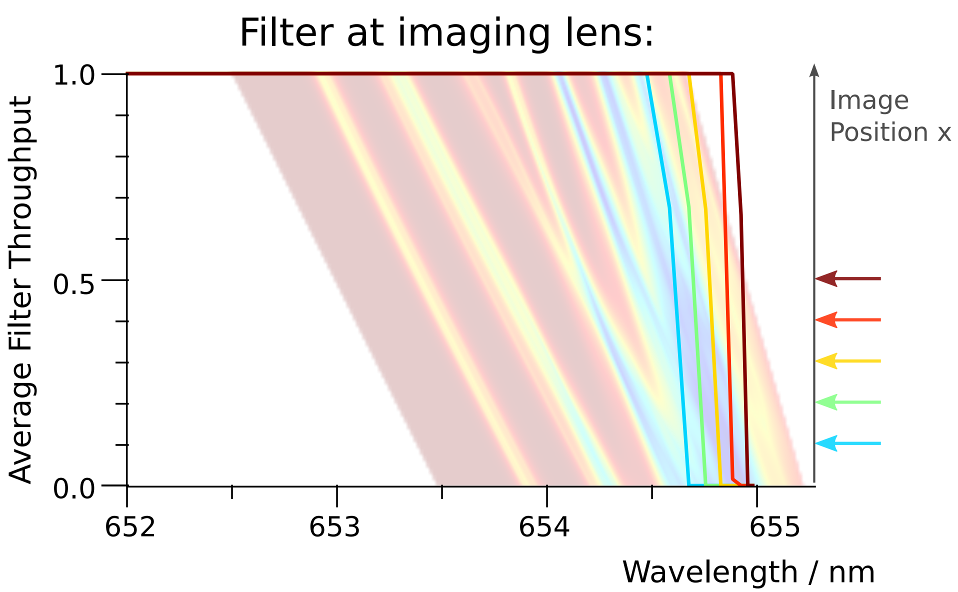

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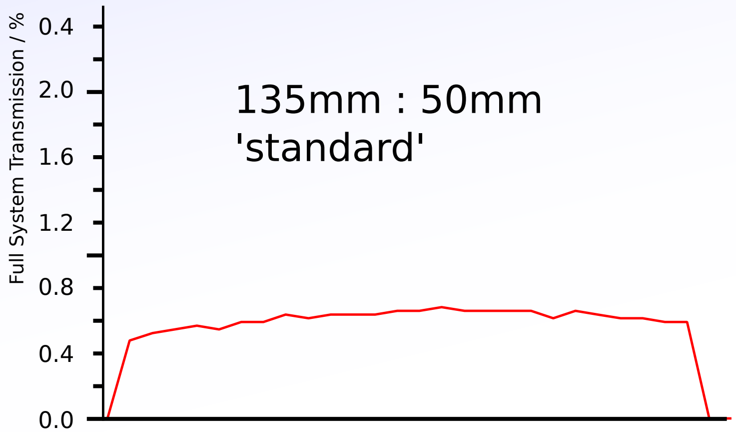

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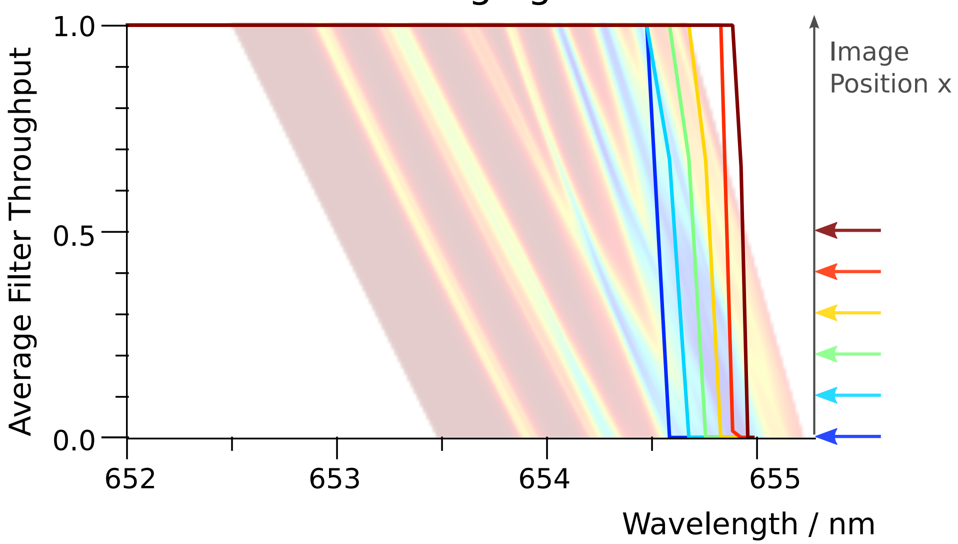

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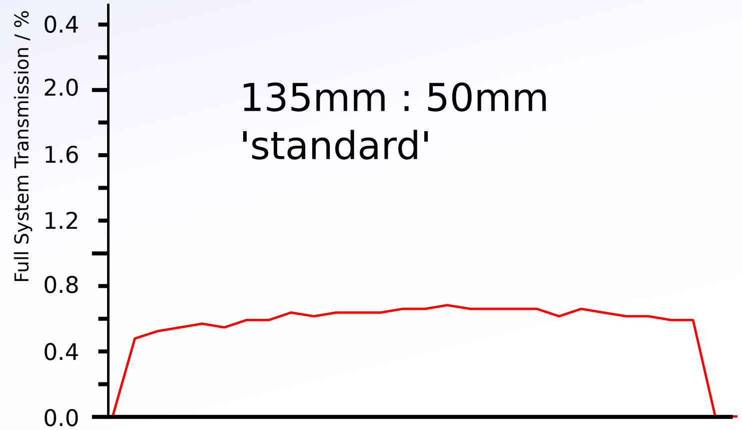

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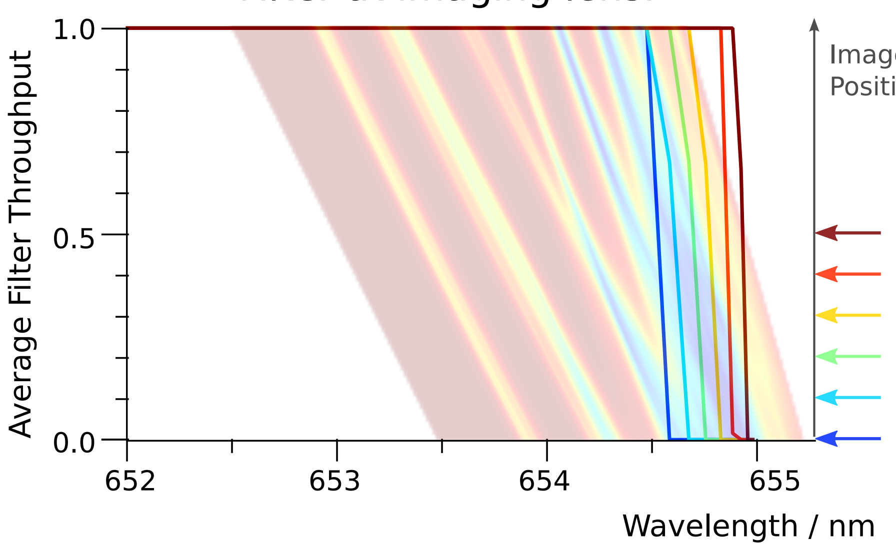
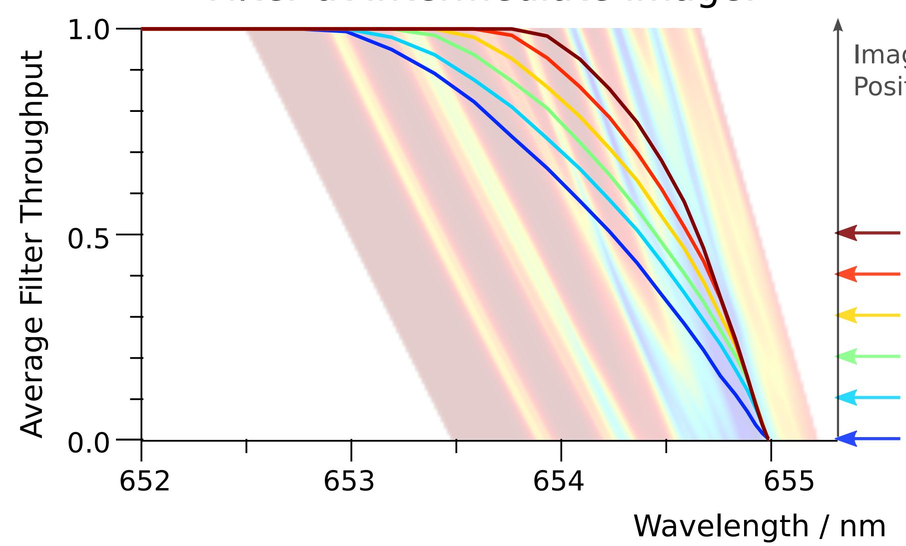


Filter at intermediate image:



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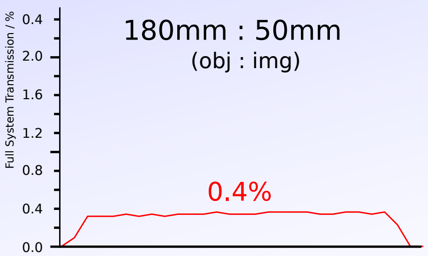
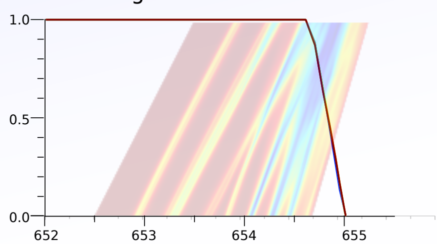
IPP Greifswald

IMSE Design - Throughput and filter shift

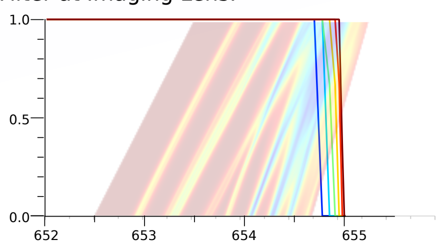
Throughput of light, and angle of light through the filter depends on the pair of lenses.
(It depends on the exact model of the lens, not just the focal length and F/#)



Filter at Image Plane:



Filter at Imaging Lens:



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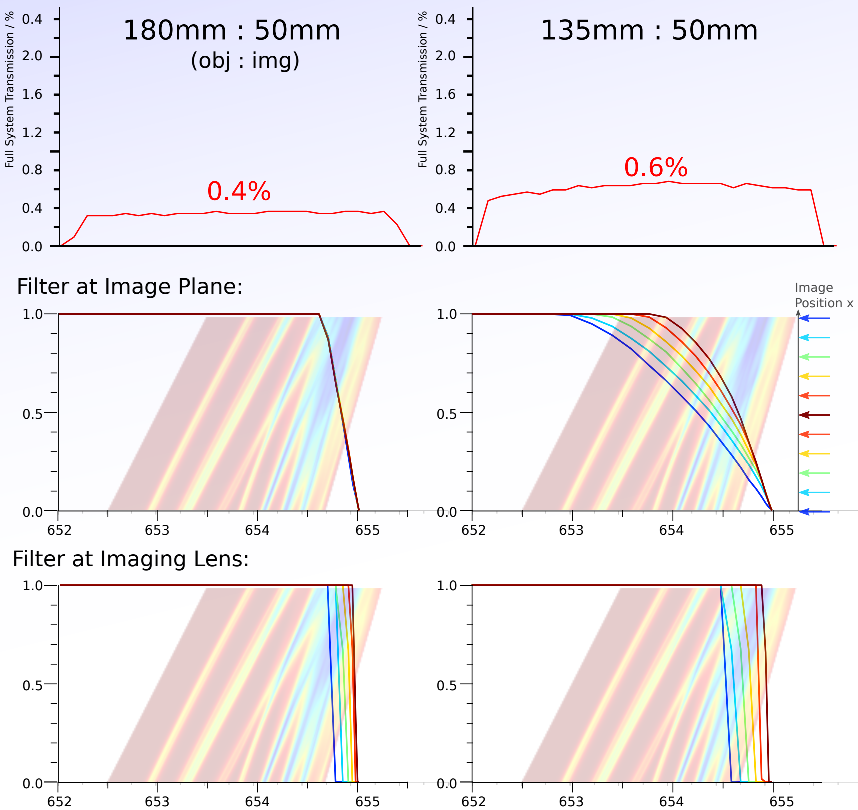

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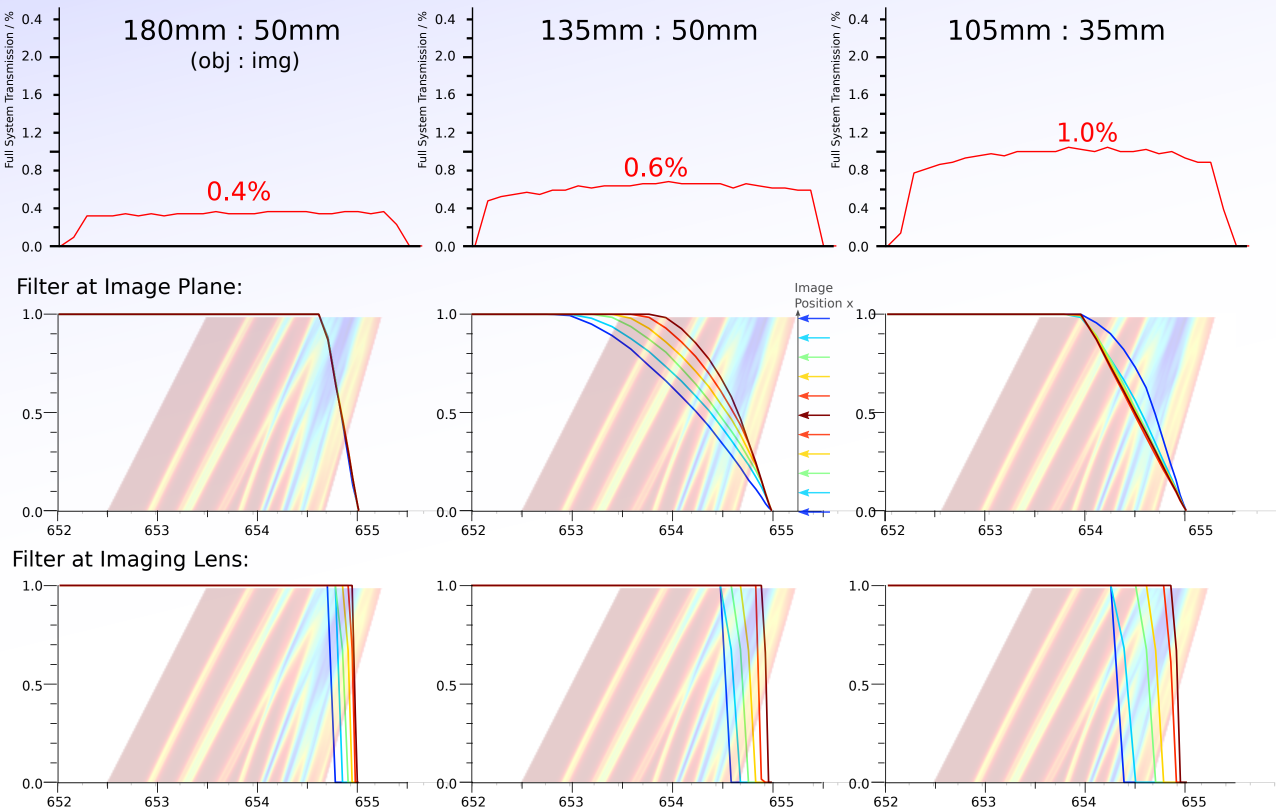

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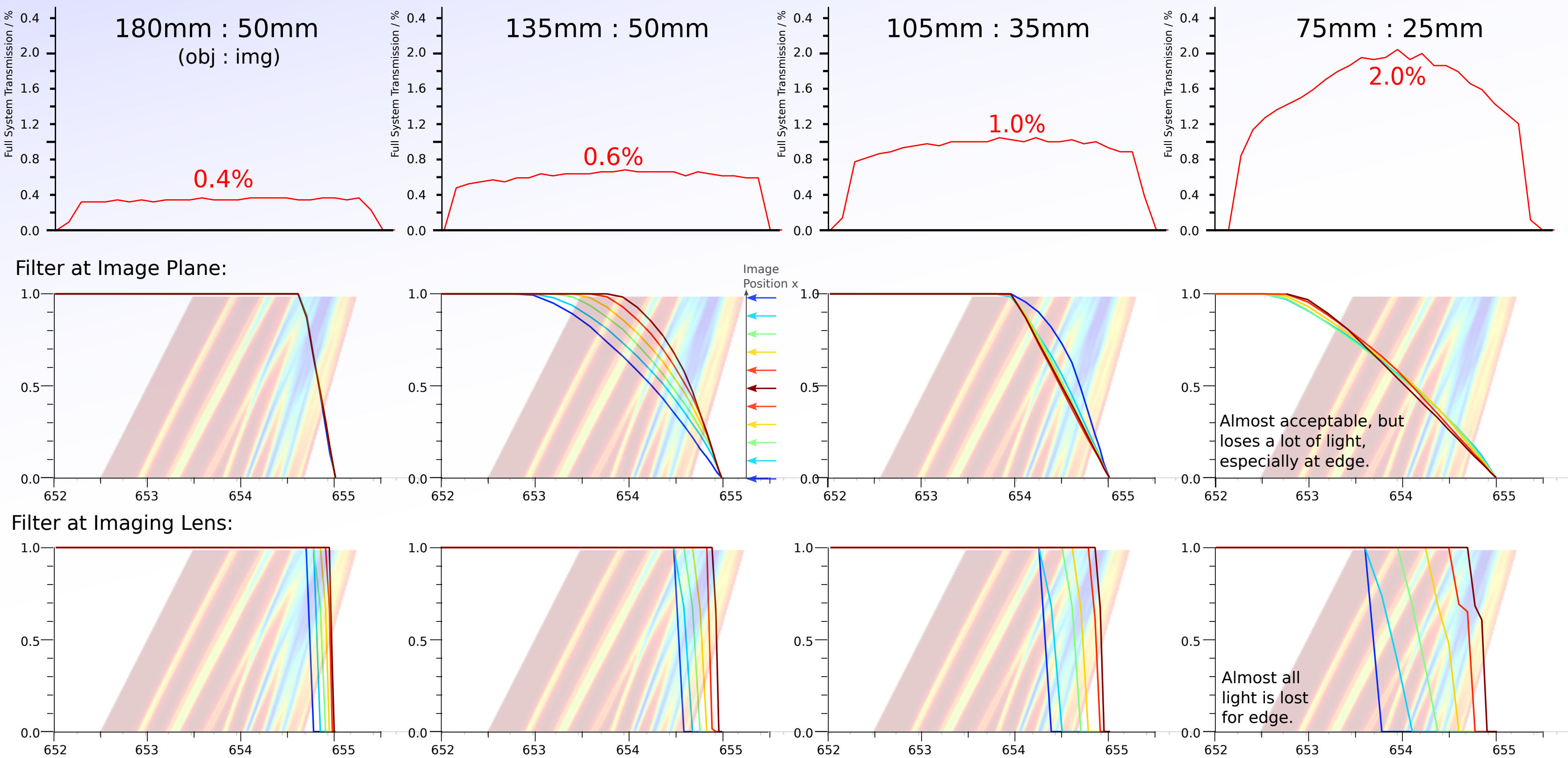

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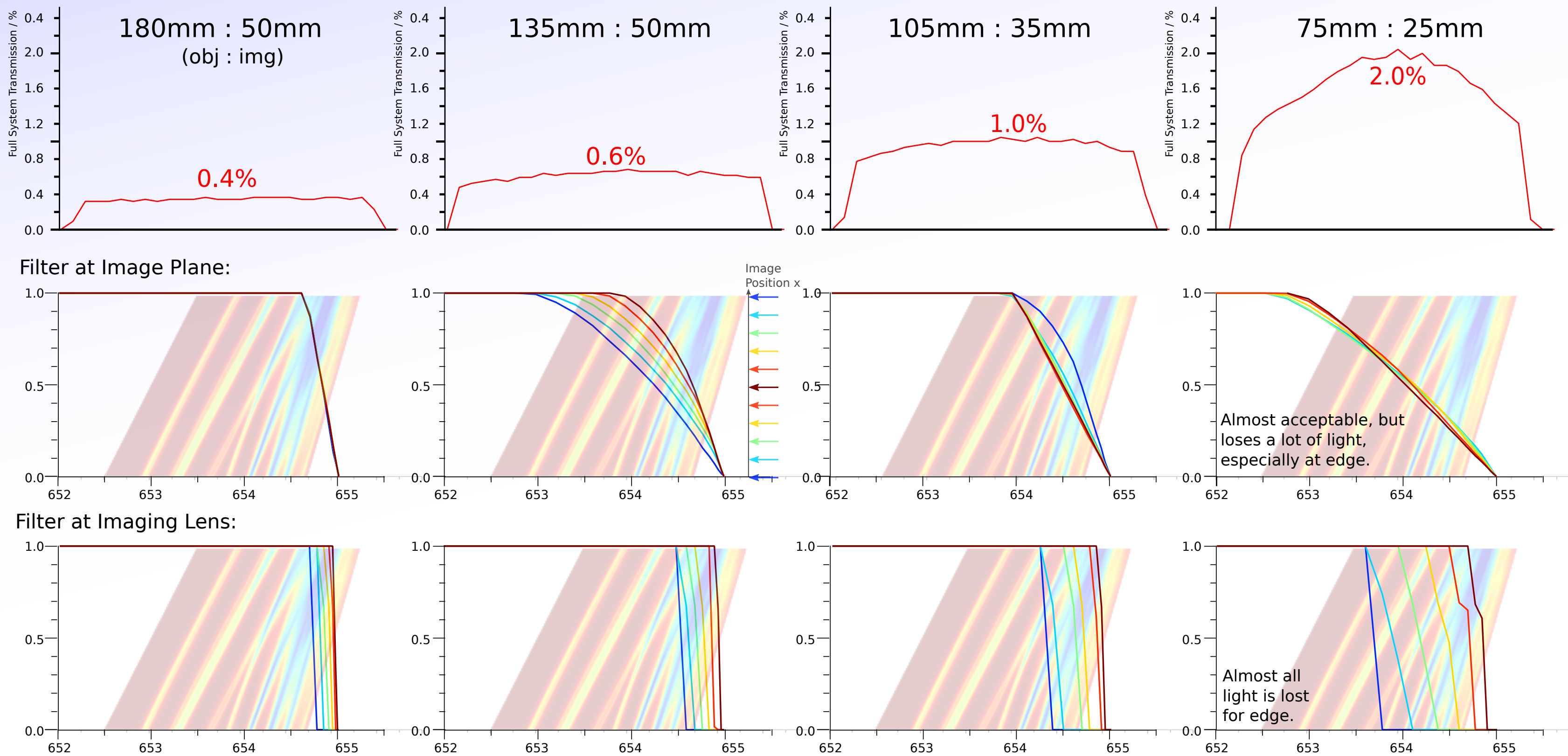

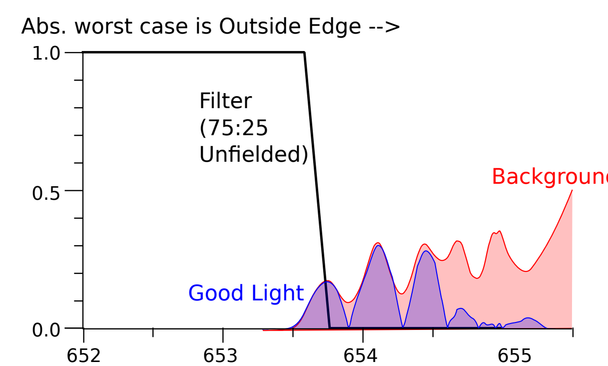

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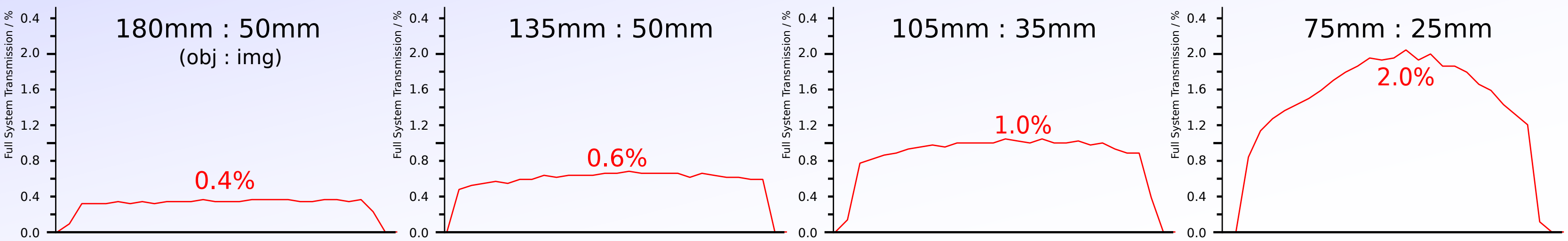
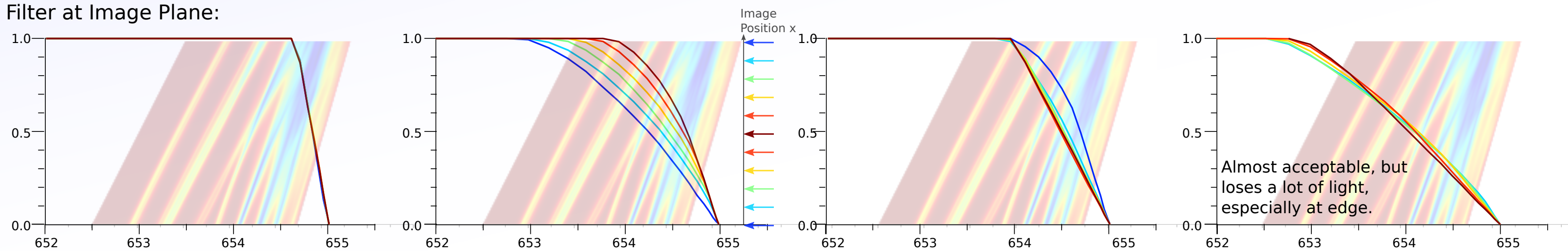
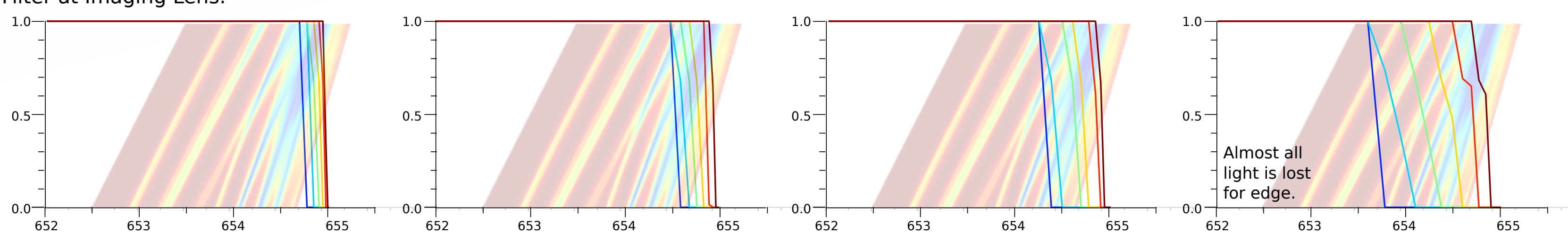


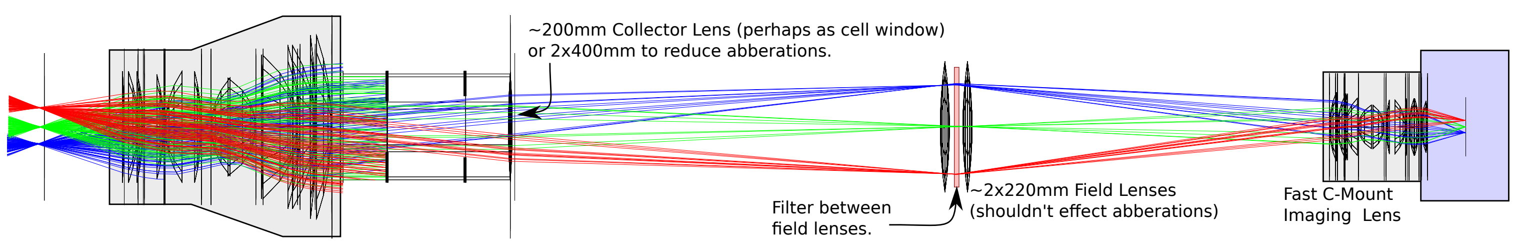
Filter at Image Plane:



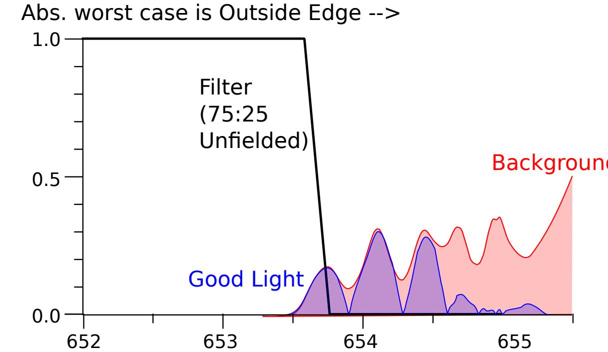
Filter at Imaging Lens:



75:25 gives ~3x more light than 135:50 but angles are too big for filter, and most/all light is lost at edge channel.
In reality vignetting was also higher and edge of image is entirely lost (can only see ~19mm of fibre plane)
Fielding the light after the cell into the imaging lens (should) solve the vignetting and It also helps with the filter a lot:



Abs. worst case is Outside Edge -->

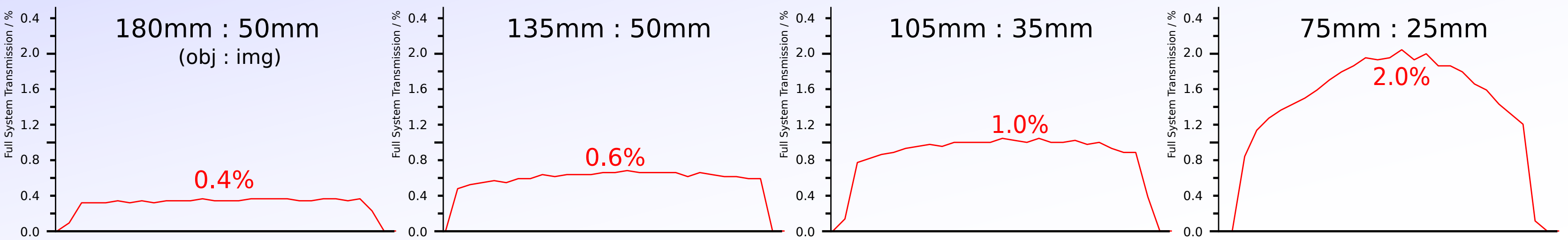


Oliver Ford
IPP Greifswald

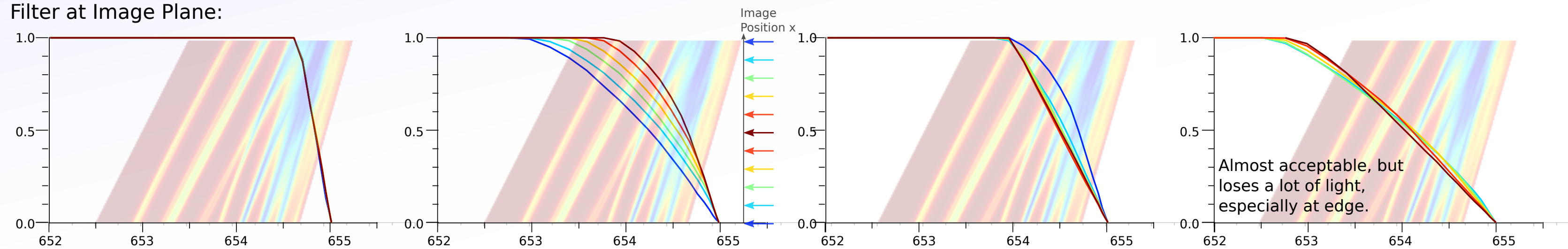
IMSE Design - Throughput and filter shift

Throughput of light, and angle of light through the filter depends on the pair of lenses.

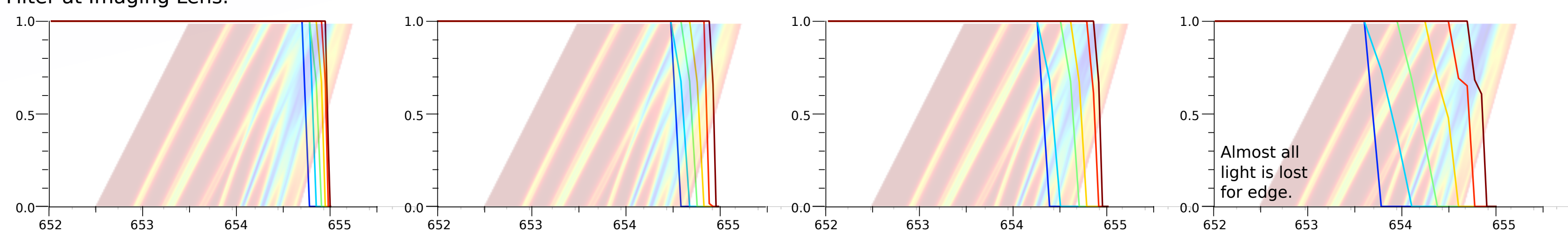
(It depends on the exact model of the lens, not just the focal length and F/#)

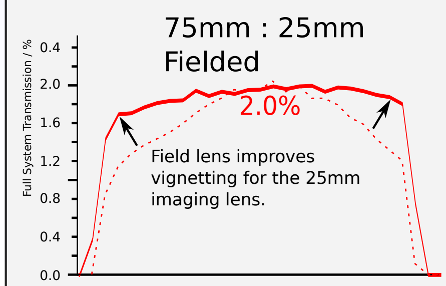


Filter at Image Plane:

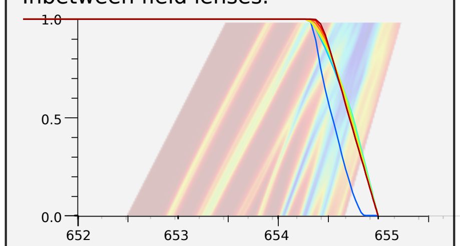


Filter at Imaging Lens:





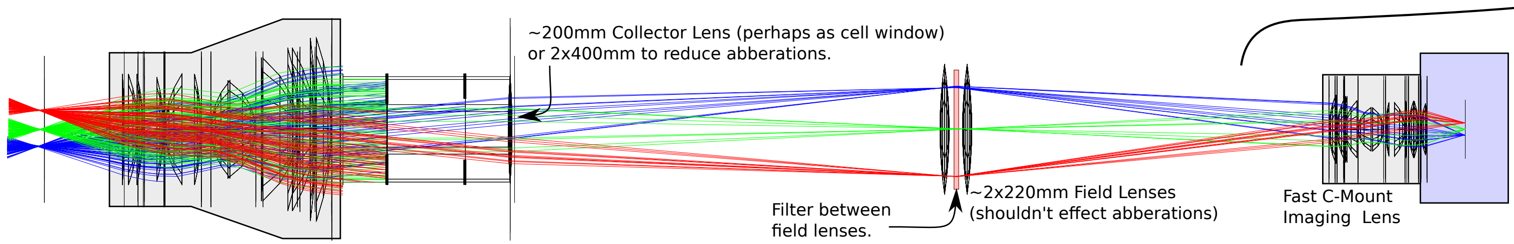
Inbetween field lenses:



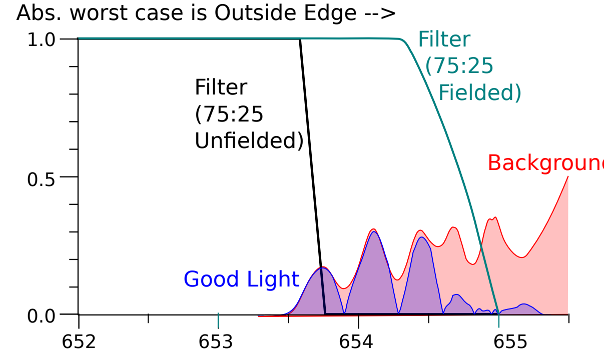
Significant improvement for the filter, and now with the possiblity of tuning it by tilting it.

However, it requires a bigger filter.

75:25 gives ~3x more light than 135:50 but angles are too big for filter, and most/all light is lost at edge channel.
In reality vignetting was also higher and edge of image is entirely lost (can only see ~19mm of fibre plane)
Fielding the light after the cell into the imaging lens (should) solve the vignetting and It also helps with the filter a lot:



Abs. worst case is Outside Edge -->



For the fielded case at the very edge, it integrates up to about 66% of the good light under the filter which is 66% * 1.6% = 1% of collected light, this is already > 2x the safe 135:50 case, and we're still at ~3x for the rest image.

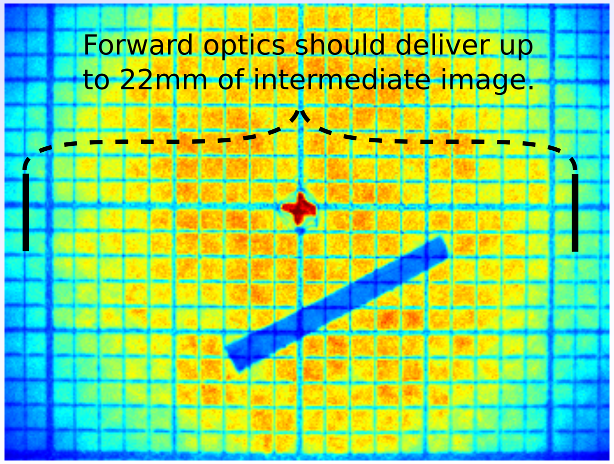
But... abberation after plates hurts our fringe contrast so the collector lens needs to be good (without being a camera objective lens)

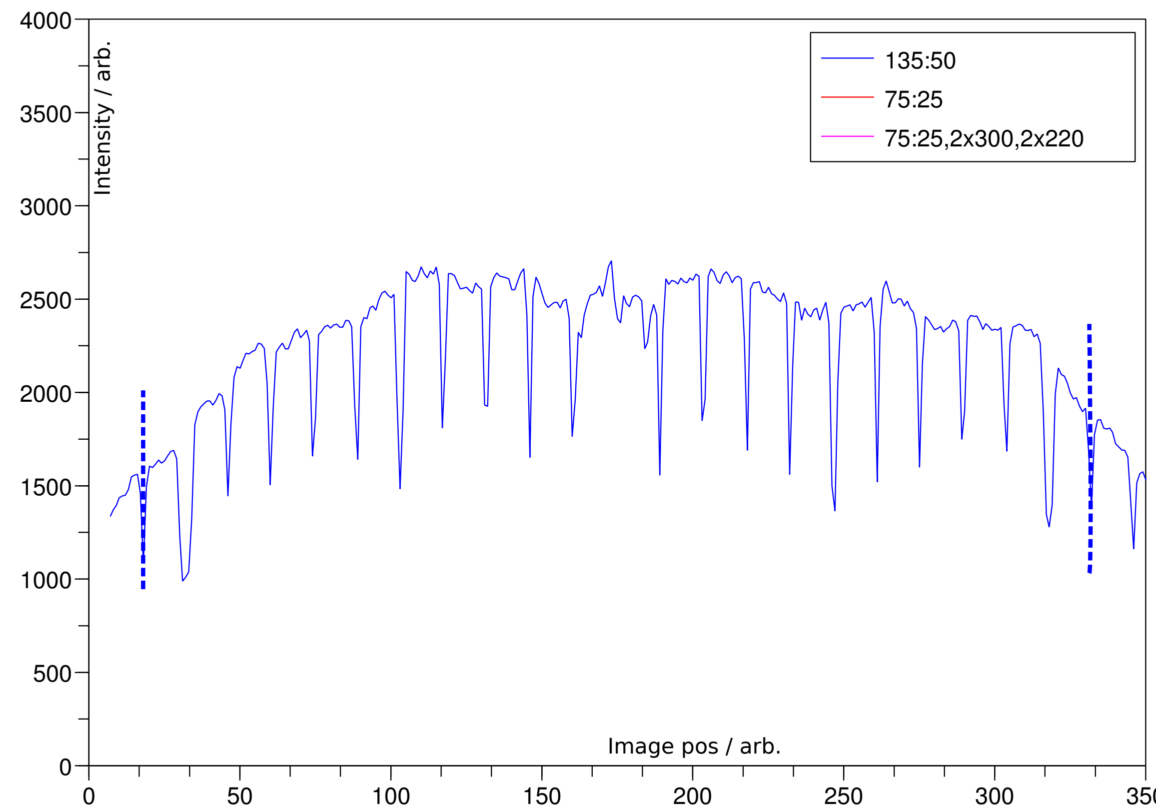
IMSE Design - Throughput and vignetting (lab test)

Oliver Ford
IPP Greifswald

In the lab, the situation is similar, but a bit worse:

135:50 'standard'





IMSE Design - Throughput and vignetting (lab test)

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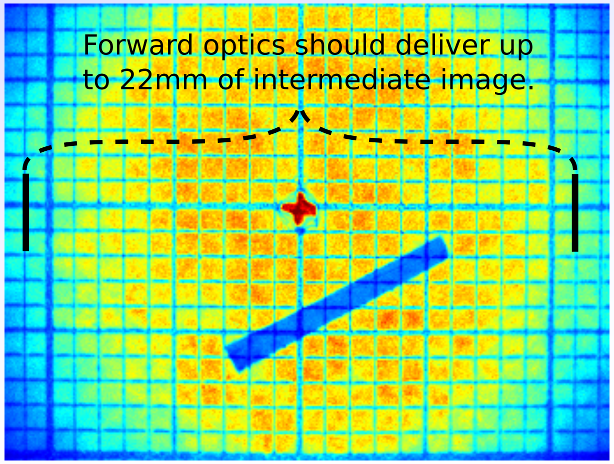
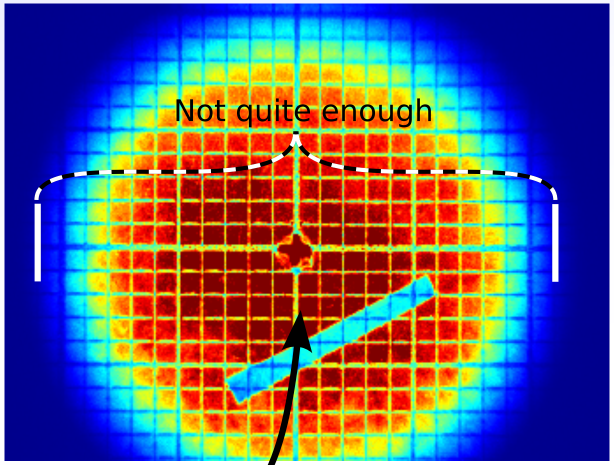
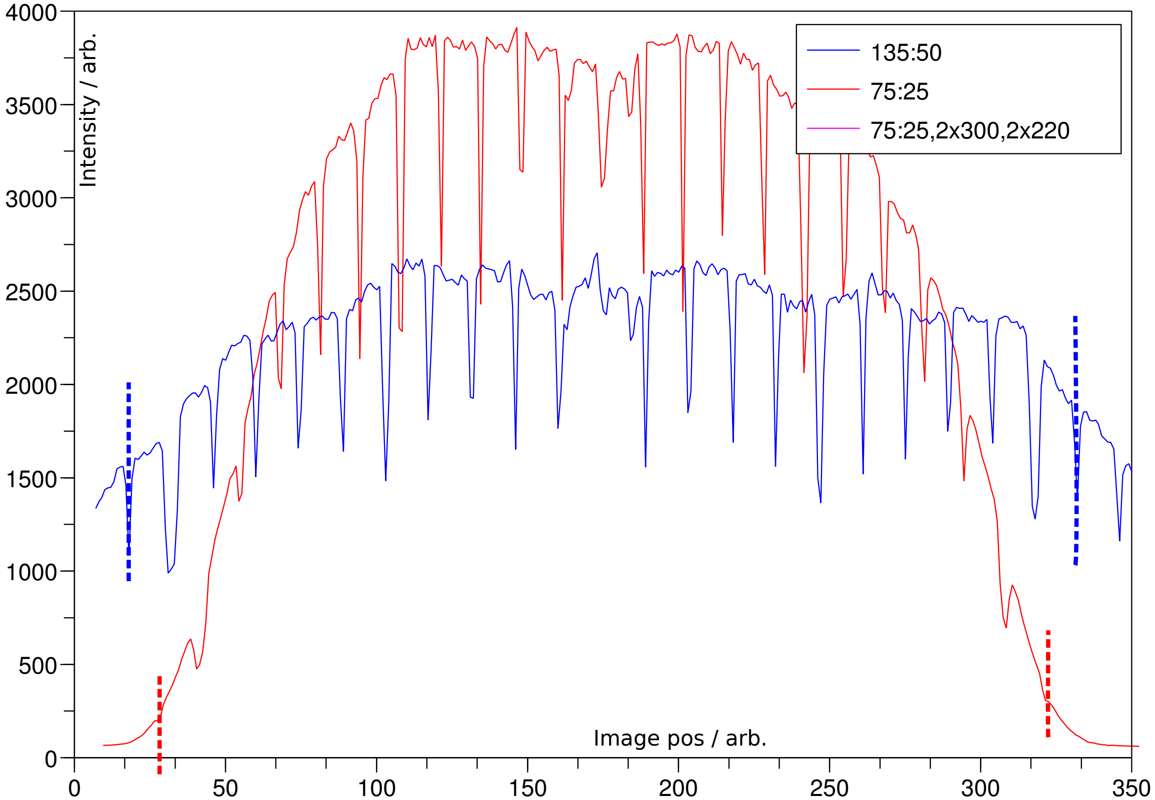


75:25 unfielded



75:25 gives only a 50% increase in light in centre (1.5x as much as the 135:50) but the vignetting loses too much of the edge. The graph paper is at first image plane and we probably need to see 22mm of it.



IMSE Design - Throughput and vignetting (lab test)

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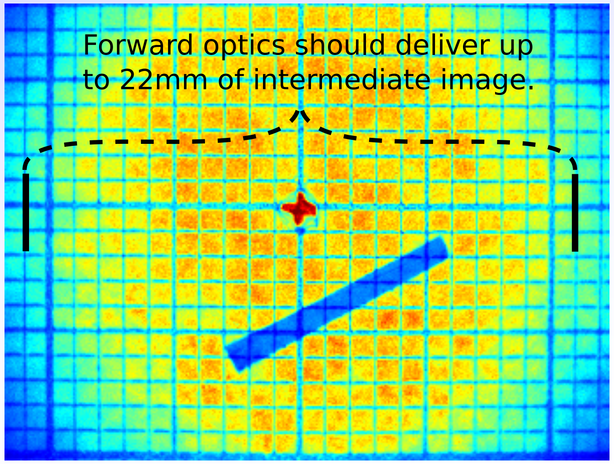
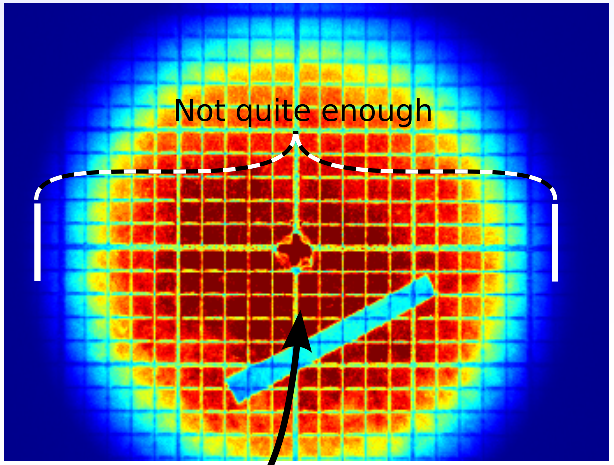
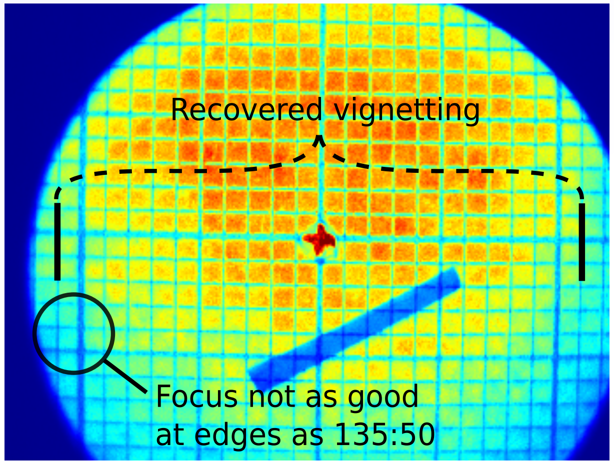


75:25 unfielded



75:25 fielded +2x300mm collectors,
+2x220mm fields



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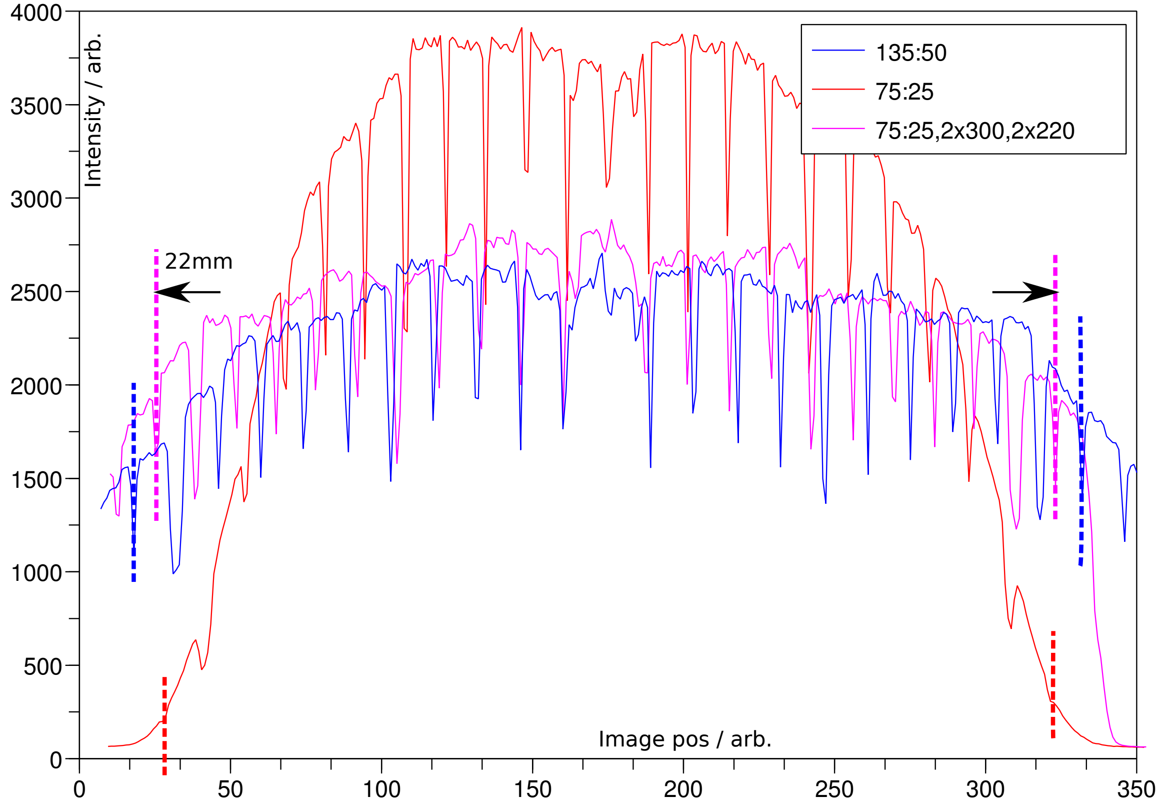

IMSE Design - Throughput and vignetting (lab test)

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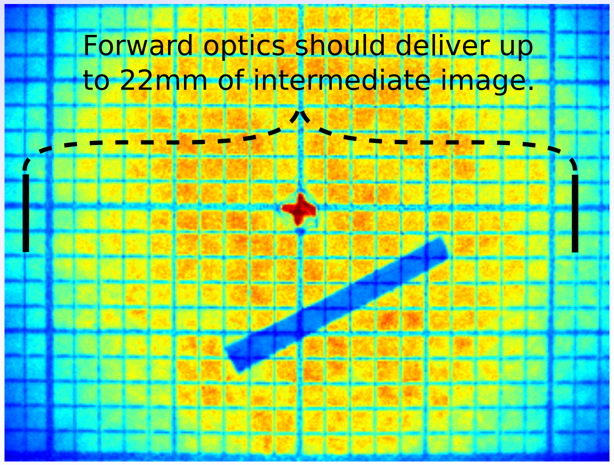
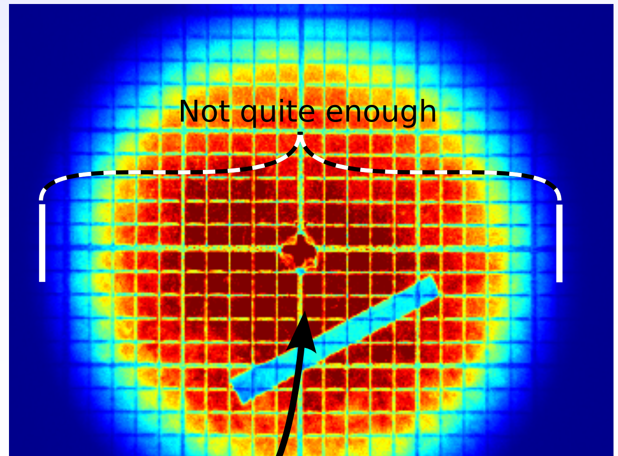


75:25 unfielded



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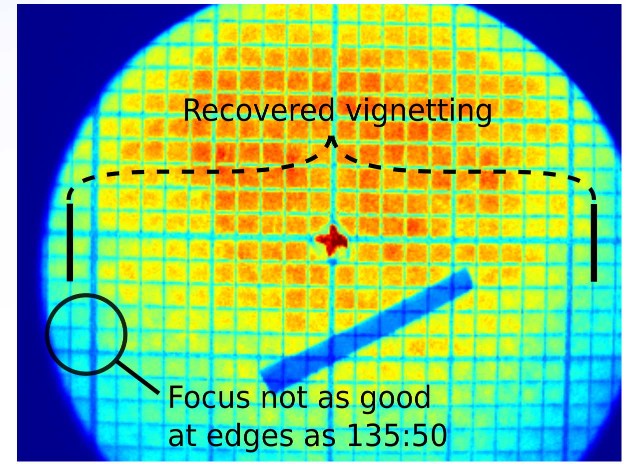

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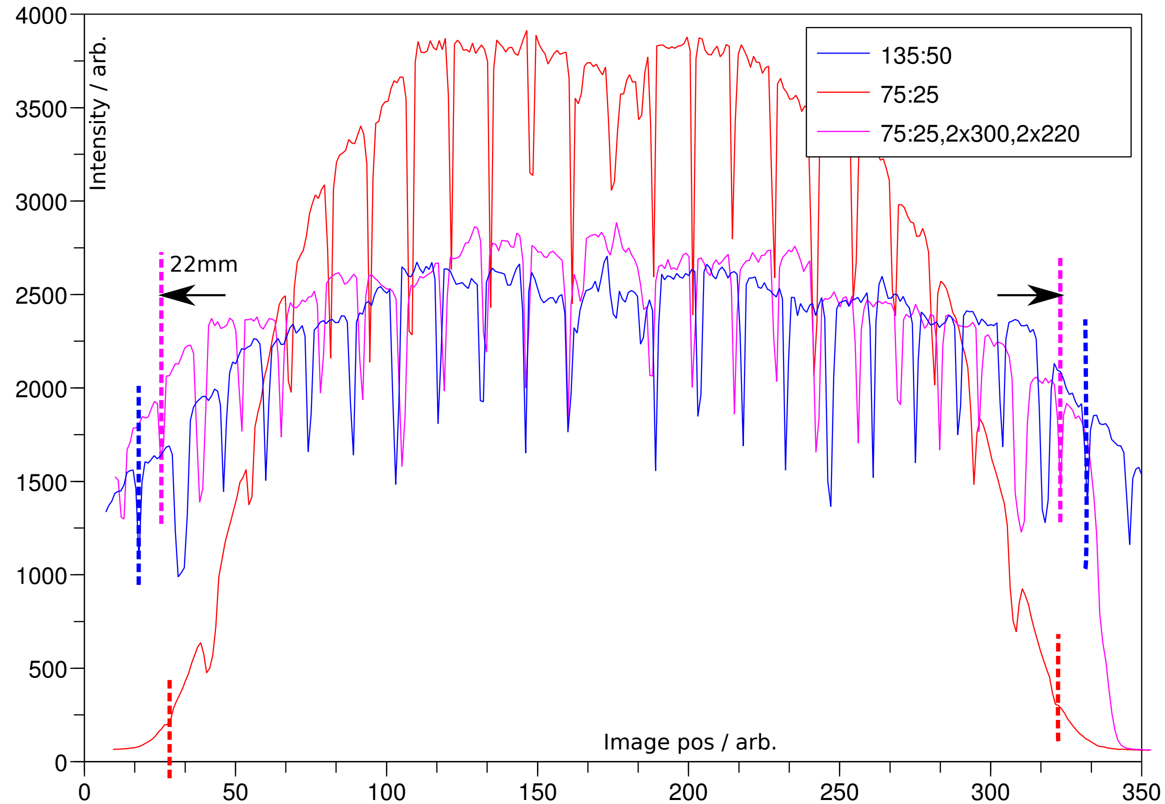

Fielding fixes vignetting for 75:25 but uses 4 lenses. They are uncoated old lenses that were sitting in a cupbaord since 1960. All 4 lenses together only transmit ~60% of original intensity (measured) and leaves light level almost exactly back where we started.

However, with coated optimised lenses coupled with the improvement in the filter angles, it will improve the S/N by at least 50%.

IMSE Design - Status

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.

Next...

- ••• Test camera under magnetic field.
- ••• 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.
- ••• Get support structure built.
- ••• 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.