Possible 2D Current Measurements at ASDEX Upgrade using Coherence Imaging.

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

1: Max-Planck Institut für Plasmaphysik, Greifswald, Germany
2: Plasma Research Laboratory, Australian National University, Canberra

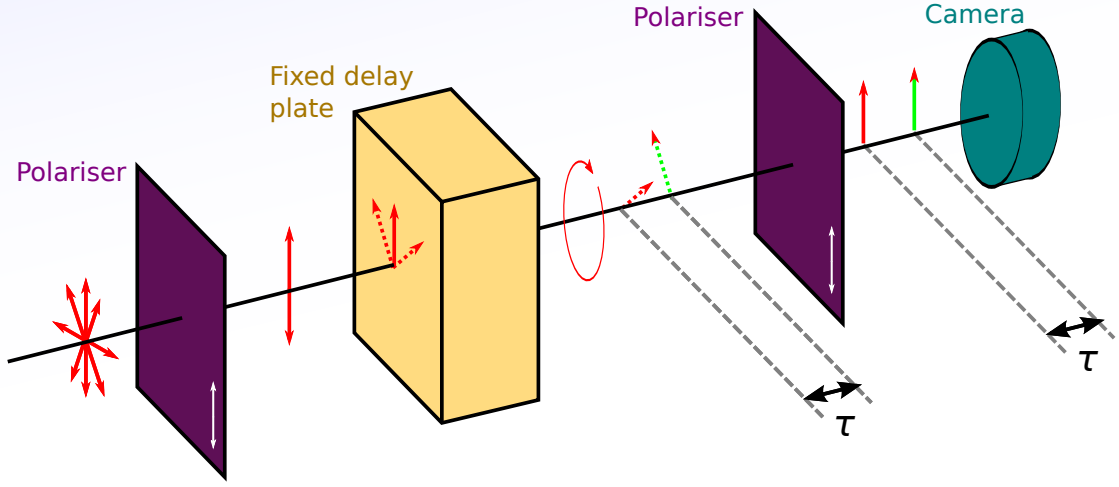
Special thanks to
René Reimer

Talk Outline

- Coherence Imaging Spectroscopy.
- Spectro-Polarimetric Imaging.
- MSE and application of CIS.
- MSE Modelling.
- Findings of MSE modelling so far.
- Another possiblity: Zeeman / Lithium Beam CIS.

Coherence Imaging I

1) Linearly polarise light.
2) Shift 1 component by τ.
3) Measure intensity of linear polarised combination (interference)

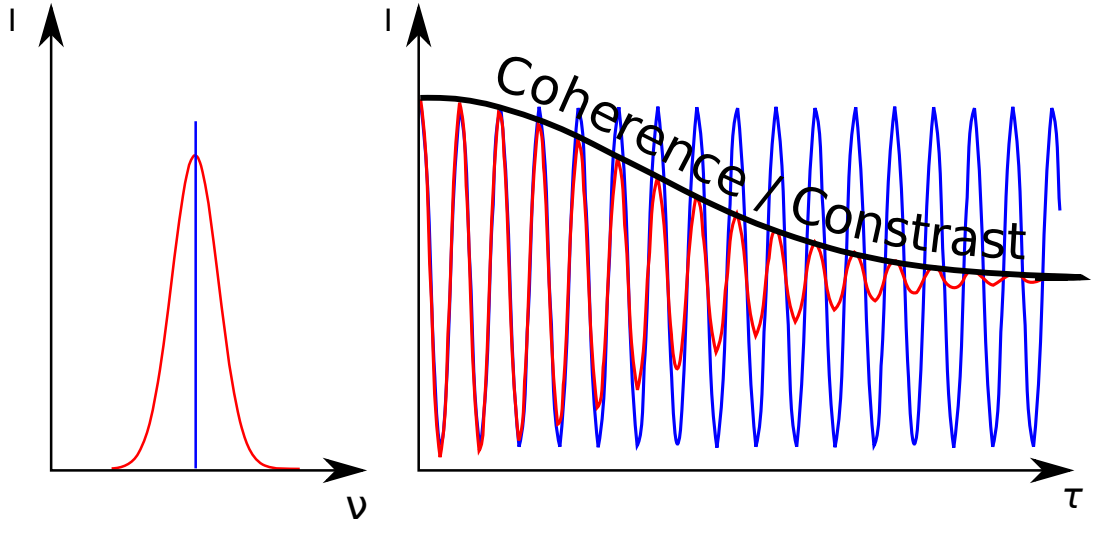


Contrast vs τ gives information about line broadening etc.

Also possible to extract line position (for Doppler shift).

All in 2D.

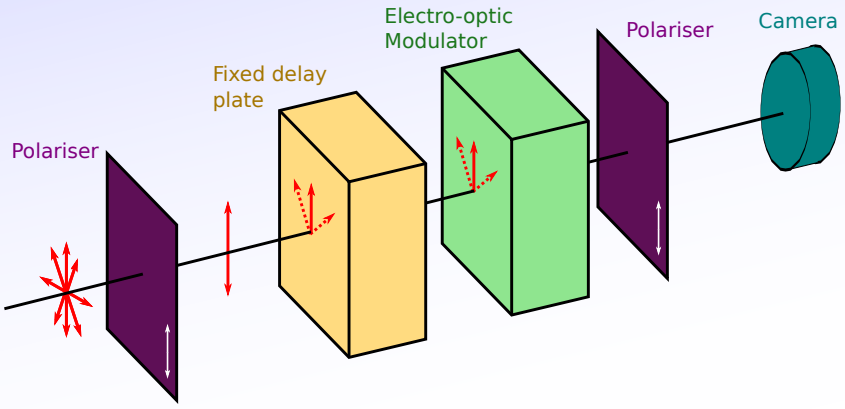
But we need information from multiple values of τ.

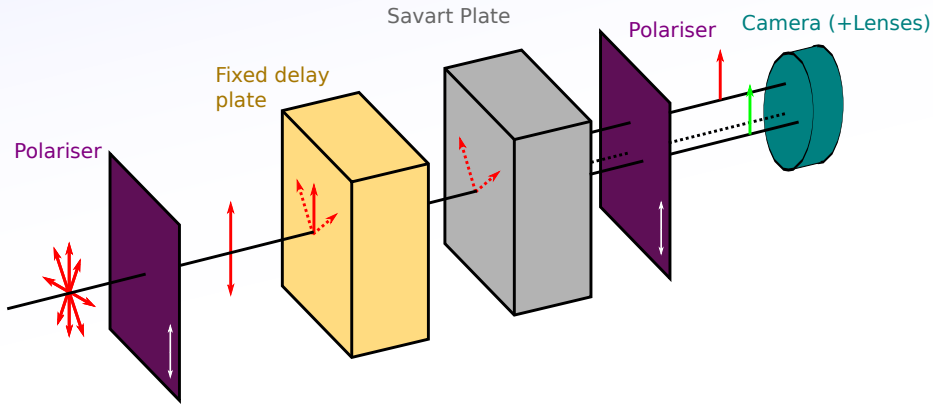


$$I = \frac{I_0}{2}\left(1 + \zeta \cos \omega \tau\right) \qquad \zeta(\tau) = Re\left[FT\left[I(\nu)\right]\right]$$

Coherence Imaging II

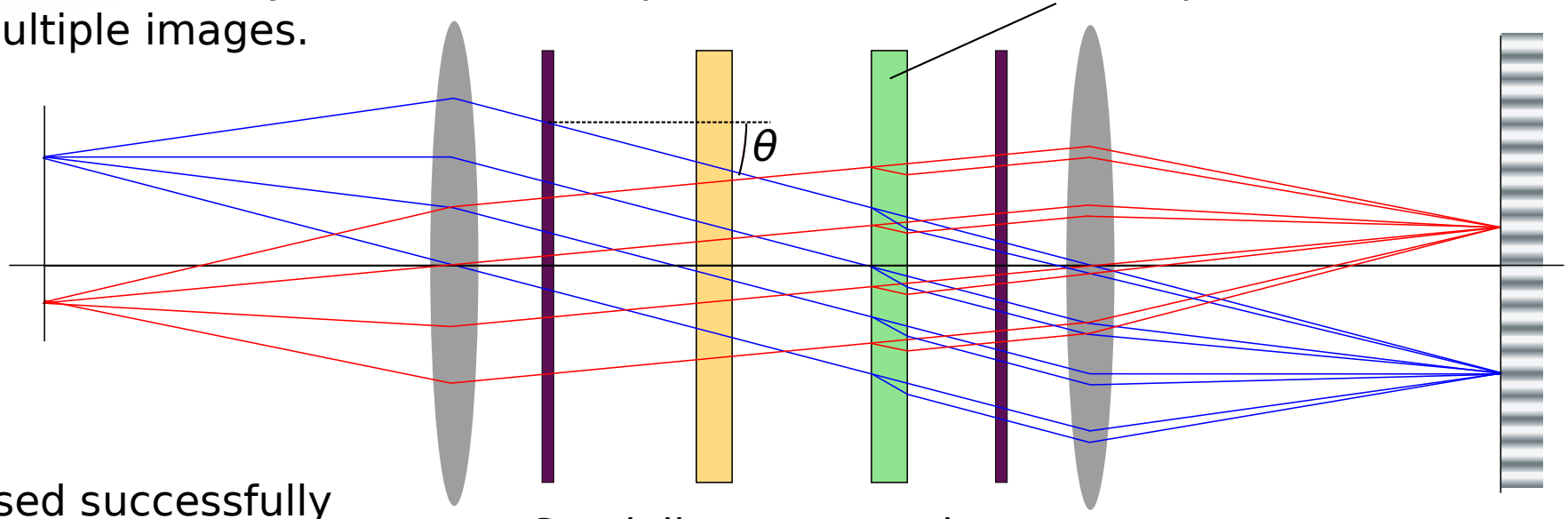
Two of the possible methods:





Temporal Modulation - vary τ in time, and record multiple images.

Spatial Modulation (Savart plate):

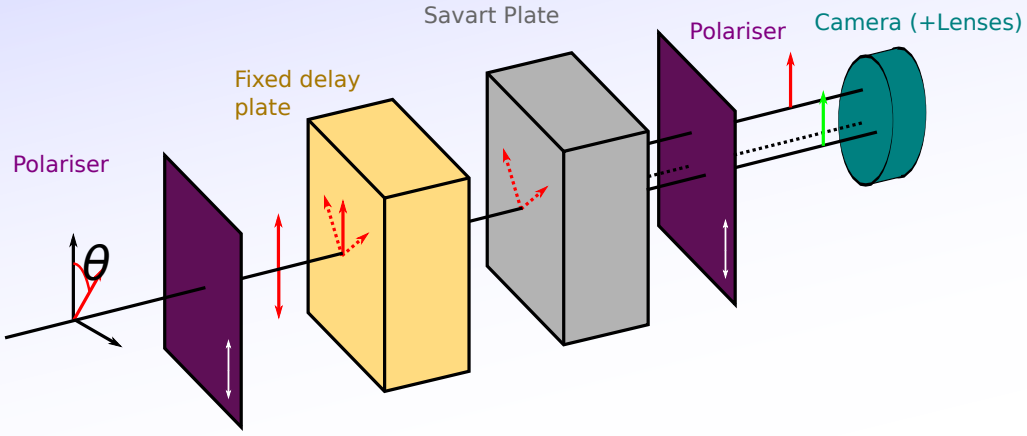


CIS has been used successfully for Doppler spectroscopy e.g. on: DIII-D, H1, WEGA, W7-AS etc.

Spatially separates into two components.
One delayed by $\tau(\theta)$. [θ in splitting plane only]
Focused to interference pattern with $\tau(x)$

Spectro-Polarimetric Imaging

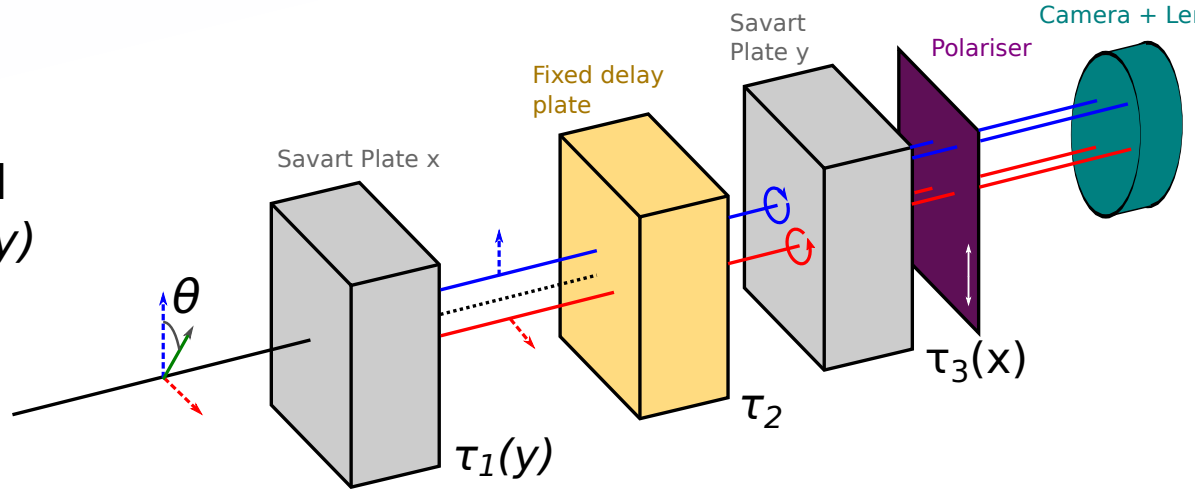
Remove first polariser



Interference contrast now also sensitive to input polarisation.

$$I = \frac{I_0}{2}\left(1 + \zeta\, cos2\theta\, cos\,\tau\right)$$

But we need to separate these.



Add primary Savart plate orthogonal to second. This introduces delay $\tau_1(y)$ between orthogonal components.

The interference of all 4 components gives:

$$I = \frac{I_0}{2}\left[1 + \zeta\left(\, cos2\theta\, cos(x) + sin2\theta\, sin(x)\, sin(y)\,\right)\right]$$

By demodulating the image in x and y, we can find θ, I_0 and ζ.

This is the '*Double Spatial Hetrodyne*' system. We can instead replace one Savart plate with a Ferro-electric crystal - (No fringes in one direction, but need multiple time slices)

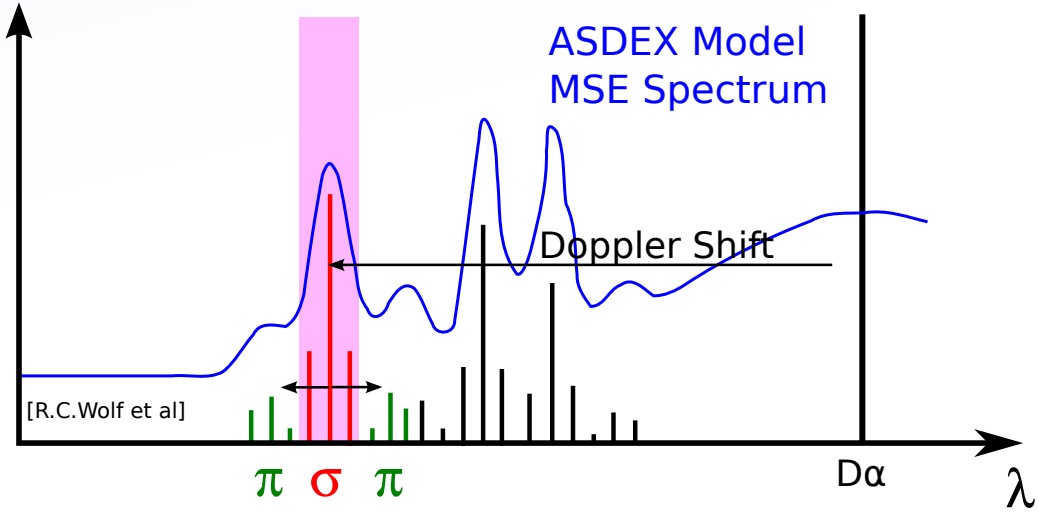
Motional Stark Effect

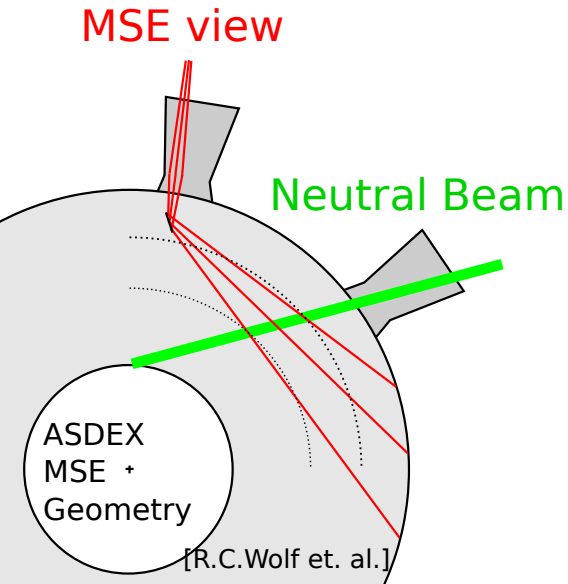
Observe D_α emission from neutral beam atoms.
Doppler shifted by velocity toward/away from observer.
Stark split by electric field in rest frame of atom: $E = v \times B$

View parallel to E: No π
σ unpolarisaed.

View perp to E: π polarised parallel to E.
σ polarised perp' to E.

Polarised intensity scales with $sin^2\ \gamma$ for both π and σ with always 90° between them.





Together, whole multiplet is always net unpolarised.

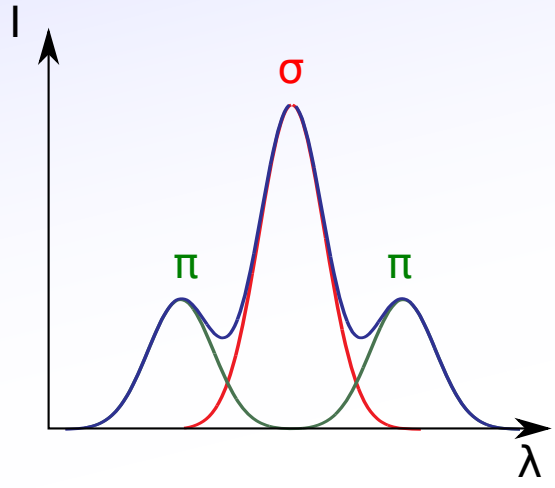
Conventional systems often:
- Select only σ from spectrum and measure degree of polariastion.
- Select only π or σ and measure polarisation angle.
- Measure ratio of π to σ instensity with spectrometer.

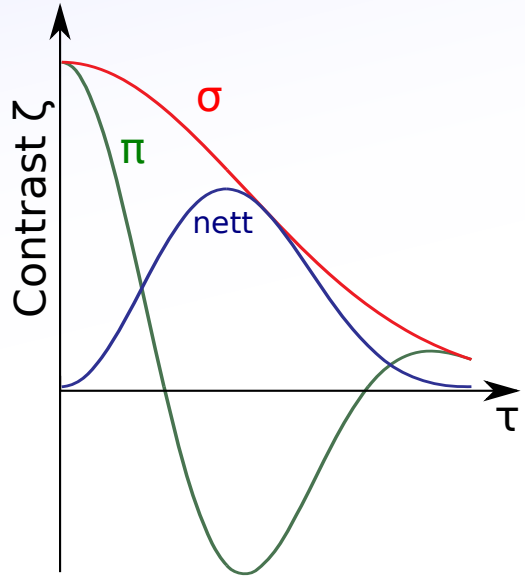
Complex hardware - requires separate filter for each channel.
Low light levels - filter removes large part of light.

Motional Stark Effect Imaging

MSE π and polarised σ are orthogonal and always the same intensity, but they have different spectral profiles, and hence different ζ:

$$\zeta_{nett} = \frac{I_\sigma \zeta_\sigma - I_\pi \zeta_\pi}{I_\sigma + I_\pi}$$





$$I = \frac{(I_\pi + I_\sigma)}{2}\left[1 + \zeta_{nett}\left(\, cos2\theta\, cos(x) + sin2\theta\, sin(x)\, sin(y)\,\right)\right]$$

Recovery of θ is not sensitive to I_π/I_σ or to unpolarised background. As long as ζ_{nett} is large enough, it does not need to be known.

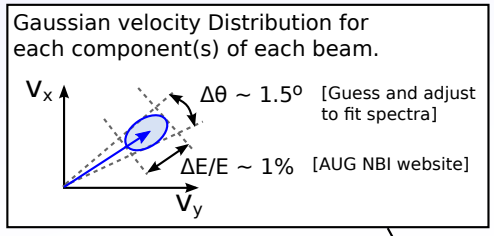
Whole multiplet (and possibly other energy components) can be included.
--> more light --> better signal to noise.

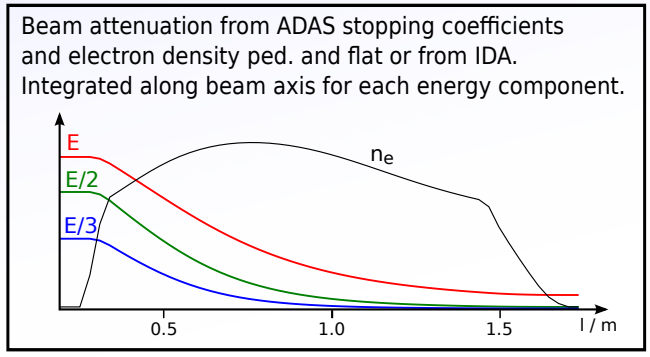
No need for individual filters for different dopper shift, so we can capture a complete 2D image.

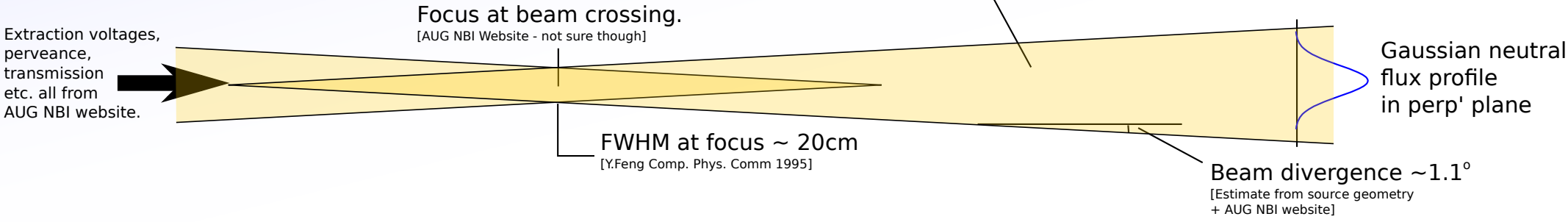
Modelling for AUG: Beams and MSE

To model the MSE CIS System, a few new components had to be added to our general forward modelling environment...

1) A fairly simple neutral beam model.



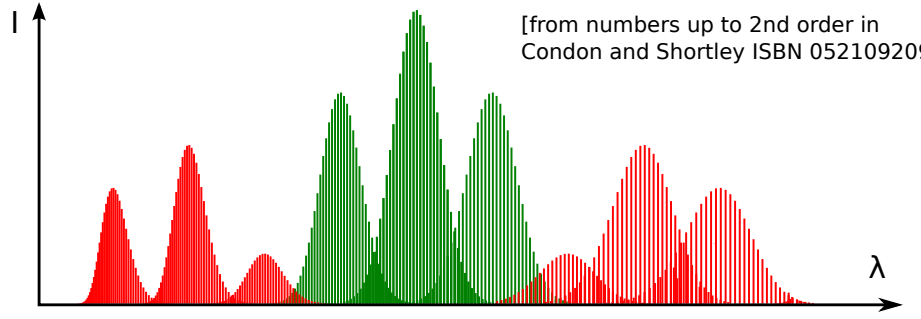




2) MSE Emission Module:

Lists of stokes vectors with Guassian spectral distribution along any given line of sight.

Absolute intensitites calculated using ADAS effective emission coefficients.

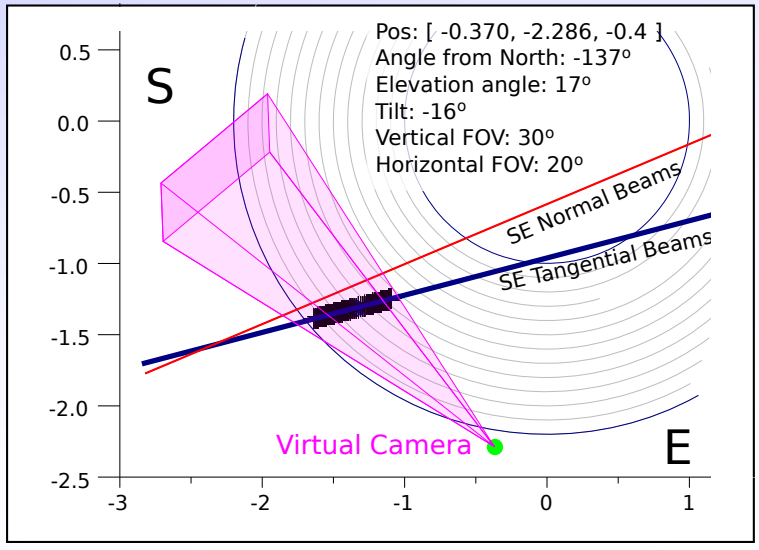


3) Very simple camera base model (optics):

2D fan of lines of sight over given field of view.

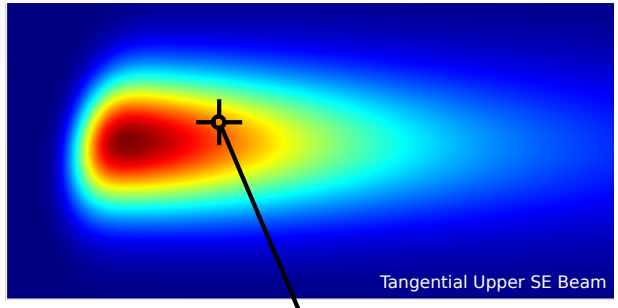
This part probably needs the most work to make the model realistic (optical effects)

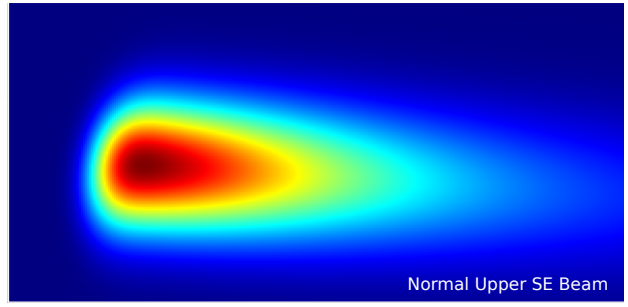
Modelling for AUG: Geometry and spectrum.



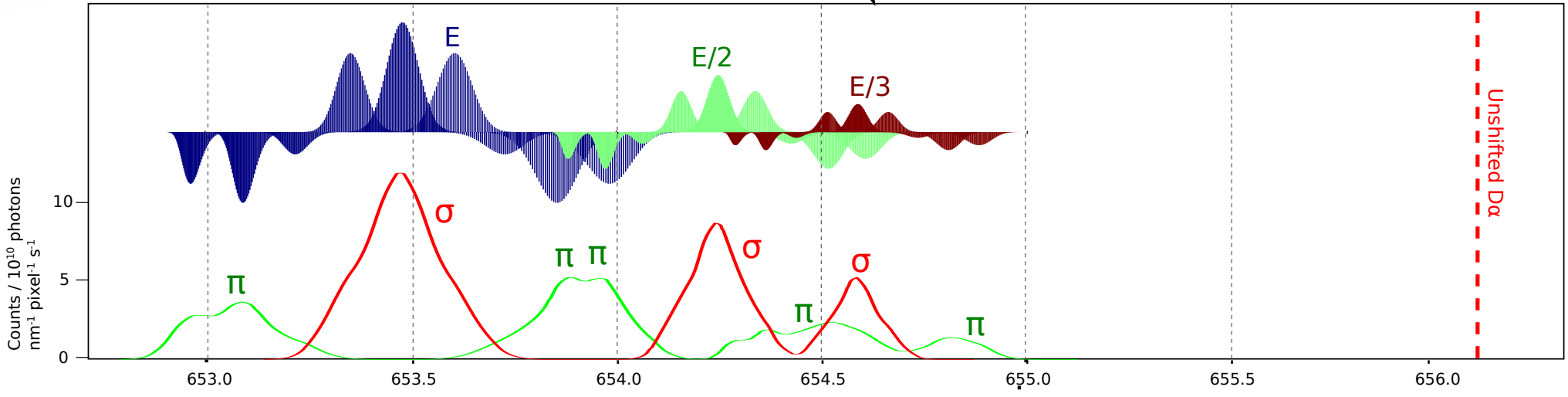
Initial modelling with MSE CIS 'virtual camera' placed at location of mirror in current MSE system.

From here, the total MSE emission looks like this:



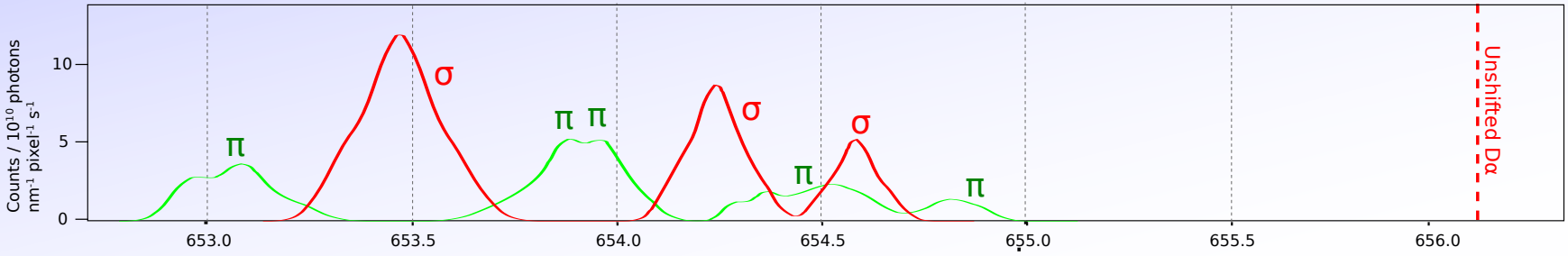


Examination of the spectrum from a single pixel:

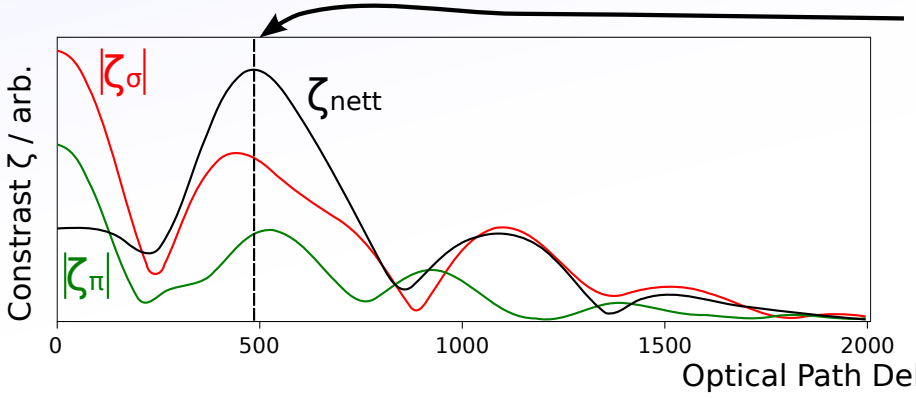


π wings of *E* and *E/2* overlap but this just improves the fringe contrast here.
We can in principal take the light from all the energy components together.

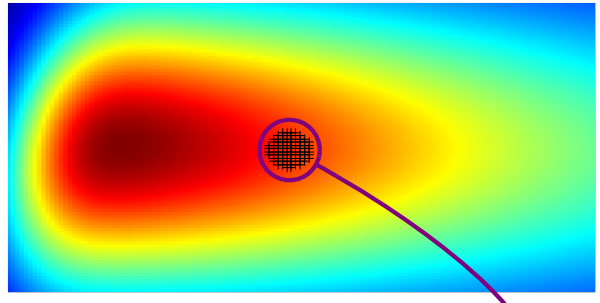
Modelling for AUG: MSE Spectrum



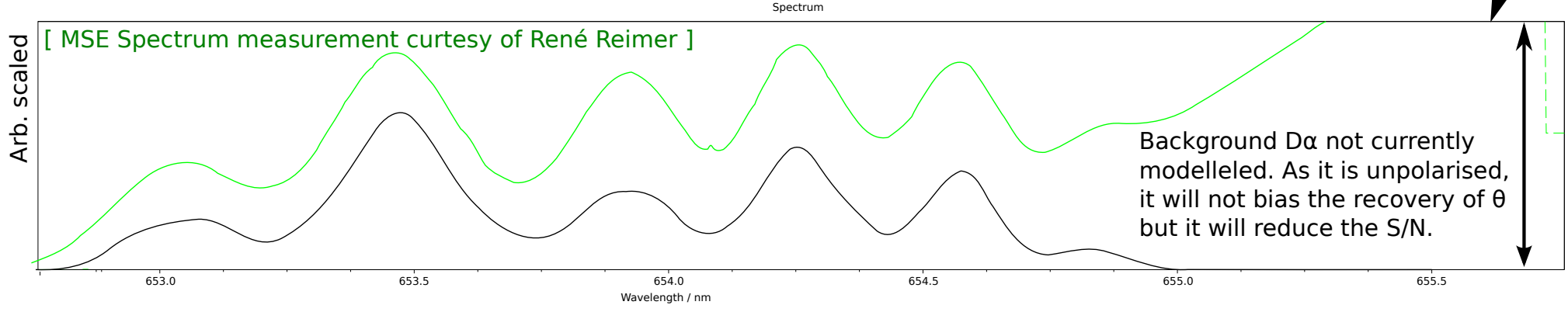
We can also calculate the nett contrast:



Set the fixed delay plate to the OPD of the max nett contrast.



We can also integrate up the spectrum of the pixels that look at the spot covered by the existing MSE spectrometer, to check the model.

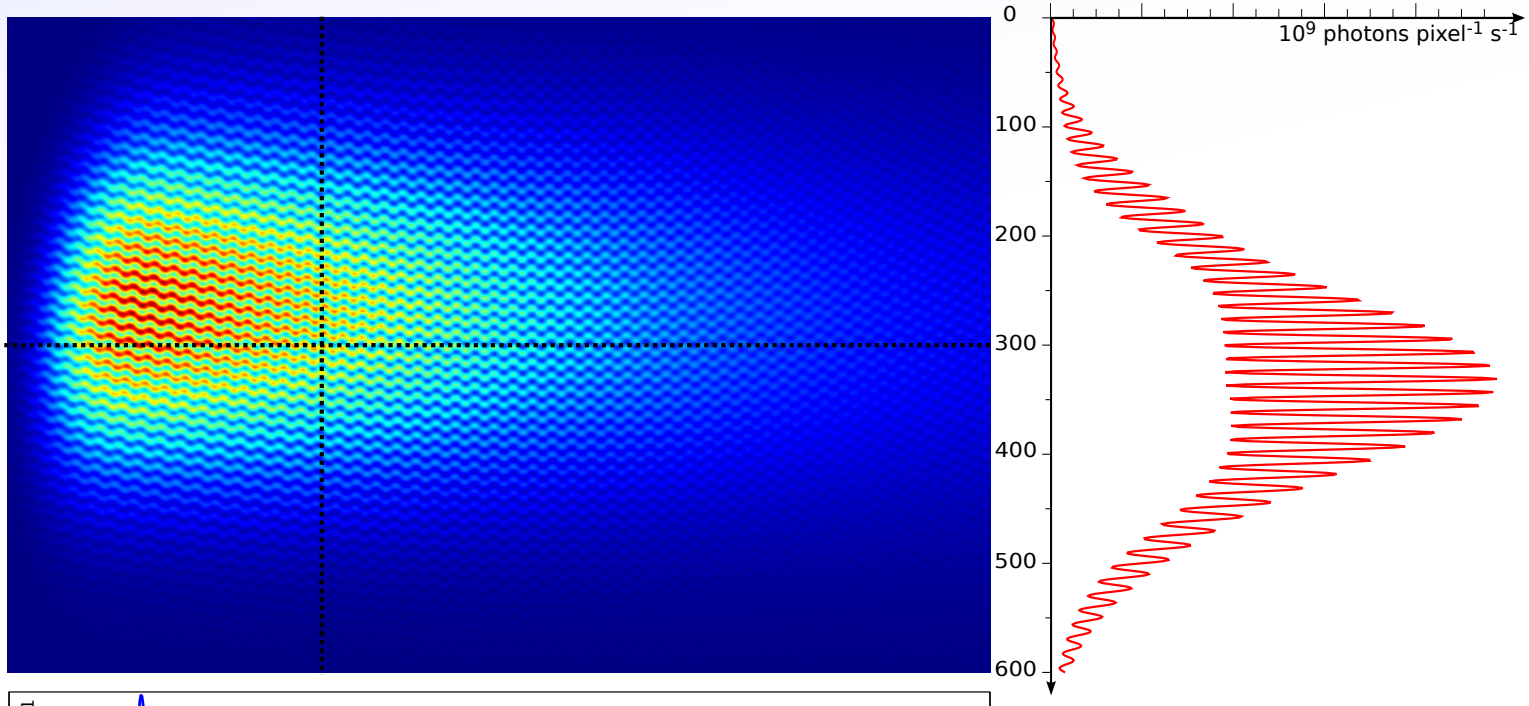


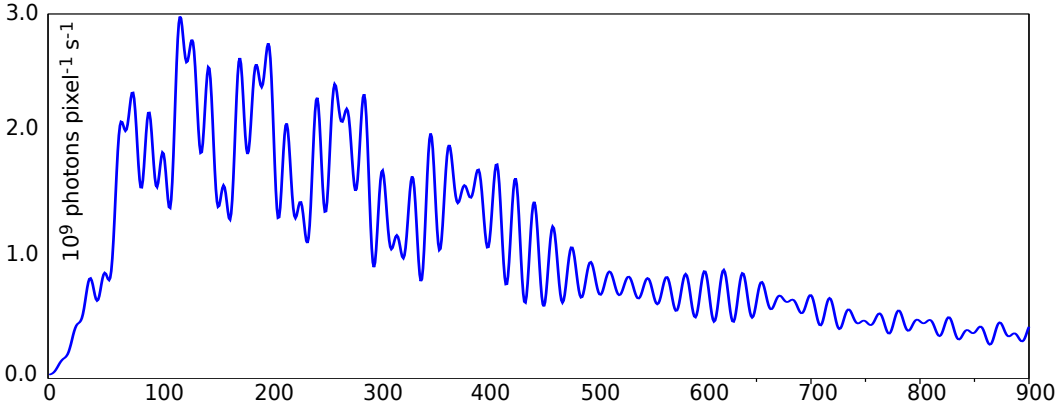
Generally a good match in spectrum. Absolute values match within an order of magnitude.

Double Spatial Heterodyne Model

Thickness of Savart plates sets fringe period in each direction.
Roughly: Shorter fringes = better spatial resolution.
Longer fringes = better S/N.

Using arbitary choice, the DSH model output gives:

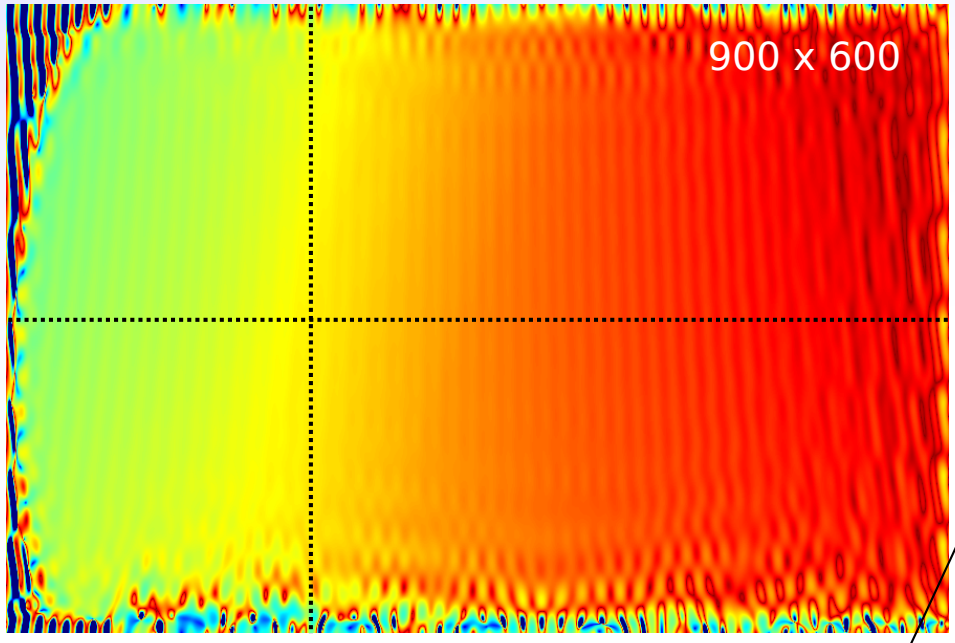


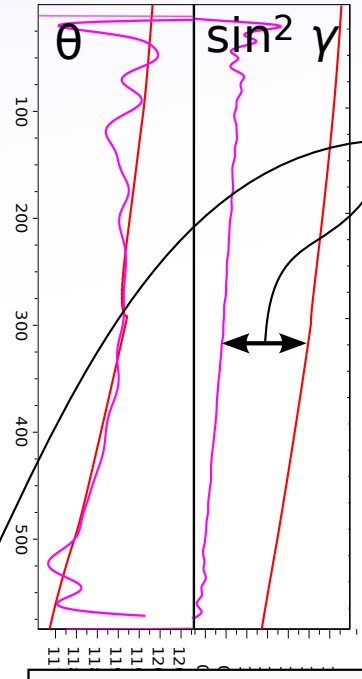


Simple Demodulation

Simple attempt at recovering polarisation projection angle θ from image (with photon noise)

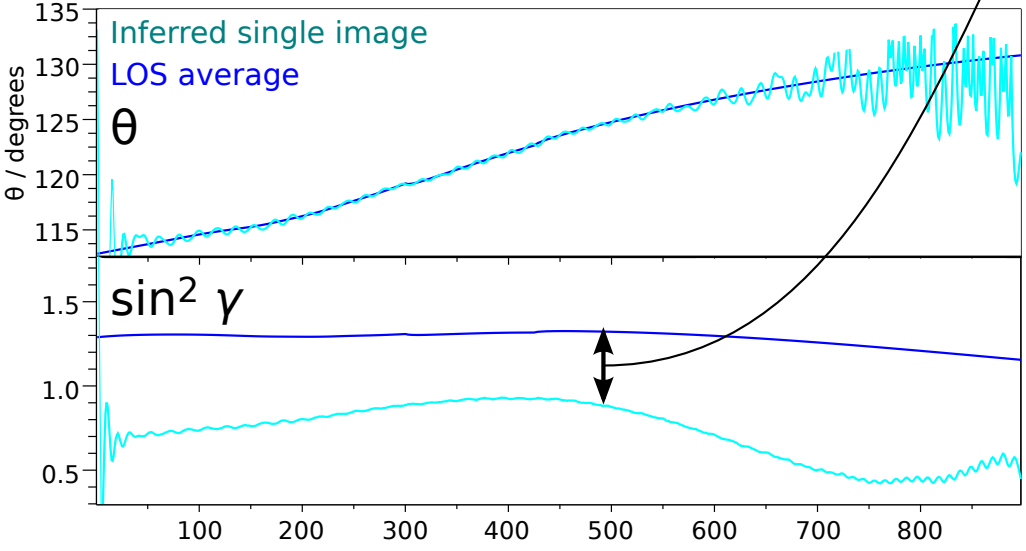
$$I = \frac{(I_\pi + I_\sigma)}{2}\left[1 + \zeta_{nett}\left(\, cos2\theta\, cos(x) + sin2\theta\, sin(x)\, sin(y)\,\right)\right]$$

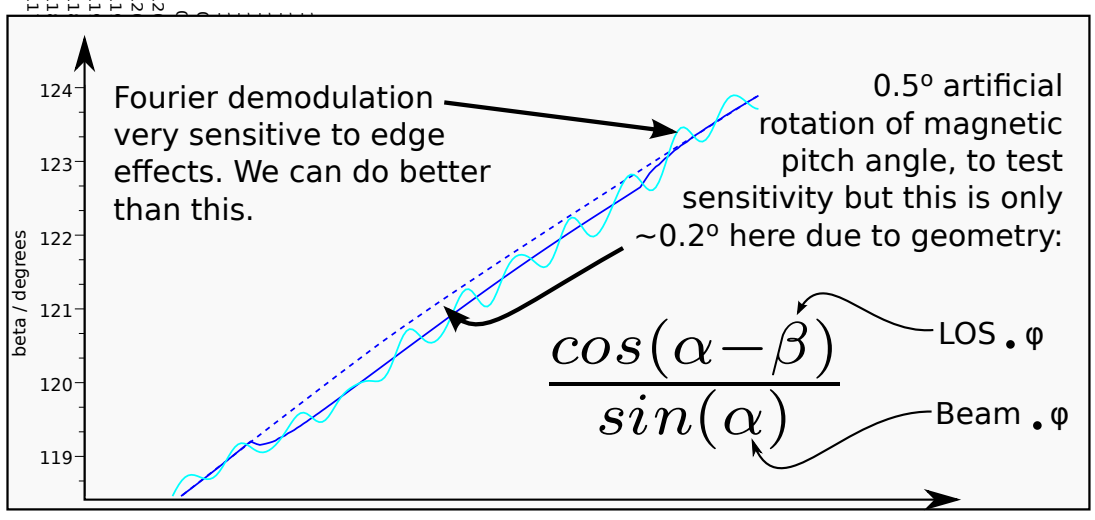




Inferred single image
LOSaverage

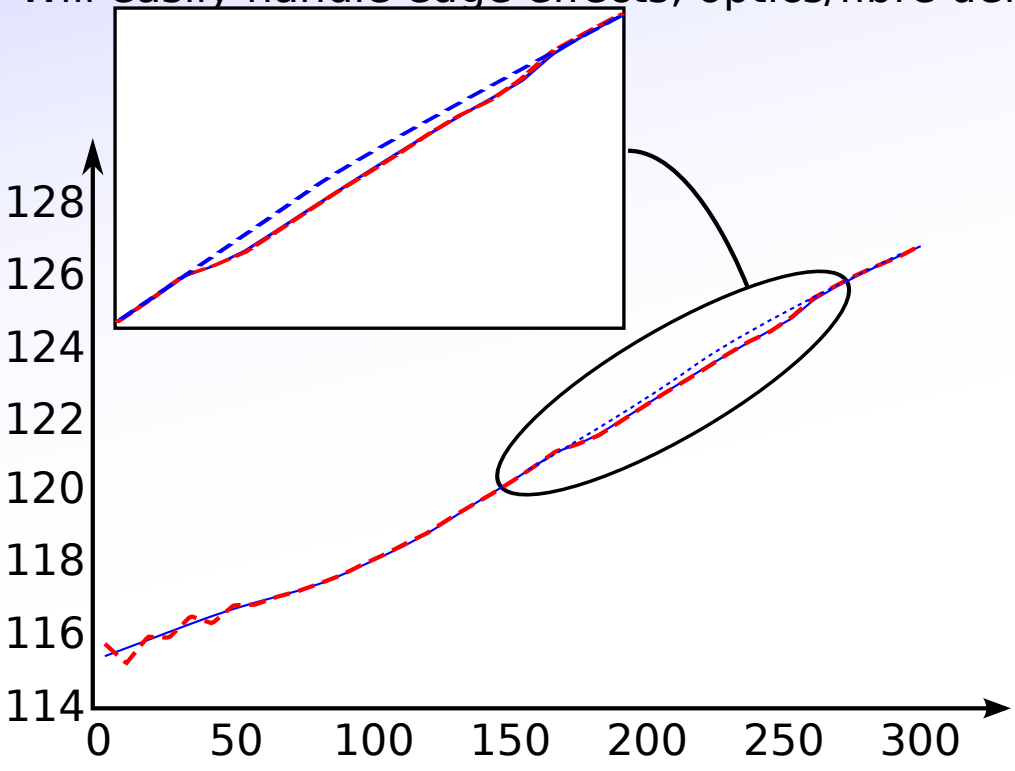
ζ_{nett} also contains the angle γ of E toward/away from camera. LOS integration effects make it difficult but with full Bayesian analysis we may be able to get some more information from this (This is effectively the Iπ/Iσ method).

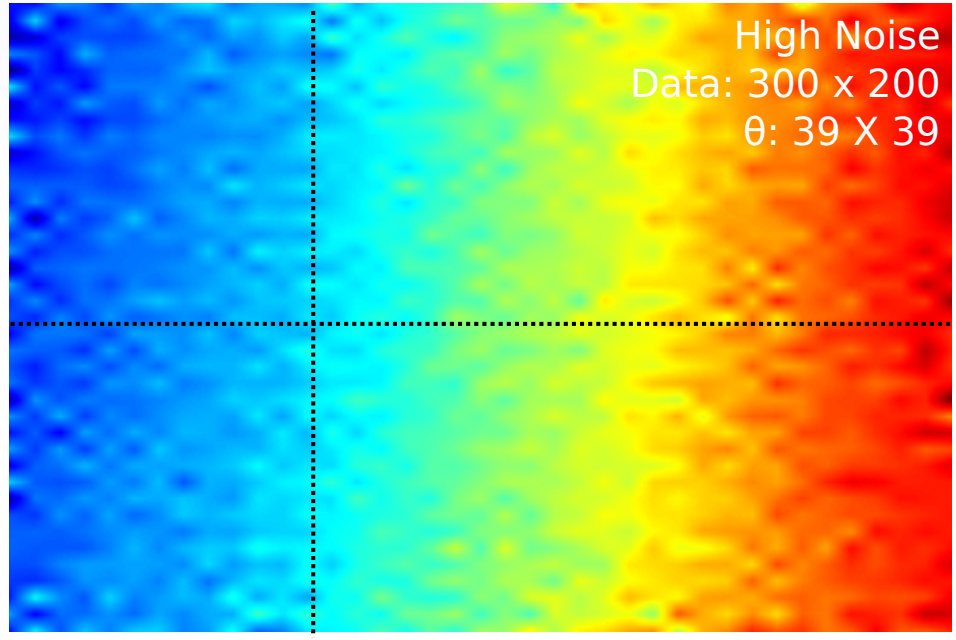




Inference with forward model (Preliminary)

One of the forward modelling/Bayesian techniques (from my PhD work) is very promising.
Will easily handle edge effects, optics/fibre defects, LOS integration etc.





For low noise, it gets nearly perfect reconstruction and remains well behaved with high noise.
For predicted photon counts, recovery to possible to within 0.1^{o} in polarisation angle.
This is for each ~10x10 pixel cell (5mm x 5mm on beam).

Image contains 90x60 of these cells with theoretically independent errors.
Inference of equilibrium (or even a more general but self-consistent field) should be very good.

Needs more development to handle the large images though (we've never had to handle this much data before!)

Outlook for MSE CIS at AUG.

The MSE CIS system has many advantages over traditional MSE systems:
- Much simpler hardware: Series of optical plates and a camera.
- Much higher light collection: Whole multiplet or even all 3 can be collected.
- Insensitive to changes in beam energy (Doppler shift changes).
- Full 2D view of polarisation - much more data so much better statistics.
- High spatial resolution - each pixel covers a small beam area.

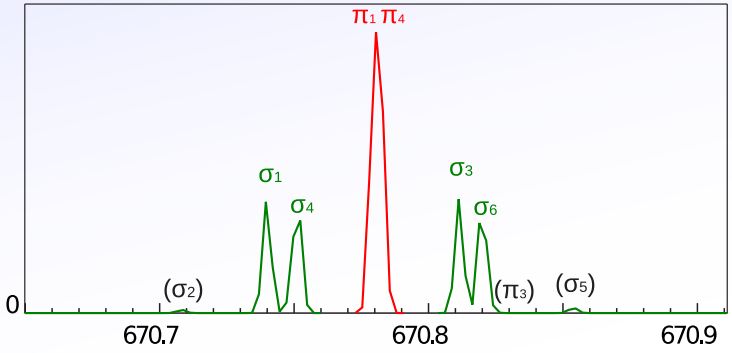
Modelling so far based on using existing MSE optics,
For this, the polariser would need to be removed and PEMs switched off.

To complete the sensitivity study, we need to:
- Check all the inputs to the model are correct / realistic.
- Find other views/port locations - I need an idea of what is possible.
- Add a model for background Dα.
- Improve optics model to investigate things which will introduce systematic errors.

- Complete a systematic study of the accuracy of inferred pitch angle image so we can decide what is best to build.

Lithium Beam Zeeman Splitting

We are also looking at the possiblity of using a CIS system to measure H-mode pedestal current via the Zeeman splitting of Lithium beam emission.



[Graph and all imformation so far courtesy from 'Zeeman Feasibility' report (E. Wolfrum et. al.)]

Polarisations are slightly different: π components polarised parallel to magnetic field.

Full image across the very small Lithium beam (~1.5cm) should give very good spatial resolution, when view is parallel to flux surfaces.

However, projection of polarisation requires viewing at some angle to field, so the LOS integration reduces the resolution.

Modelling work started but the details of Lithium beam (intensity/flux, attenuation model etc) are still needed.

Finally...

We are proposing to design and build a 2D MSE and/or Zeeman coherence imaging system to help improve diagnostic capability at AUG.

This presentation has been of just the modelling work and should give an idea of what these systems are, and what they capable of.

Please tell me if you have any corrections to models and input parameters or if you have any other ideas or concerns. Any input is welcome!

We also want to know what everyone at AUG would want from either system.

Thanks for listening.