Motional Stark Effect Coherence Imaging for ASDEX Upgrade.

Design and evaluation progress.

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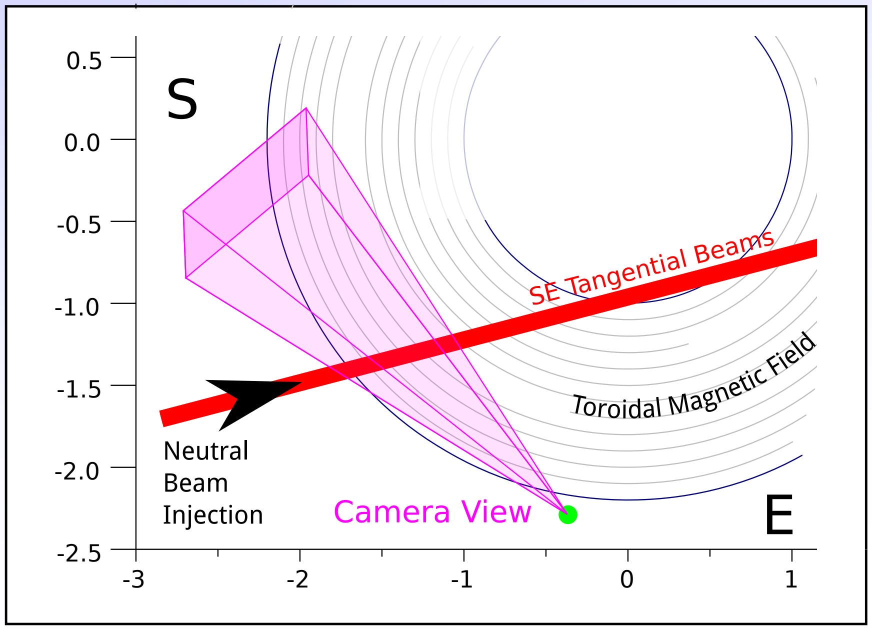
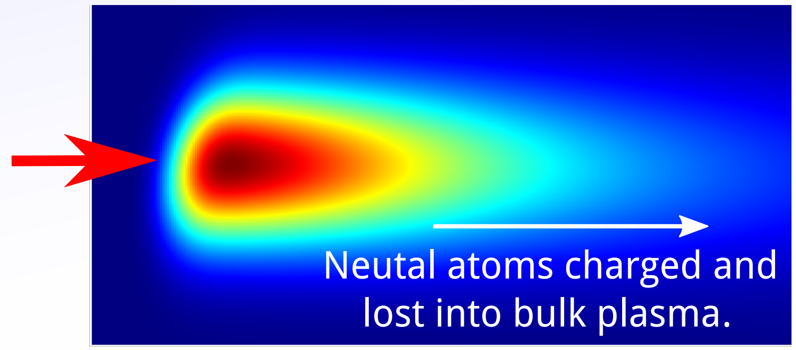
- Brief (re)introduction.
- Line integration and resolution.
- What do we gain with 2D measurements?
    - in Theory,
    - in Practice
- Model improvements.
- Outlook

Very Brief Introduction



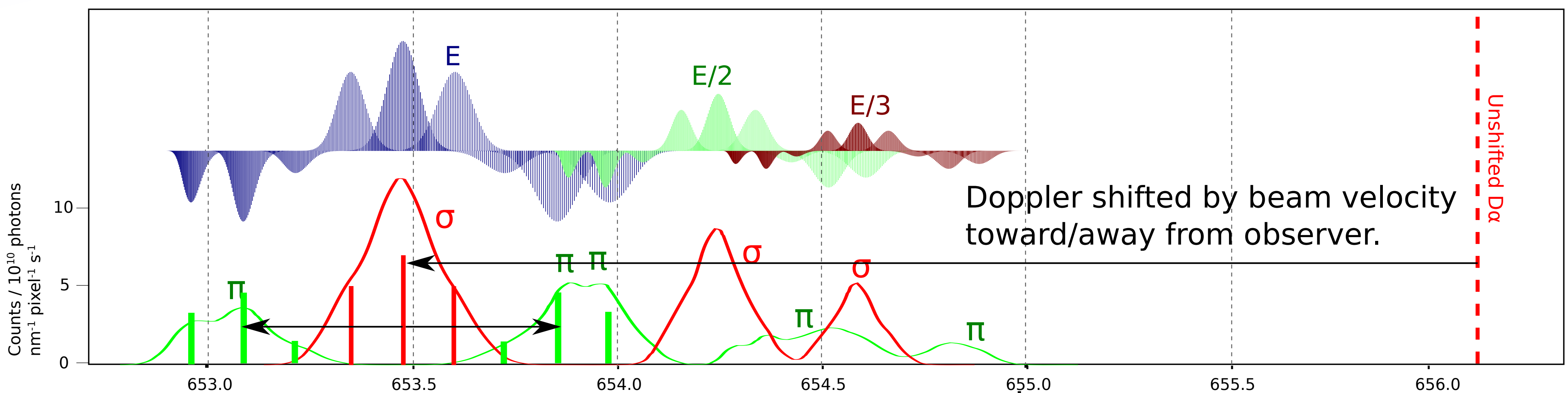
Neutral beam atoms injected into plasma.
Excited by plasma, then emit Hα/Dα radiation.



Complications:

Atoms with different injection energy: different Doppler shift.
Doppler broadening: Beam divergence, line integration etc.
Background Dα (not shown).

Spectrum from a single pixel:



Stark split by electric field in rest frame of atom:

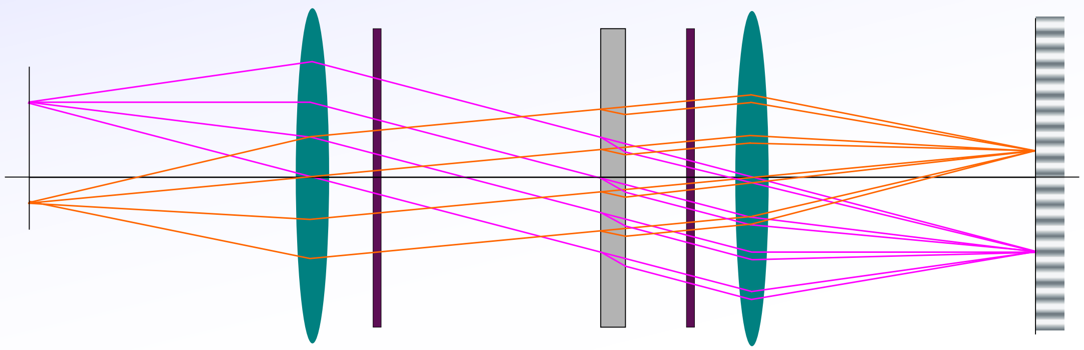
$\boldsymbol{E} = \boldsymbol{v} \times \boldsymbol{B}$

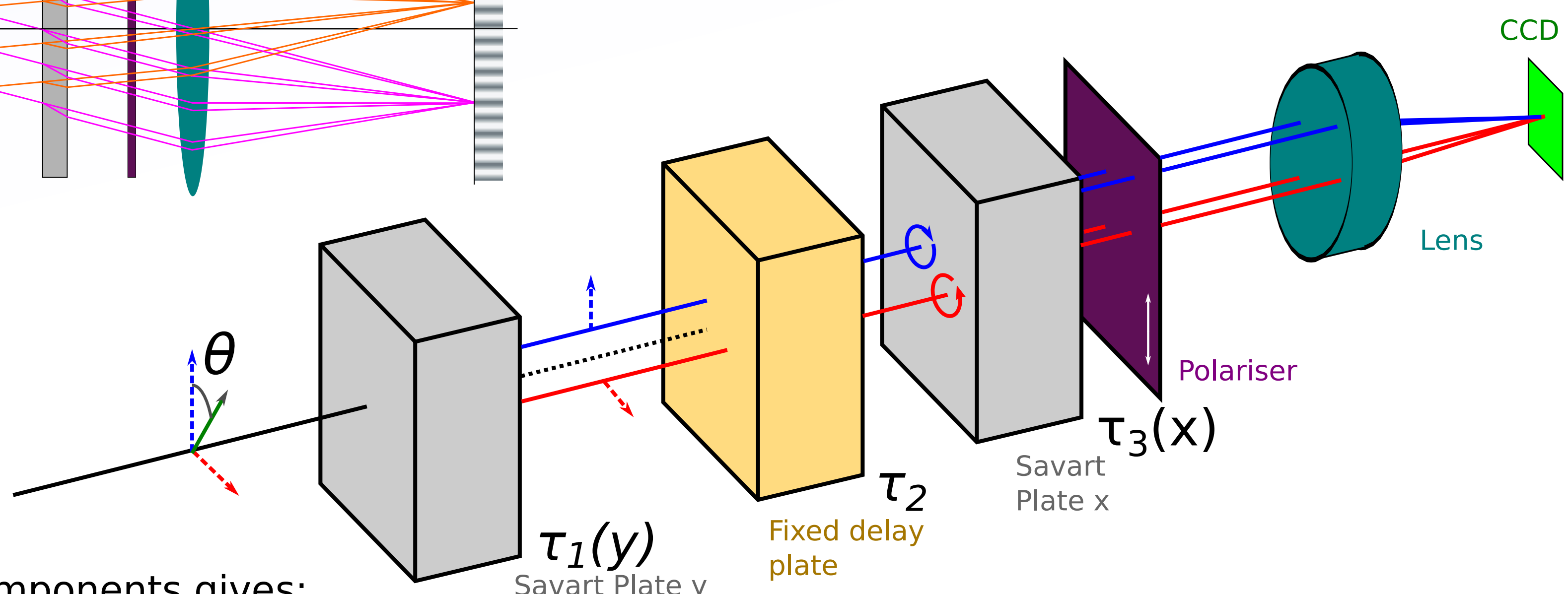
Roughly: π polarised parallel to E.
σ polarised perp' to E.

Introduction: Spectro-Polarimetric Imaging

We want a full 2D image of polarisation of Dα emission from beam.
Needs to also be sensitive to spectrum and polarisation.

Savart plates: Split light into 2 components and time delay one depending on incident angle (i.e. position in image/object plane).





The interference of all 4 components gives:

Intensity Fringe Contrast Polarisation Angle

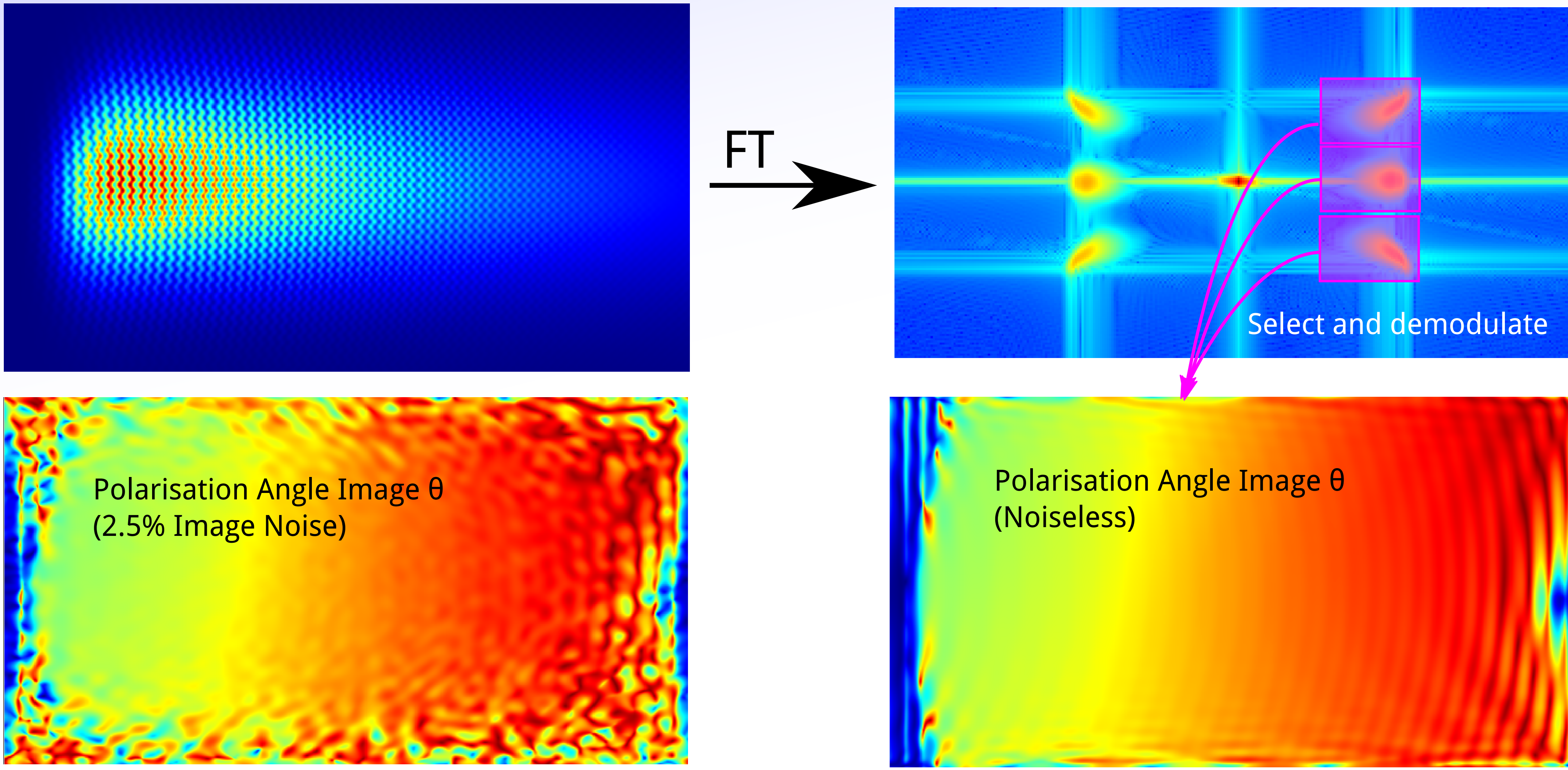
$$I = \frac{I_0}{2}\left[1 + \zeta\left(\cos 2\theta \cos(x) + \sin 2\theta \sin(x)\ \sin(y) \right)\right]$$

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

(For the record: This is the '*Ampltiude Modulated Double Spatial Hetrodyne*' system).

Simple Demodulation

The image will look something like this:



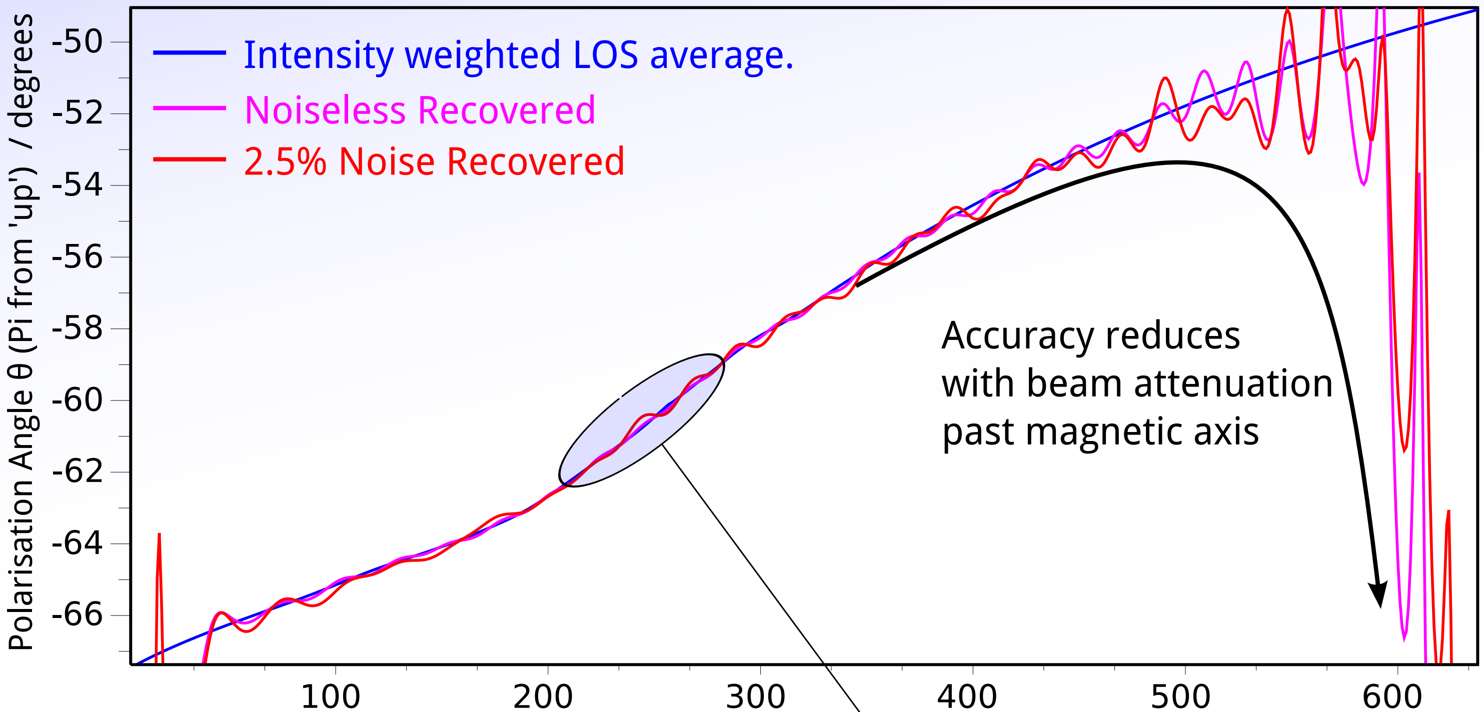
$$I \neq \oint \frac{I_0}{2}\left[1+\zeta\left(\,\cos 2\theta\,\cos(x)+\boldsymbol{\sin 2\theta\,\sin(x)\,\sin(y)}\,\right)\right]\,dl$$

$$\neq \frac{<I_0>}{2}\left[1+<\zeta>\left(\,\cos<2\theta>\;\cos(x)+\sin<2\theta>\;\sin(x)\,\sin(y)\,\right)\right]$$

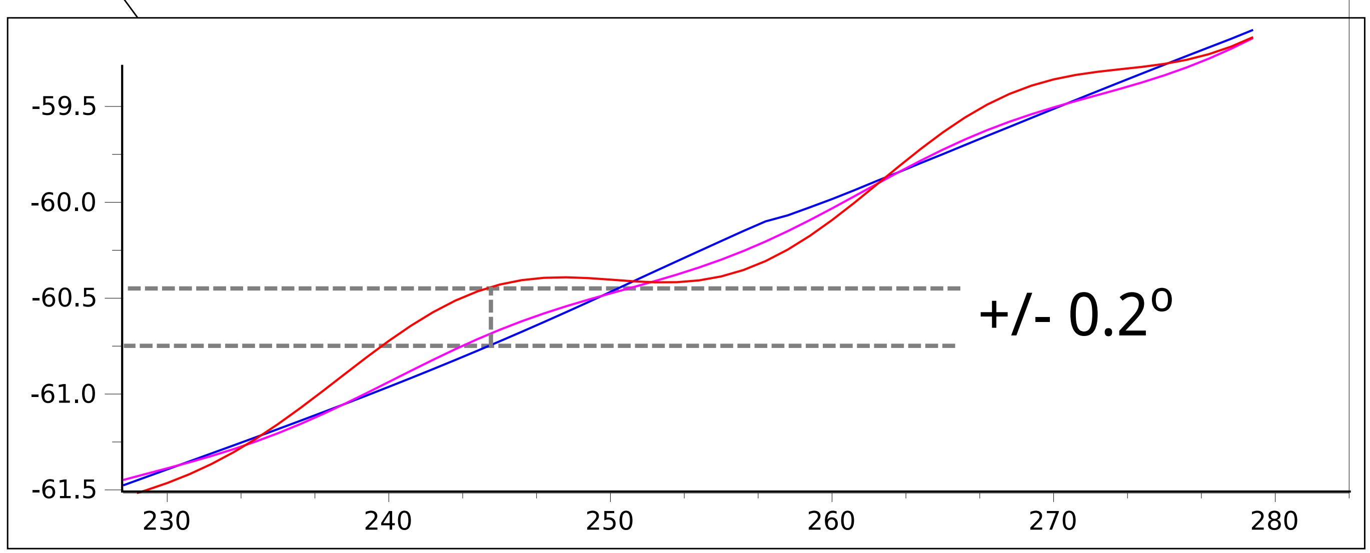
Actually, this is wrong. The image is really the integral of this over the LOS.
However - it seems that if we assume it is, the recovered θ is the same as the LOS average for each pixel.
The other terms are not equal to their LOS averages and introduce extra phases.

Demodulation: Accuracy of θ recovery.

Recovery of θ from a noiseless and noisy images gives us our probably accuracy:

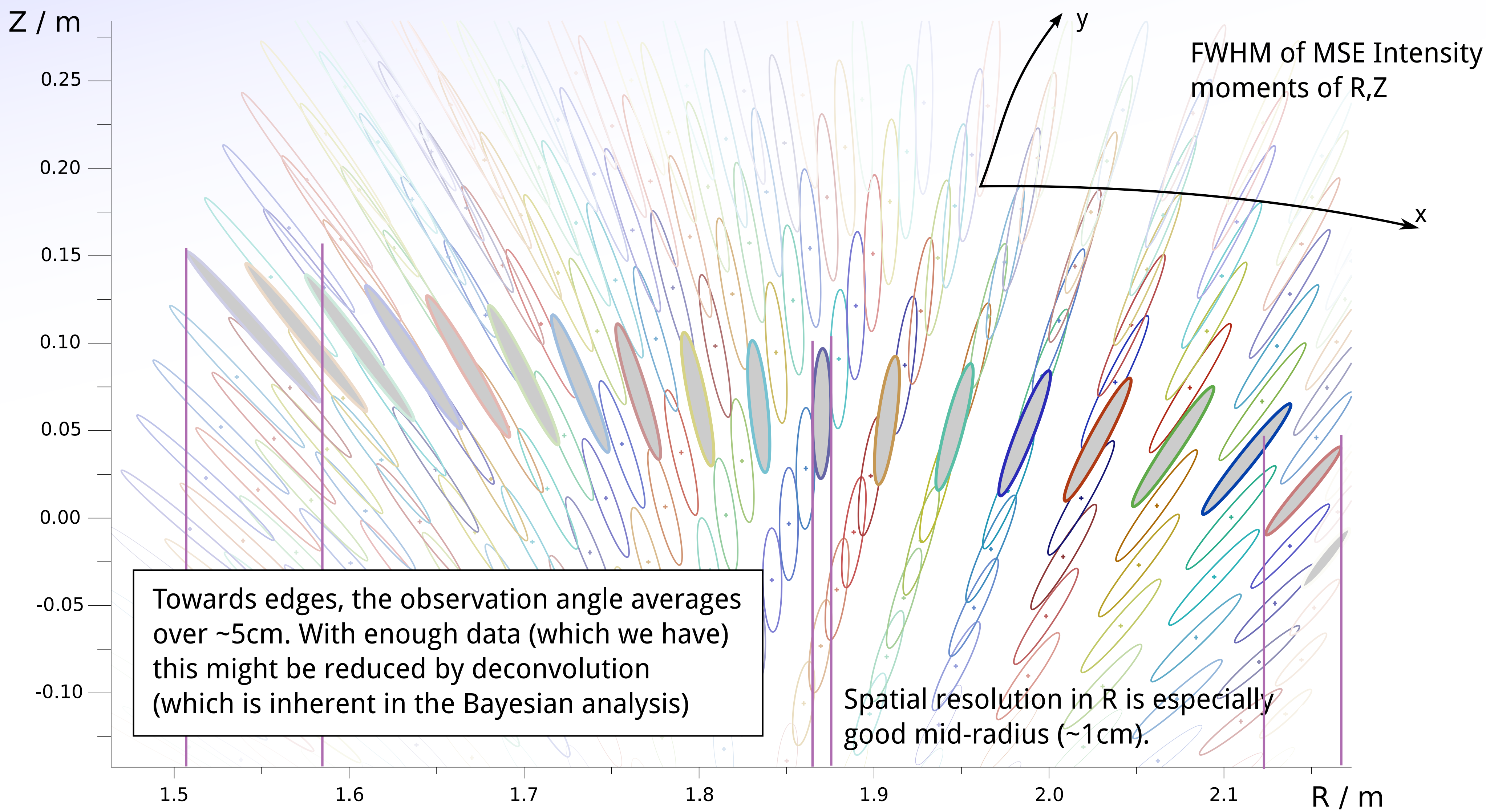


It might be better than this, since these are partly artifacts of the demoulation. However, for now we can take θ +/- 0.2° as the accuracy.



Spatial Resolution

The recovered θ are really $\langle\theta\rangle$ over the LOS. Spatial resolution is a combination of pixel-pixel averaging due to modulation (1cm) and the LOS averaging.
The LOS averaging varies over image (x,y):



Recovery of plasma current.

To final objective is to measure plasma current *j*.
For normal 1D measurements: not possible so θ used as a constraint for equilibrium.
Does having 2D measurements make it possible to calculate *j* without equilibrium?

Assuming toroidal symmetry, the current is:

$$-\mu_0 j_\phi = \frac{\partial B_z}{\partial R} + \frac{1}{R}\frac{\partial^2}{\partial Z^2}\int_0^R R' B_z(R', Z)\, dR'$$

Assume we know B_ϕ as the vacuum field, then we can calulate B_Z from θ.

However, we only see where the MSE emission is, so can only integrate from some $R = R_0$:

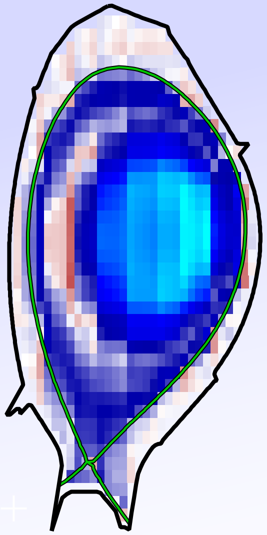
$$-\mu_0 j_\phi = \frac{\partial B_z}{\partial R} + \boxed{\frac{1}{R}\frac{\partial^2 \psi(R_0, Z)}{\partial Z^2}} + \boxed{\frac{1}{R}\frac{\partial^2}{\partial Z^2}\int_{R_0}^R R' B_z(R', Z) dR'}$$

This we have
with 1D MSE.

Function of Z that
we cannot know.

The new term gives
localisation of current
in Z (~via curvature of field).

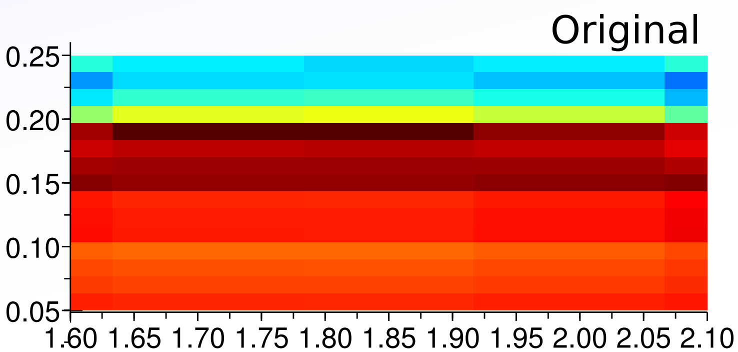
A normal MSE system has only $B_z(R)$ so cannot calculate the 3rd term.
In theory, with 2D measurements, we can.

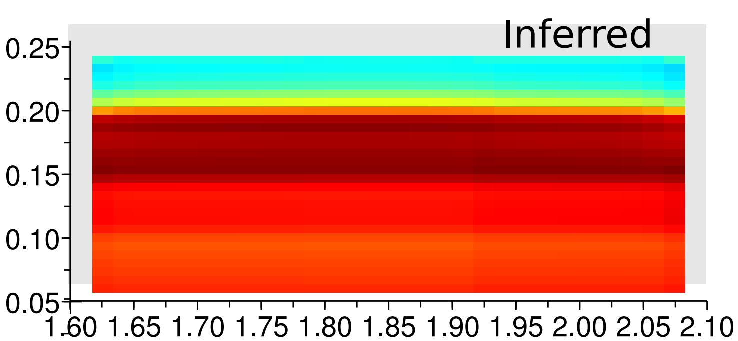


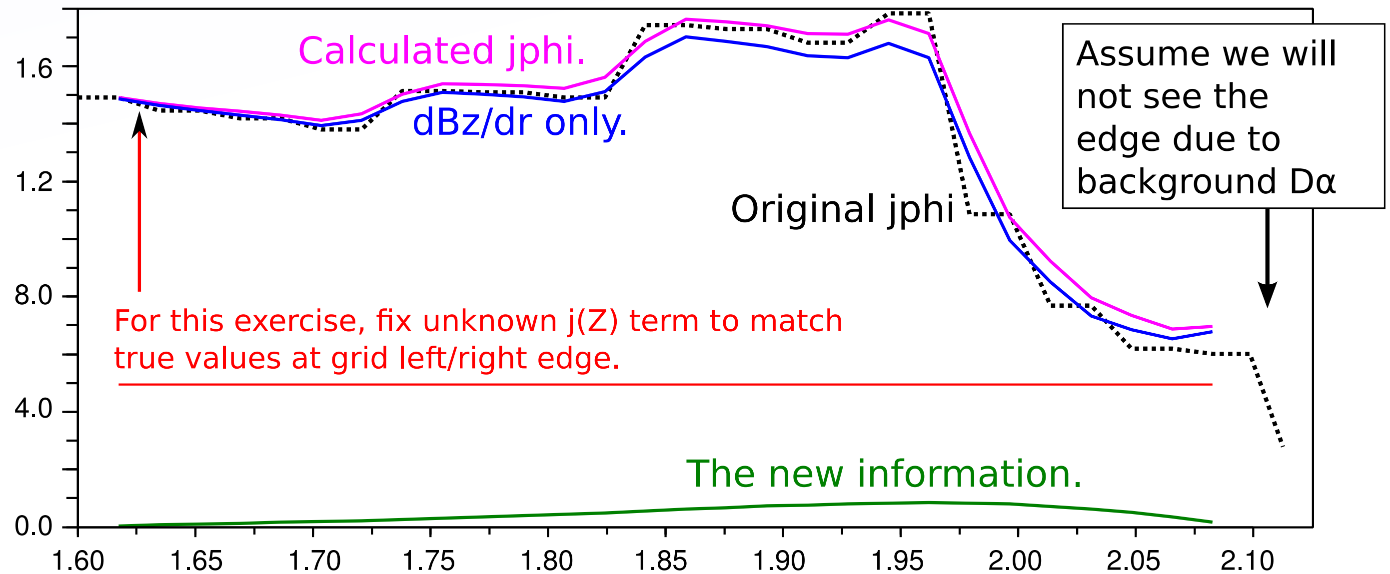
So can we directly calculate $j\phi$?

- Take CLISTE current distribution
- Predict 30x30 grid of Bz.
- Try to directly calculate jϕ

$$-\mu_0 j_\phi = \frac{\partial B_z}{\partial R} + \frac{1}{R}\frac{\partial^2 \psi(R_0,Z)}{\partial Z^2} + \frac{1}{R}\frac{\partial^2}{\partial Z^2}\int_{R_0}^{R} R' B_z(R',Z)\,dR'$$





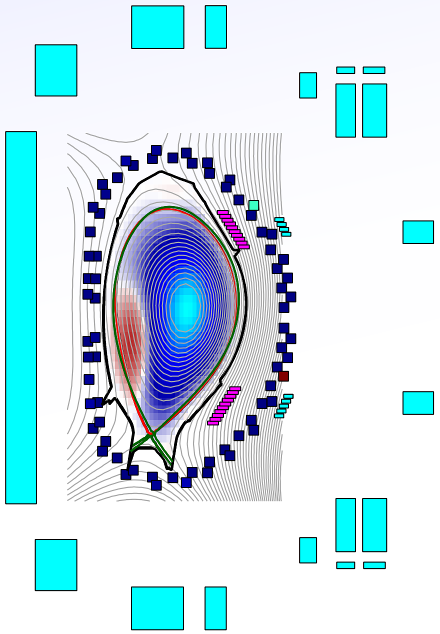


The new part is < 10%. We do gain it mathematically but it will be entirely lost in the noise. Anyway, the f(Z) term is still not known.

Conclusion: **No**. You still cannot exactly calculate j_ϕ directly.

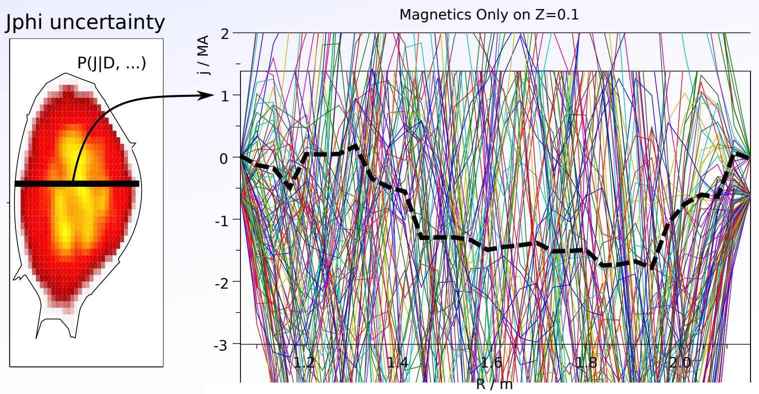
However, we still might not need to go as far as equilibrium as we also gain measurements of dBz/dR at different Zs. Together with normal coil measurements, it is now part of a complex tomography problem that we have done before.

By current tomography...



AUG PF coils and pickups model now in Minerva, so we can do Current Tomorgraphy and Bayesian Equilibrium for AUG. Try simple tomography from:

1) Magnetics only: We have the usual tomography situation:

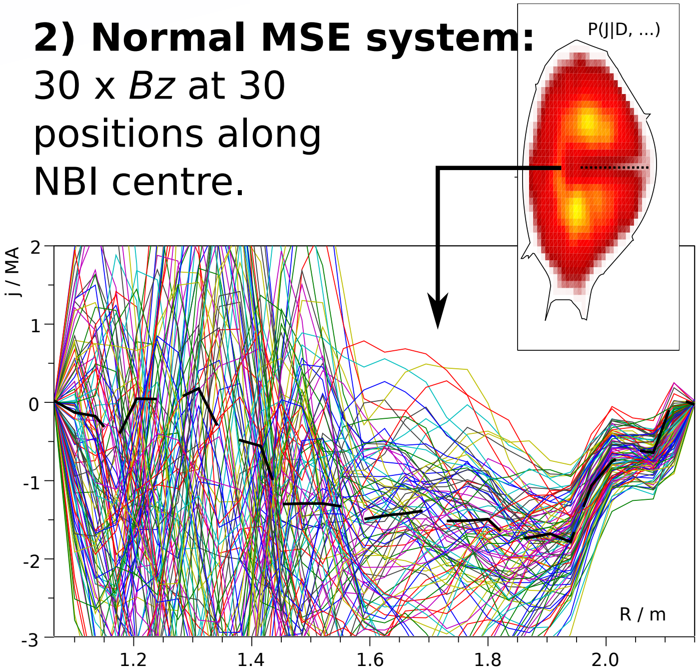


(Almost) no prior/regularisation

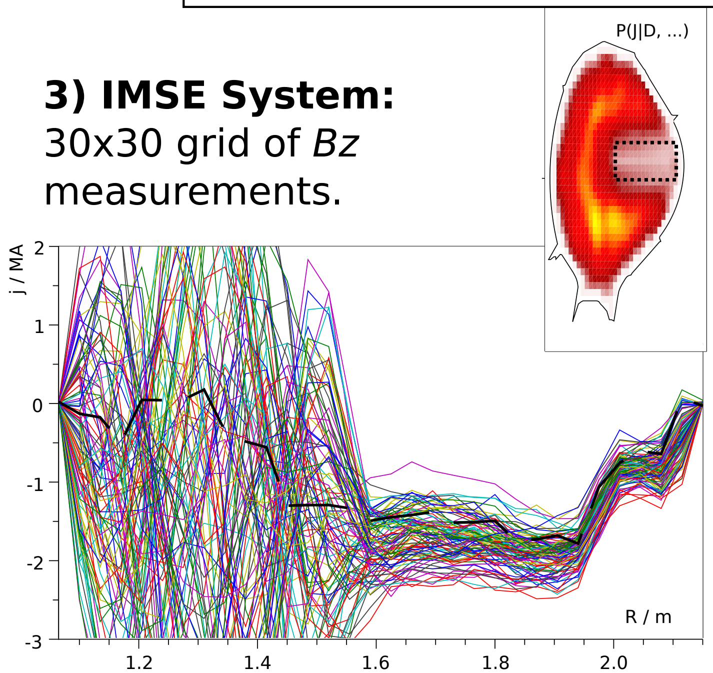
(Almost) infinite uncertainty
(but B and flux still good)

Each case has 900 measurements at sigma = 10mT.
So difference is only in the ***type*** of information.

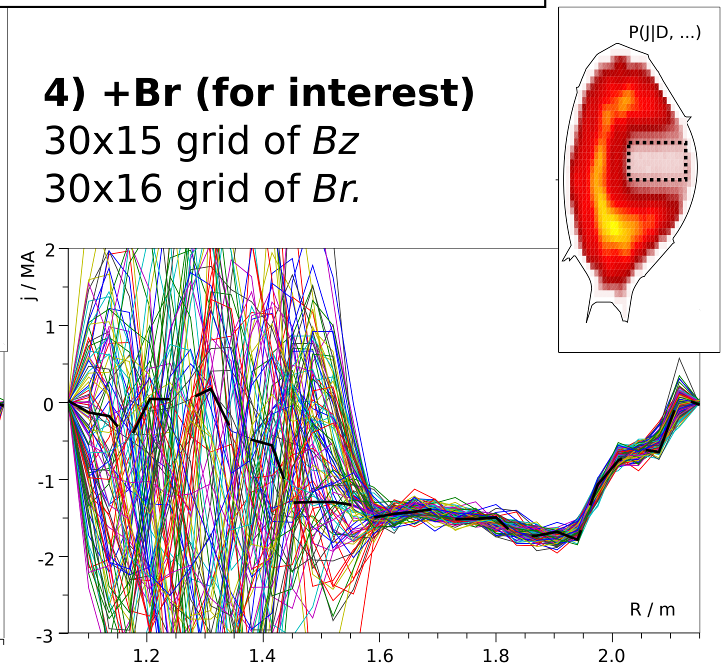
2) Normal MSE system:
30 x *Bz* at 30 positions along NBI centre.



3) IMSE System:
30x30 grid of *Bz* measurements.

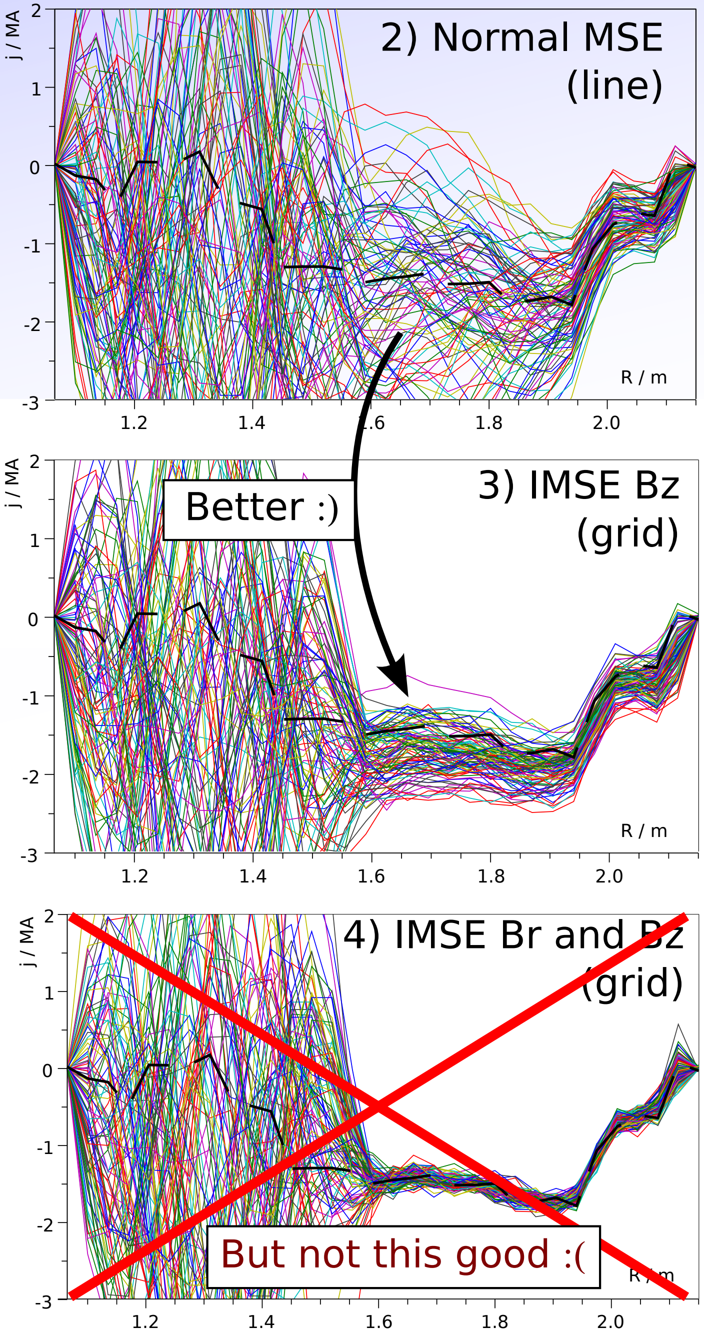


4) +Br (for interest)
30x15 grid of *Bz*
30x16 grid of *Br*.



All sigmaBr = sigmaBz =10mT

By current tomography II

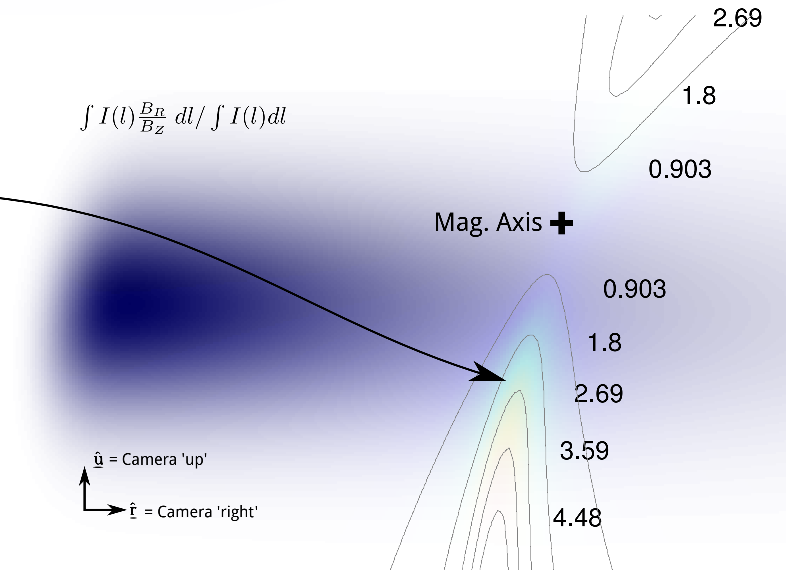


The IMSE still has a large uncertainty in j_ϕ offset. The unknown term it is not entirely pinned down by the magnetics.

The 2D IMSE inference is much better than the equivalent MSE system.

Result with B_r is much better: If we could get B_r as well, we could infer the current almost exactly.

Off axis and near the core, the AUG IMSE system will see B_r with reasonable strength:



Relative stength of Br: MSE Intensity weighted LOS integral Br/Bz

Unfortunately, information about Br is always swamped by Bphi.

Even here, the LOS average polarisation angle, in terms of the field is:

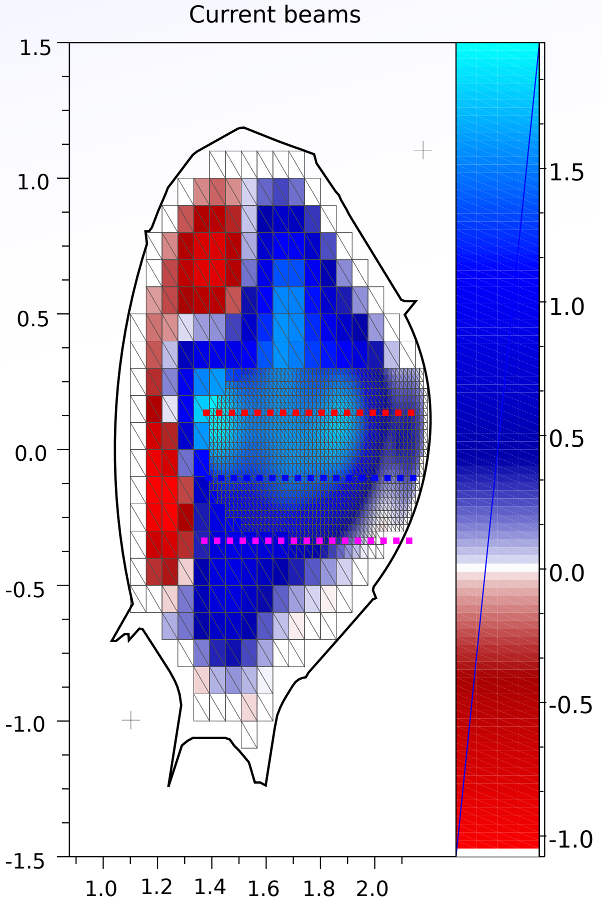
$$\tan\beta \approx 0.17 + 0.54\frac{B_Z}{B_\phi} + 0.05\frac{B_R}{B_\phi}$$

At 5 - 10%, it will have an effect, but we do not expect to see the full current recovery from 2D tomography.

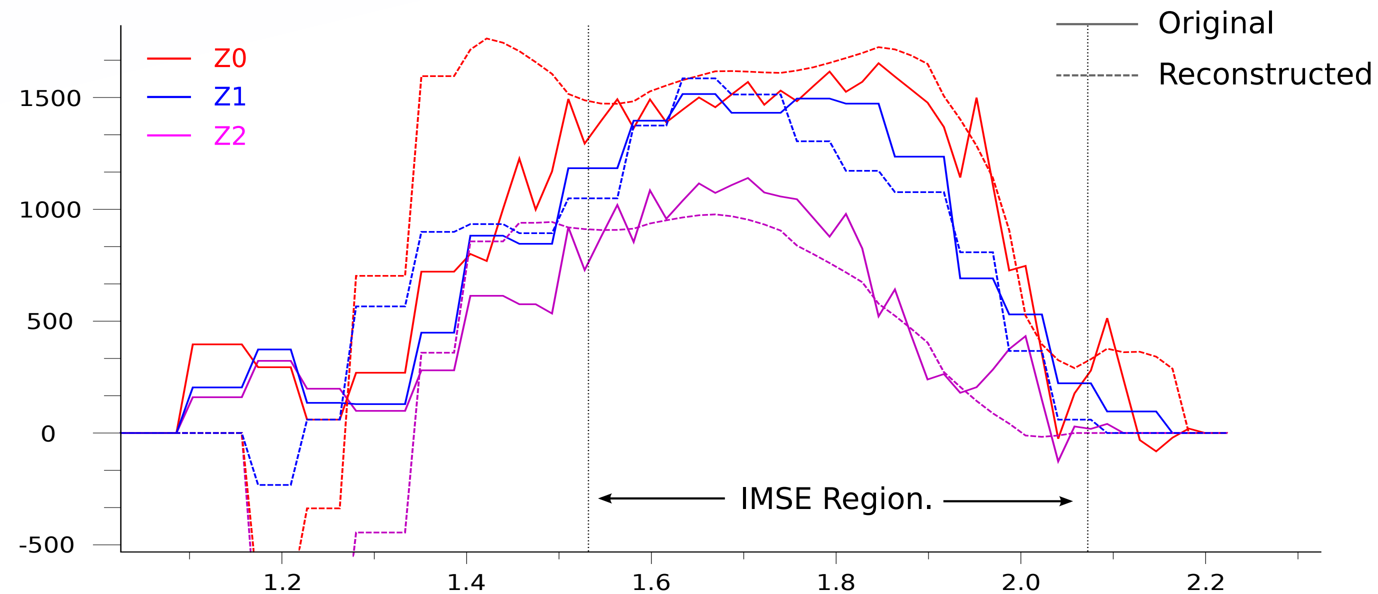
Full Inference

From this week, I can now do the full inversion from polarisation angle to plasma current *θ(x,y)* --> $j_\phi(R, Z)$, (without equilibrium) thanks to some new non-parametric (Gaussian process) priors (J. Svensson) and getting access to an unloaded linux cluster (on wednesday).

With Minerva's automatic parallelisation and irregular grid support (from my PhD work), it is possible to concentrate parameters under the IMSE region, and invert from θ on each fringe (= 60x40 'data').

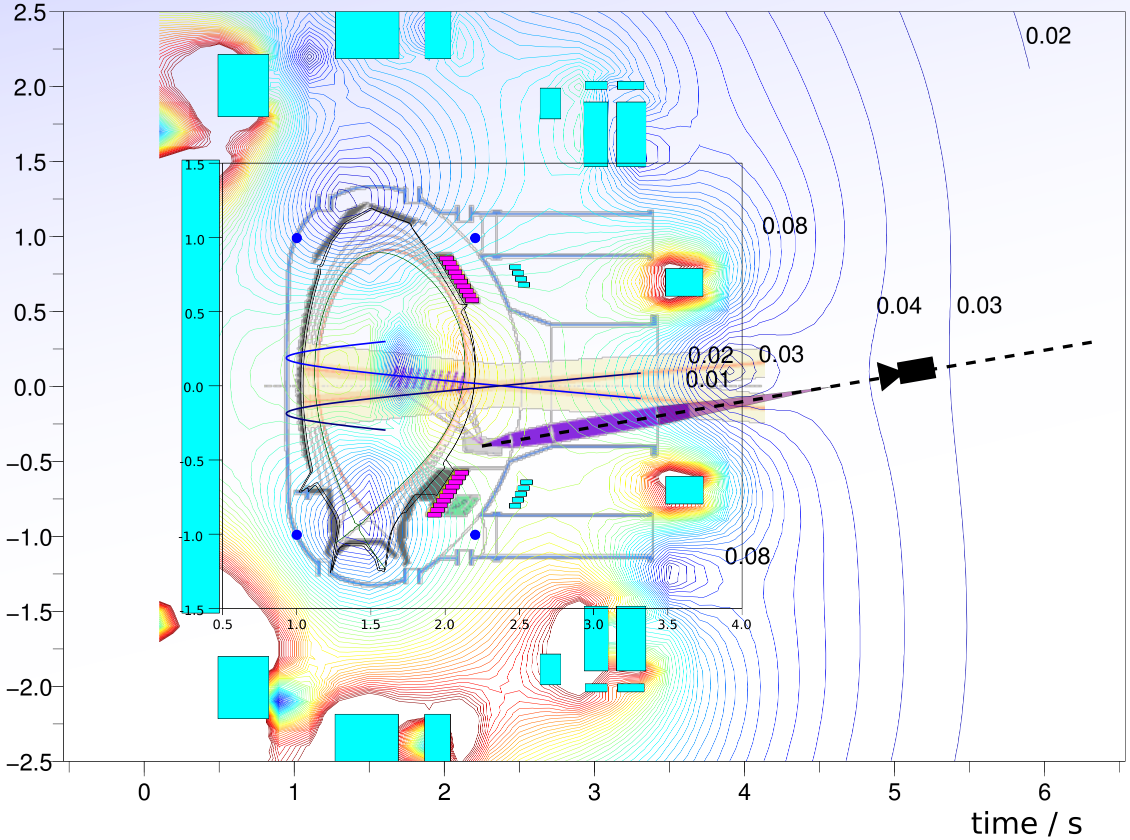


This requires calculating 3960x1496 magnetostatic responses $B_p(j_\phi)$, 1496x2400 image responses θ(jϕ) and a 1496^2 inversion. (hence the linux cluster).



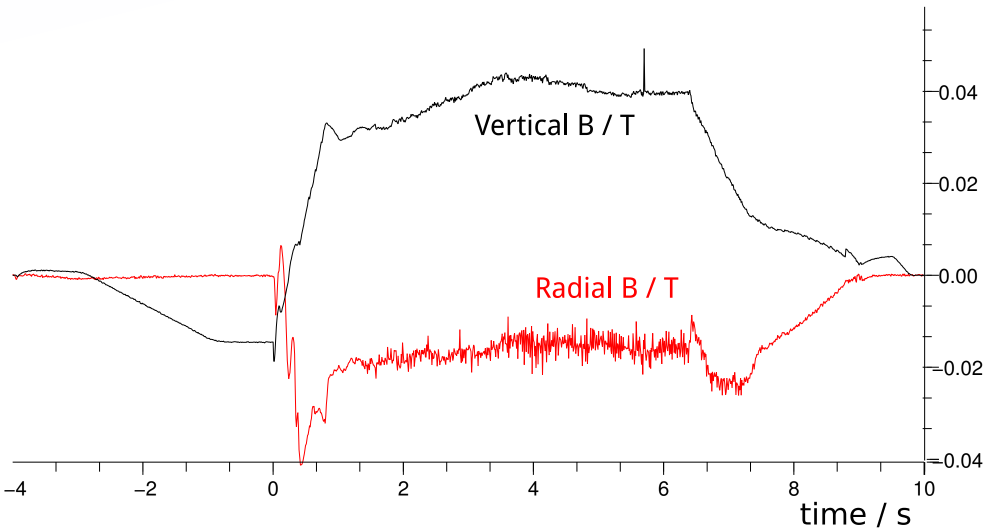
Initial results indicate that it is possible to recover the $j_\phi(R, Z)$ to at least a good resolution for studying the bulk plasma (e.g. testing different equilibrium models etc). This is MUCH better than is currently possible. Resolution is processing limited - Higher resolution may be possible,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

Other progress (Hardware)



Ideally, we want to fix the camera and optic plates directly to the viewing optics (no fibre etc).

Camera will be subject to magnetic field, which Minerva can predict from the PF coils.
For the highest plasma current (I_p = 1.2MA),
$|B| < 50$mT:

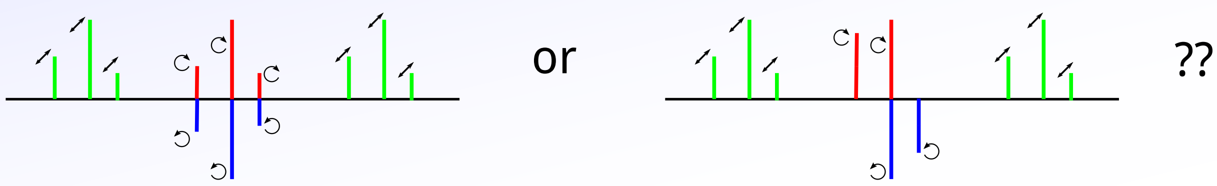


- The camera we have (12bit 1376x1040 Imager QE) was used next to the coils in Pilot (PSI) last year, so may survive this. Apart from a very slow frame rate (10Hz), it is otherwise perfectly suited, so could be used for a first attempt.

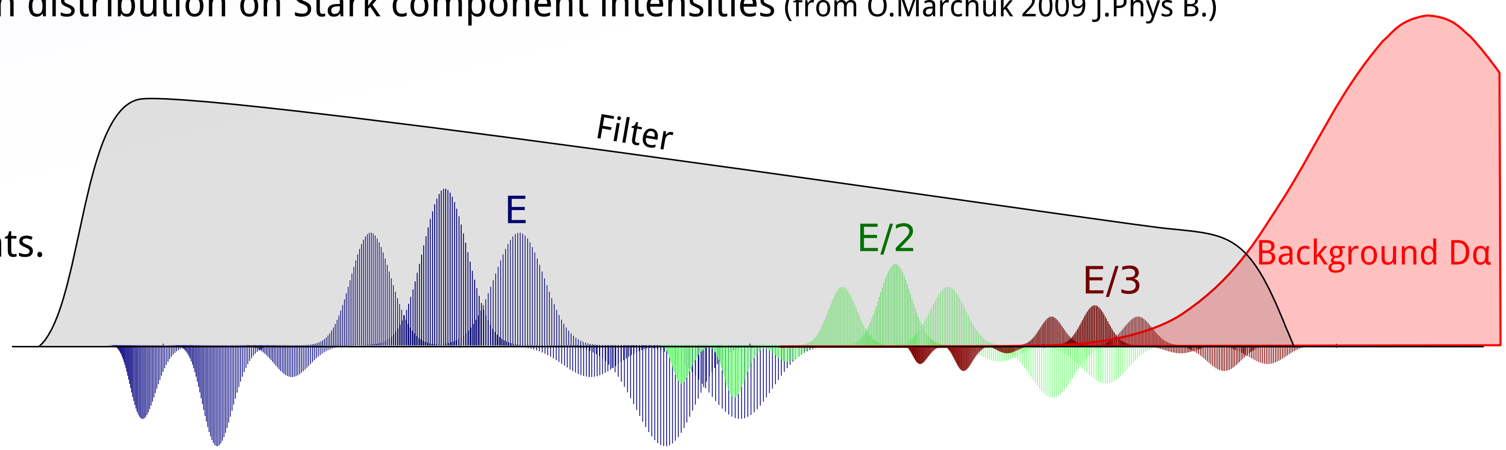
- Faraday rotation due the field in the Savart plates will not be a problem, but the main delay plate might be. (I'm assuming Lithium Niobate, but I can't find a Verdet constant for it in the Literature. Any suggestions?)

Other progress (Model)

Various other effects have been corrected in the forward model:
- Detail of Stark splitting and component polarisations. (Thanks to R. Reimer for pointing this out)



- Effect of non-statistical excitation distribution on Stark component intensities (from O.Marchuk 2009 J.Phys B.)
- Non-uniform filter pass-band.
- Asymmetries in Stark components.



Some of these significantly effect the image phases, but the polarisation angle (from the amplitude) remains unaffected.

Things still to add:
- Background D-Alpha and FIDA. (These will only reduce S/N).
- CCD noise (other than photon statistics).
- Viewing optics.