By maths.

To include axisymmetry, define poloidal magnetic flux as:

$$\psi(R,Z) = \int_0^R R' B_z(R',Z)\, dR'$$

And the toroidal current is:

$$-\mu_0 j_\phi = \frac{\partial}{\partial R}\frac{1}{R}\frac{\partial \psi}{\partial R} + \frac{1}{R}\frac{\partial^2 \psi}{\partial Z^2}$$

Going back to terms of Bz:

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

We only see where the MSE emission is, so we can only integrate from some *R = R0:*

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

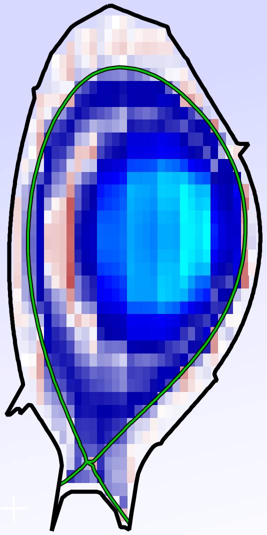
This we have with 1D MSE. (for $\frac{\partial B_z}{\partial R}$)

Function of Z that we cannot know. (for $\frac{1}{R}\frac{\partial^2 \psi(R_0,Z)}{\partial Z^2}$)

The new term gives localisation of current in Z (~via curvature of field). (for $\frac{1}{R}\frac{\partial^2}{\partial Z^2}\int_{R_0}^R R' B_z(R',Z) dR'$)

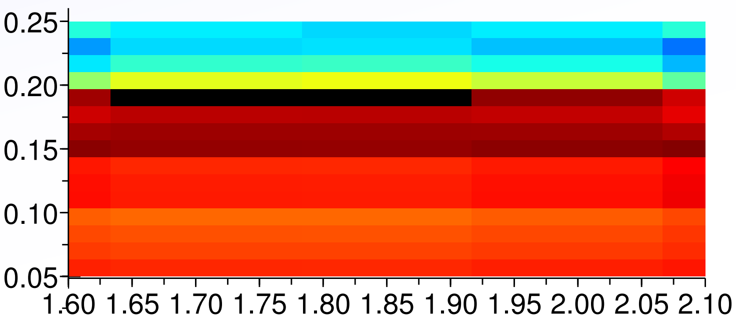
But.... Integral of a second difference of measurement... will be VERY noisy.

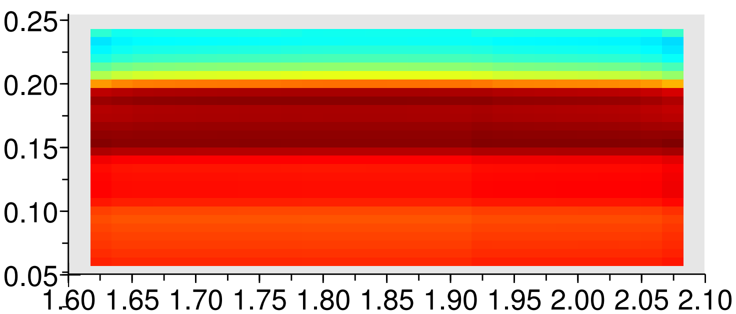
So can we directly calculate *jphi*?

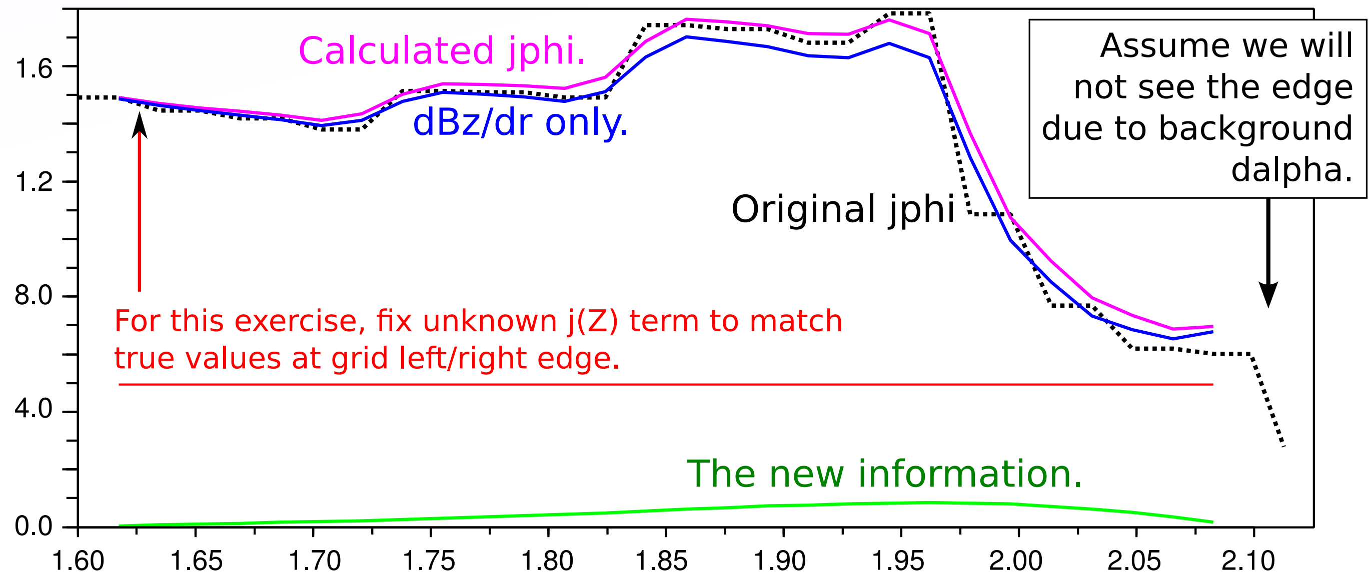


- Take CLISTE current distribution
- Predict 30x30 grid of Bz.
- Try to directly calculate j_phi

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



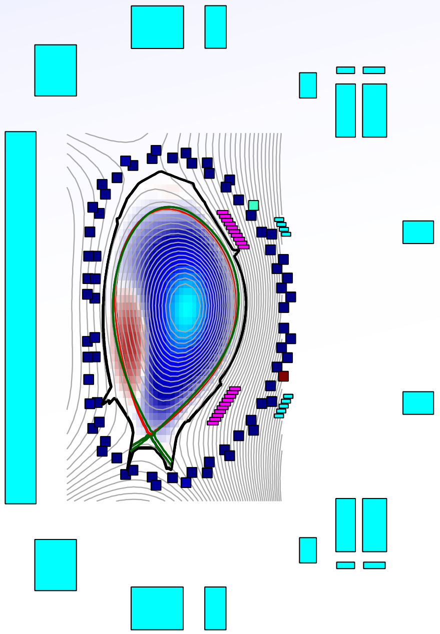




Unknown part above dBz/dR (standard MSE) is < 10% anyway. We do gain it mathmatically but as anticipated, it is entirely lost even with only 1mT noise in Bz (0.02^o pitch angle).
Conclusion: No. You still cannot exactly calculate jphi directly.

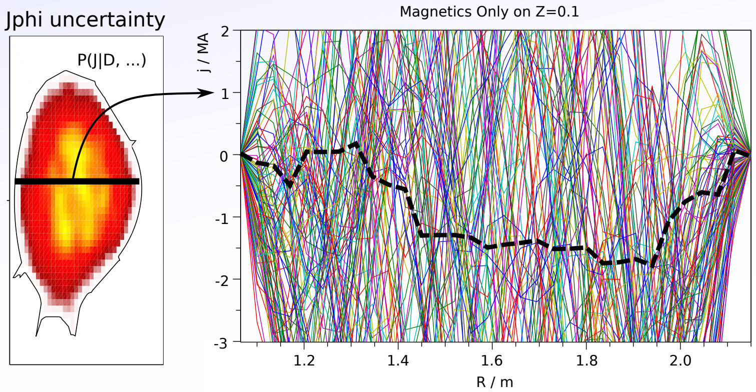
However, we do have measurements of the dBz/dR part at different Zs, and we know that this is most of jphi variation. Together with integral measurements (field pickups and flux loops), it is now part of a complex tomorgraphy problem that we have done before.

By current tomography...



Put description of AUG coils and some pickups into Minerva so we can now do Current Tomorgraphy and Bayesian Equilibrium for AUG.

For magnetics only, we have the usual tomography situation:



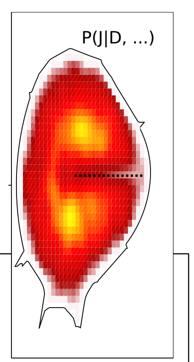
(Almost) no prior/regularisation

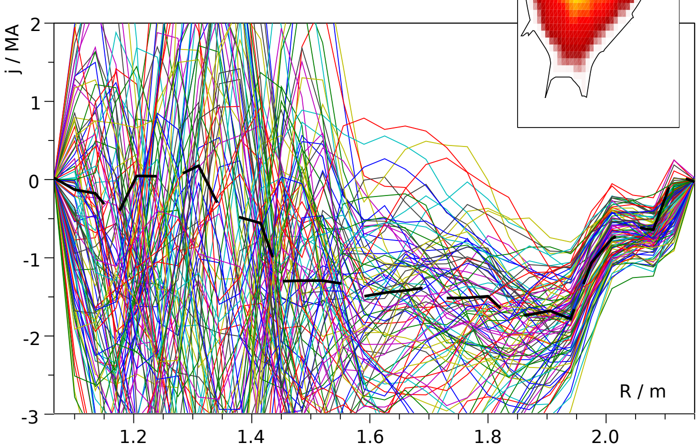
↓

(Almost) infinite uncertainty
(but B/psi still good)

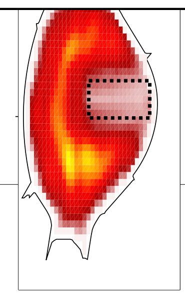
Each case has 900 measurements at sigma = 10mT.
So difference is only in the ***type*** of information.

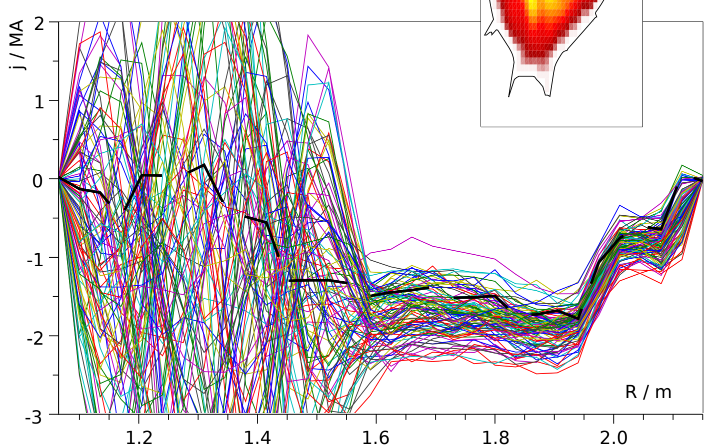
Normal MSE system:
30 x Bz at 30
positions along
NBI centre.



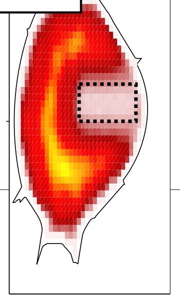


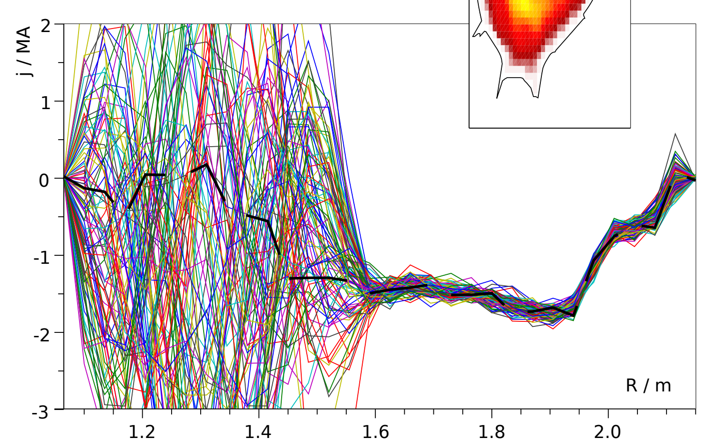
IMSE System:
30x30 grid of Bz
measurements.





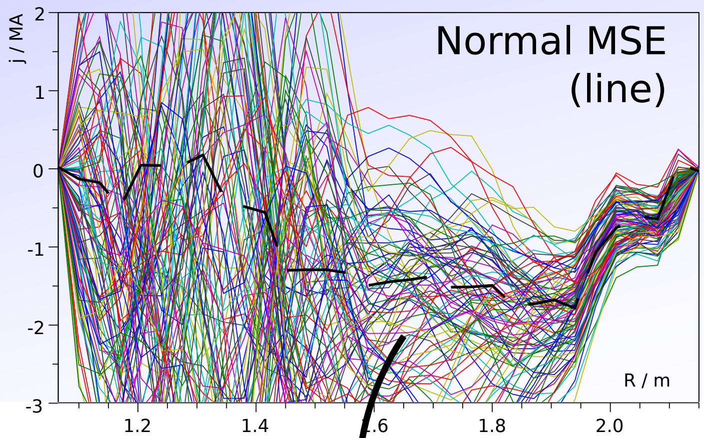
Just for interest:
30x15 grid of Bz
30x16 grid of Br.

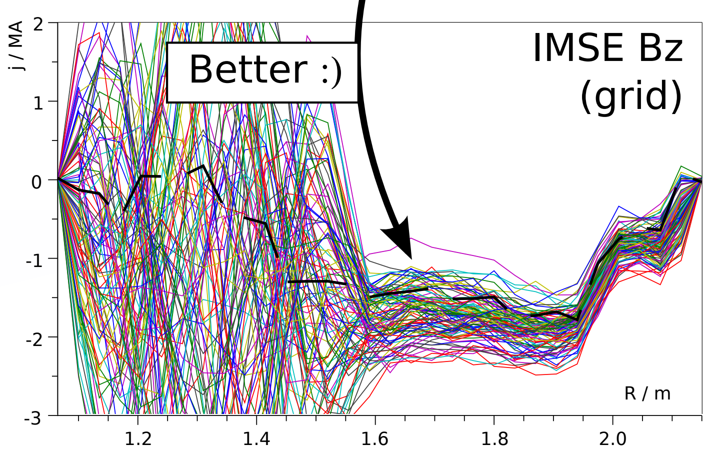


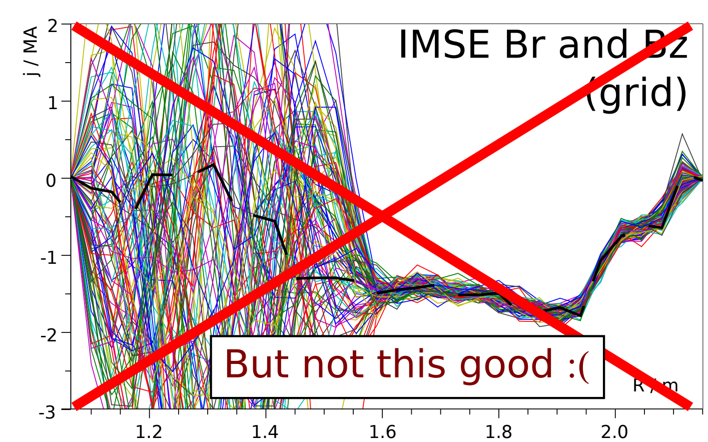


All sigmaBr = sigmaBz =10mT

By current tomography II





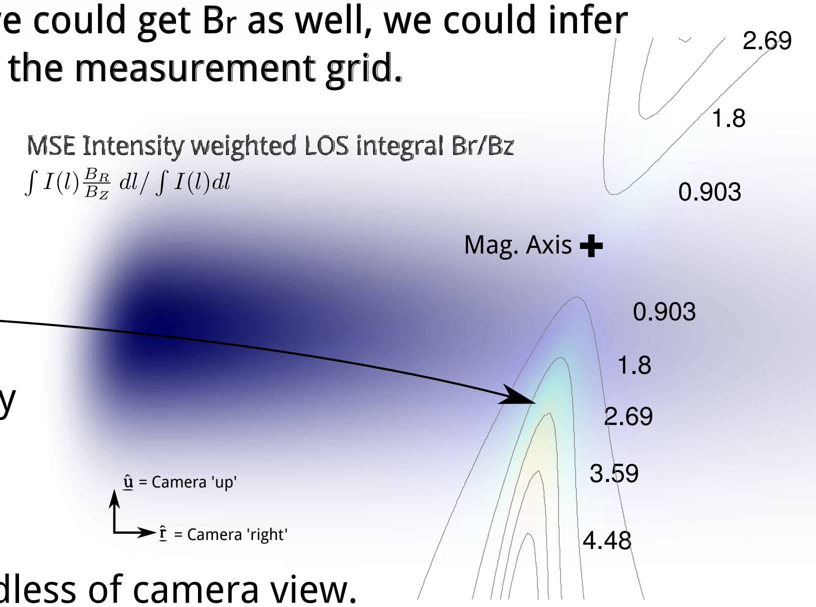


The IMSE still has some a large uncertainty in jphi offset. The unknown term it is not entirely pinned down by the magnetics.

However, the 2D IMSE inference is much better than the equivalent MSE system, for some reason.

Result with Br is much better: If we could get Br as well, we could infer the current almost exactly, within the measurement grid.

Off axis and near the core, the AUG IMSE system will see Br/Bz > 2 with reasonable signal strength:



Unfortunately, the beam geometry means information about Br is always swamped by Bphi. With NBI **v** in the midplane; **v** x **r** and **v** x **phi** are always together, regardless of camera view. There is a slight angle though. Full geomtry:

$$\tan\beta \approx \frac{(\hat{v}\times\hat{\phi})\cdot\hat{r}}{(\hat{v}\times\hat{\phi})\cdot\hat{u}} + \left[\frac{(\hat{v}\times\hat{R})\cdot\hat{r}}{(\hat{v}\times\hat{\phi})\cdot\hat{u}} - \frac{(\hat{v}\times\hat{\phi})\cdot\hat{r}}{(\hat{v}\times\hat{\phi})\cdot\hat{u}}\frac{(\hat{v}\times\hat{R})\cdot\hat{u}}{(\hat{v}\times\hat{\phi})\cdot\hat{u}}\right]\frac{B_R}{B_\phi} + \left[\frac{(\hat{v}\times\hat{Z})\cdot\hat{r}}{(\hat{v}\times\hat{\phi})\cdot\hat{u}} - \frac{(\hat{v}\times\hat{\phi})\cdot\hat{r}}{(\hat{v}\times\hat{\phi})\cdot\hat{u}}\frac{(\hat{v}\times\hat{Z})\cdot\hat{u}}{(\hat{v}\times\hat{\phi})\cdot\hat{u}}\right]\frac{B_Z}{B_\phi}$$

LOS Intensity averages of coefficients gives:

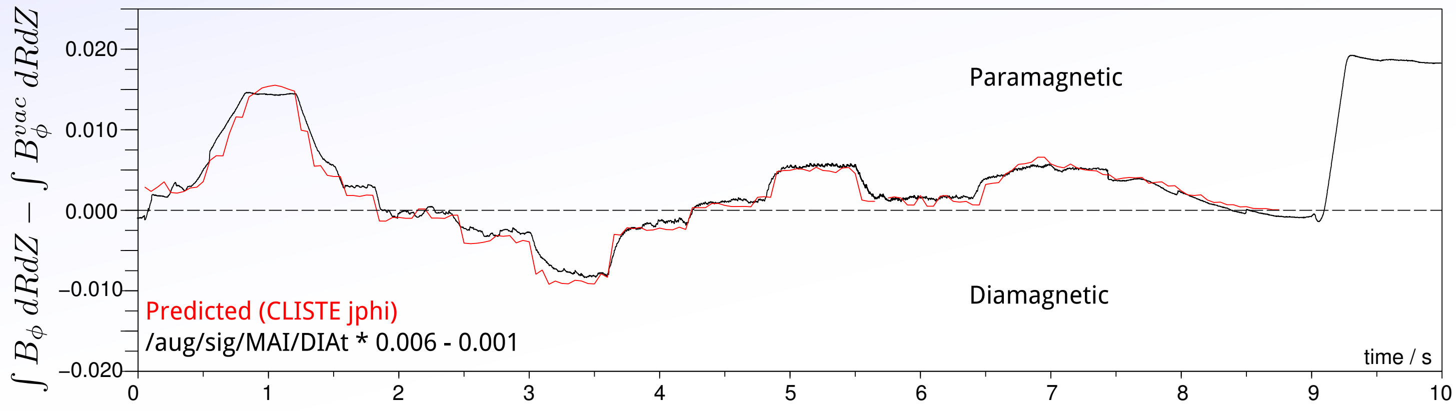
$$\tan\beta \approx 0.17 + 0.54\frac{B_Z}{B_\phi} + 0.05\frac{B_R}{B_\phi}$$

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

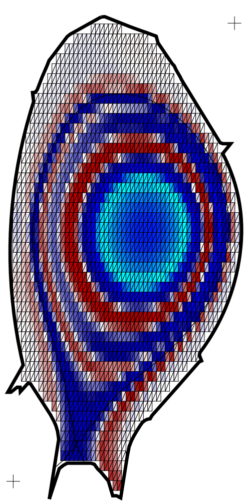
Para/Diamagnetics

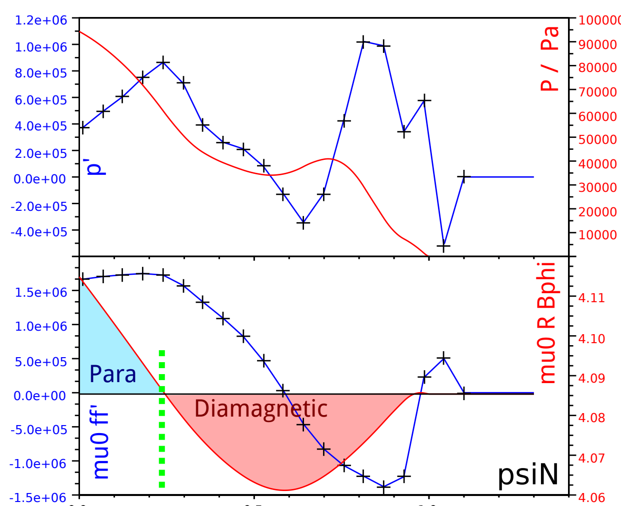
Some notes about Renee's results from the equilibrium point of view:

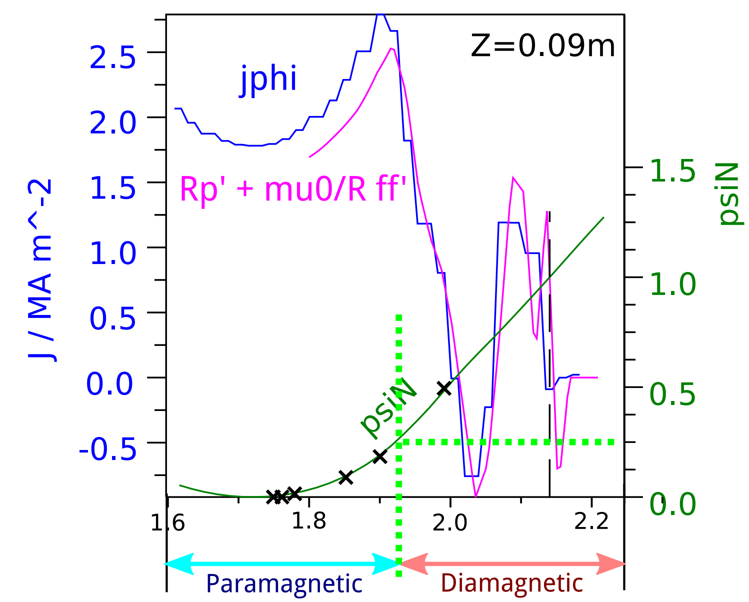
Just to see, we can load CLISTE's jphi into Minerva and integrate the toroidal flux over the whole vessel (calc. grid). There is a diagmagnetic signal outside the vessel which appears to be uncalibrated. With an offset and scale it mostly agrees with what CLISTE says:



Also, I can now run the code from my PhD work on JET which tries to extract the pedestal pressure from magnetics, wuth the AUG magnetic model. (P. McCarthy has already shown this works at AUG, as I did at JET). With sufficient relaxation of the ff' and p' smoothing priors, it actually finds an equilibrium which is paramagnetic in the very core and diamagnetic at the edge (albeit with a slightly silly pressure profile):

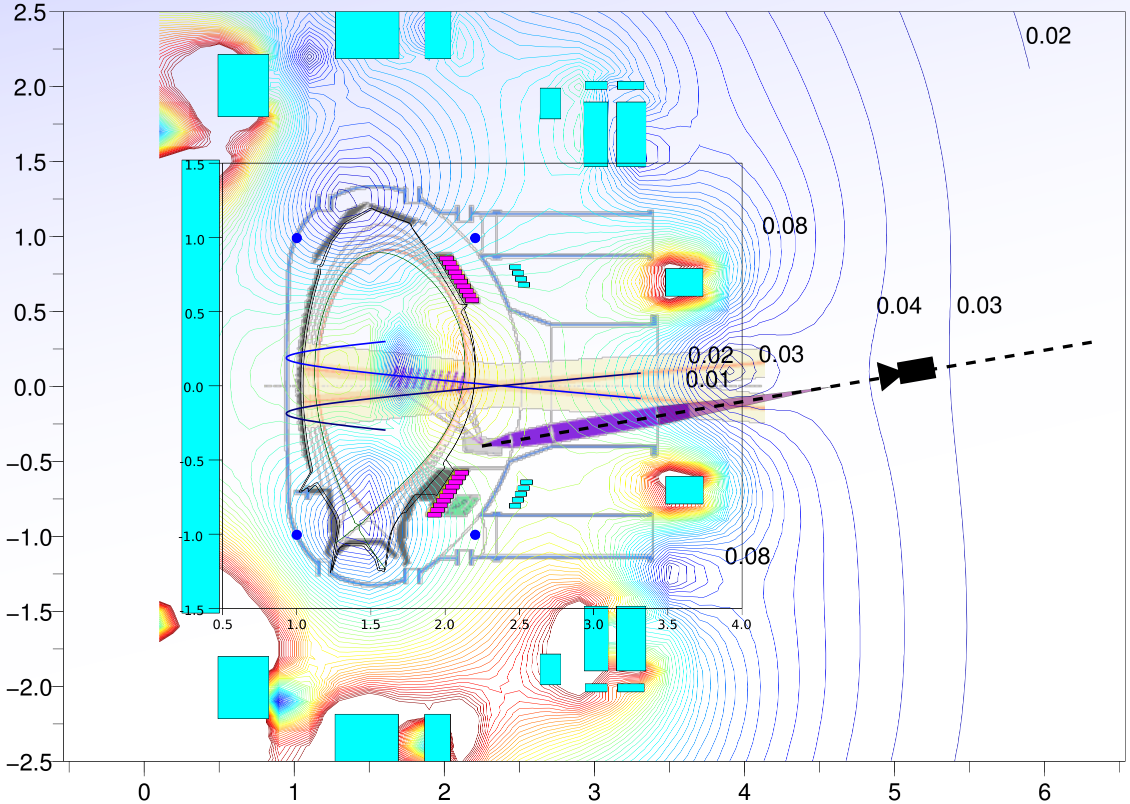






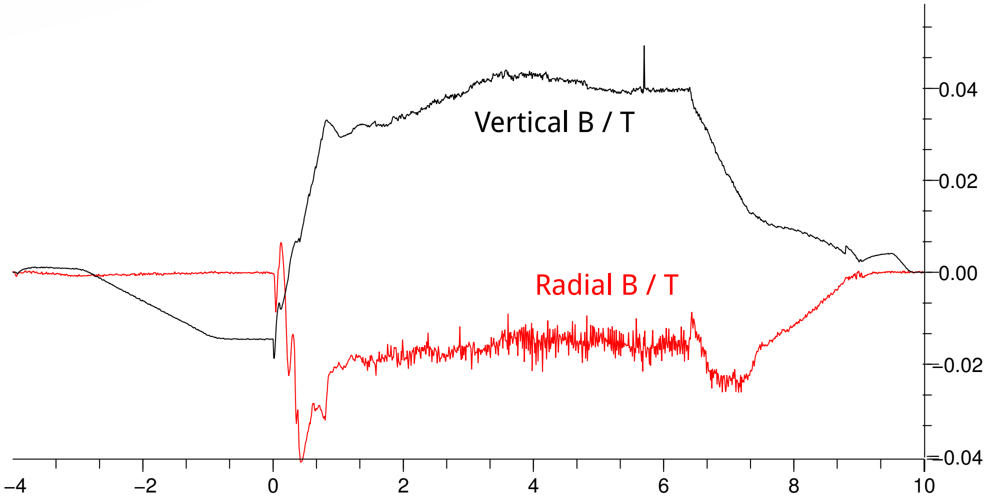
I'm not saying that this is happening, just that with a strong pedestal pressure gradient, it could be.

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 magetic field, which Minerva can predict from the PF coils.
For the highest plasma current (Ip=1.2MA), |B| < 50mT:



- The camera we have (12bit 1376x1040 Imager QE) was used, next to the coils in Pilot (PSI) 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?)

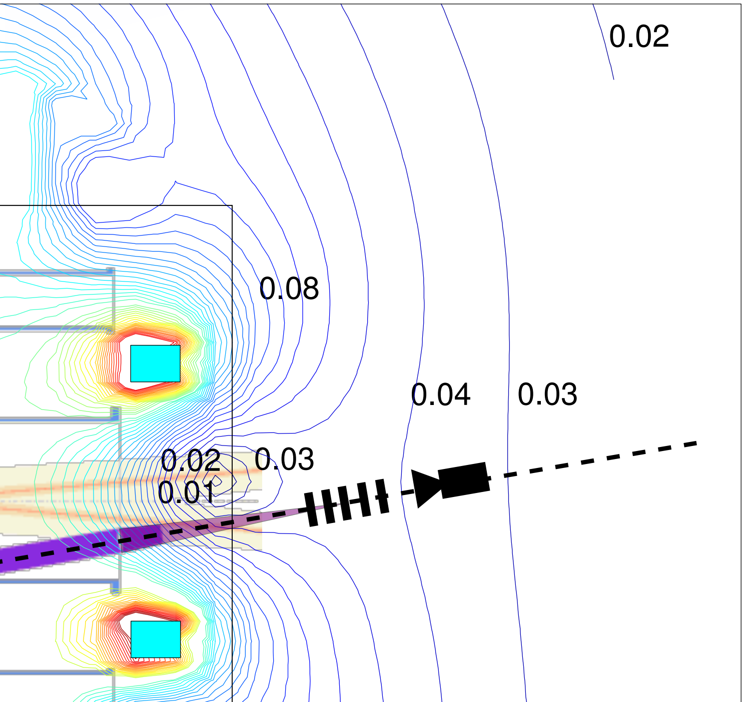
Poloidal Field at camera

50mT on the camera may be OK, and we should check direction sensitivity with whatever camera we use.
 - Could start with the imager QE that we have.

Field on optics:

Verdet constant for Quartz (Savart plates) is 16640 T-1 m-1 at 589.3nm which gives Faraday rotation of almost 0.01 deg mm^-1 in Savart plates with 50mT field perp to plate. (In reality it will be almost // to plate surface.)

Plates in sim currently 4/8/16mm. For 16mm, absolute worst case gives 0.16deg. So we are probably OK, but probably should measure the field.



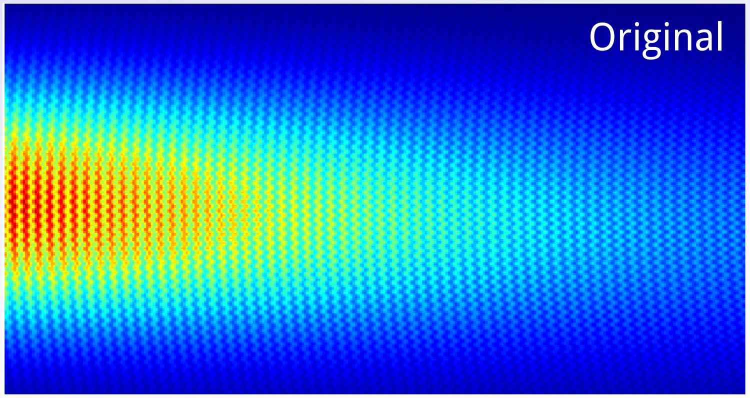
Delay Plates:
Lithium Niobate LiNbO3 (dielectric crystal)??
Can't find the verdet constant so calculated from 'becquerel' formula.
That gives 0.3 degrees per mm at 100mT, which
at e.g. t=6mm (max net constrast at 764 wave at 654nm)
--> 1.8deg
- Need to check this and ask JH.

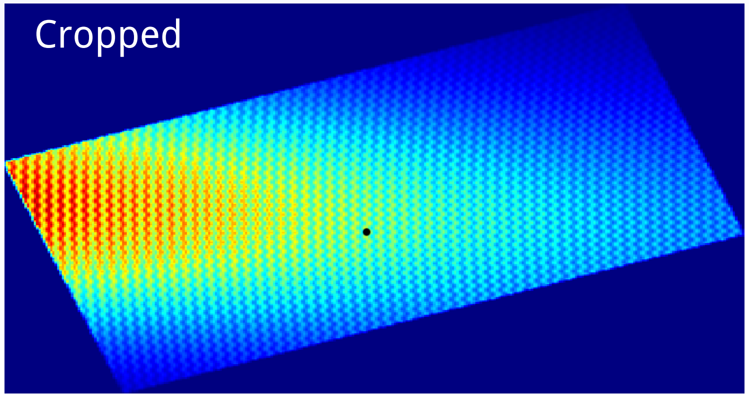
- What can the imagerQE take?
- Measure the field at AUG.

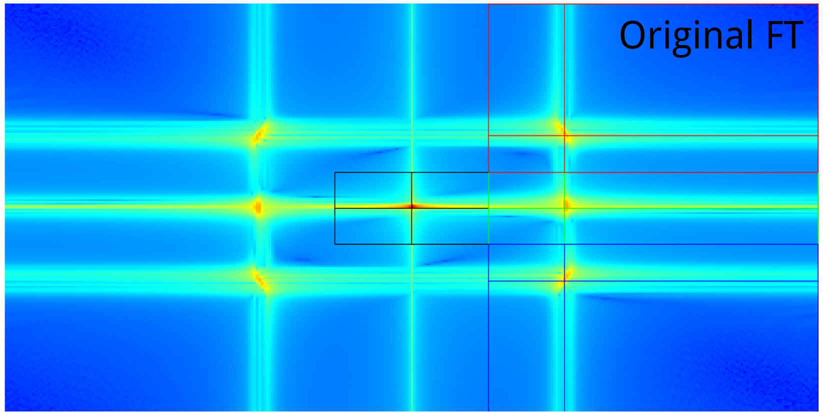
Non-statistical distribution

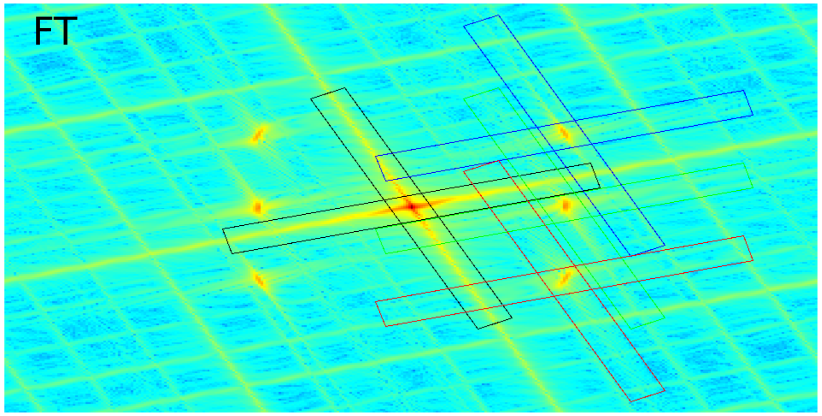
Looked at it, not important :p

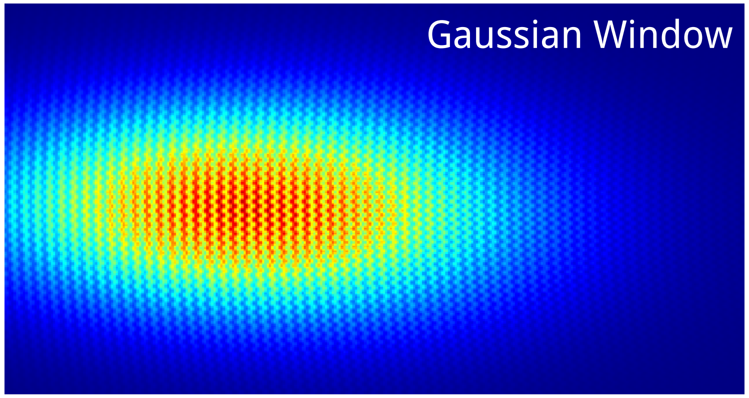
Demodulation Tweaks

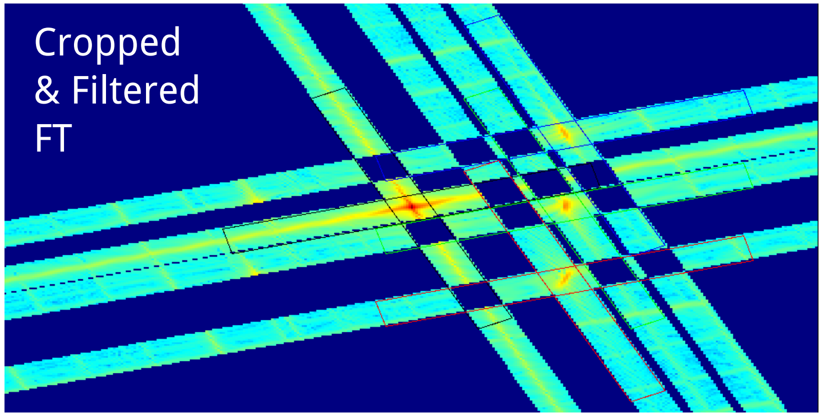


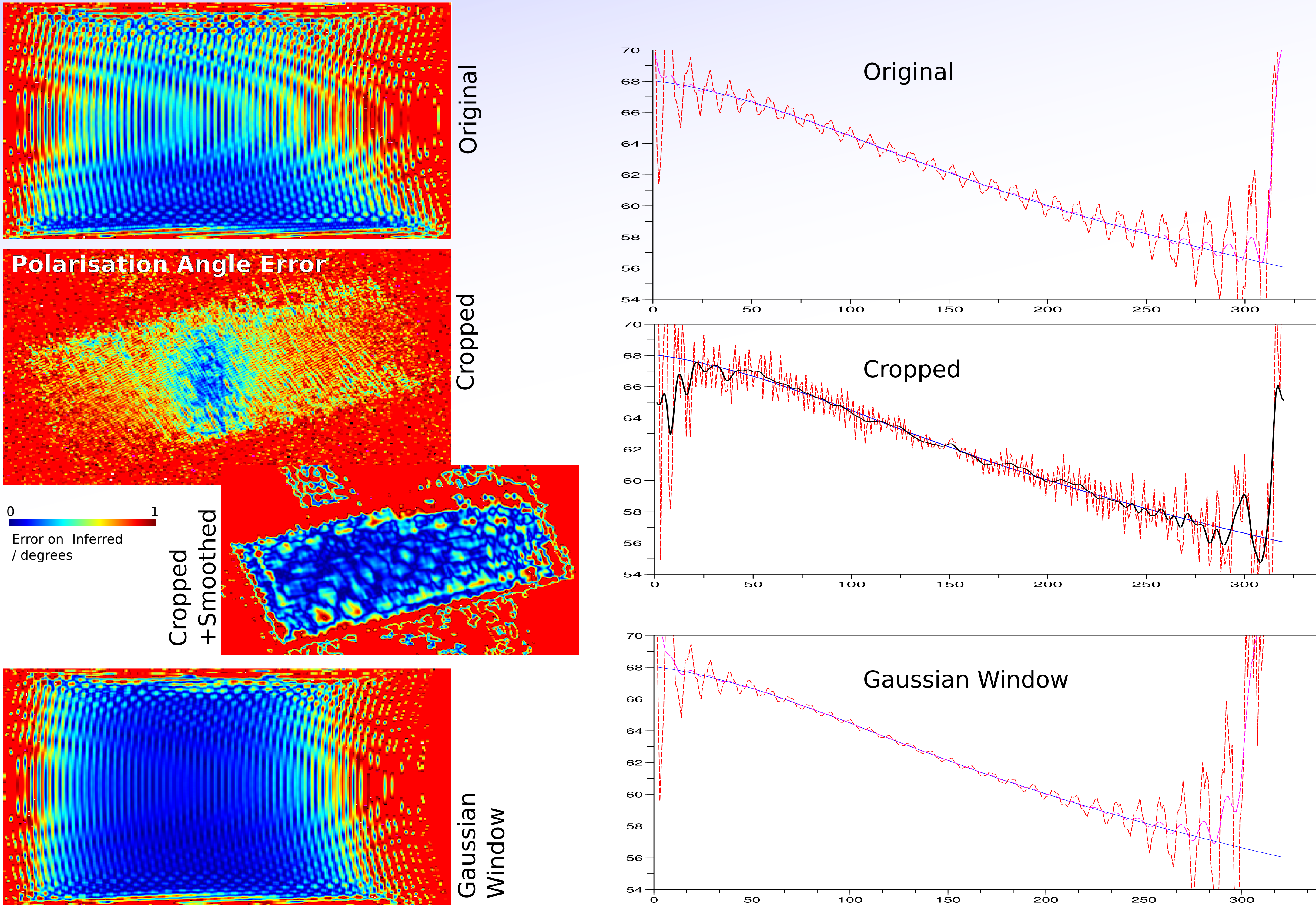




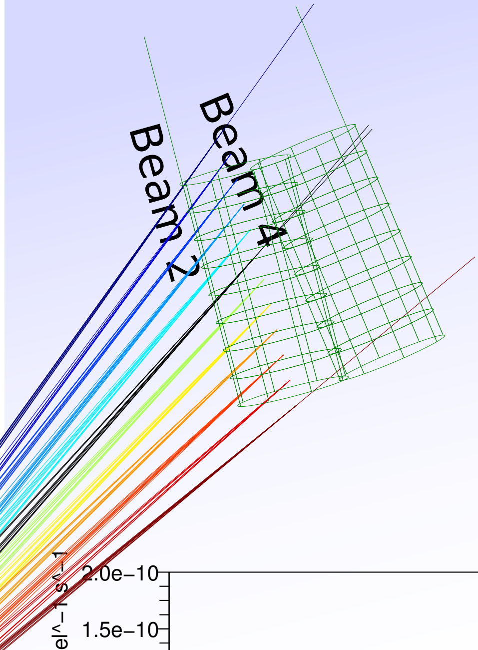


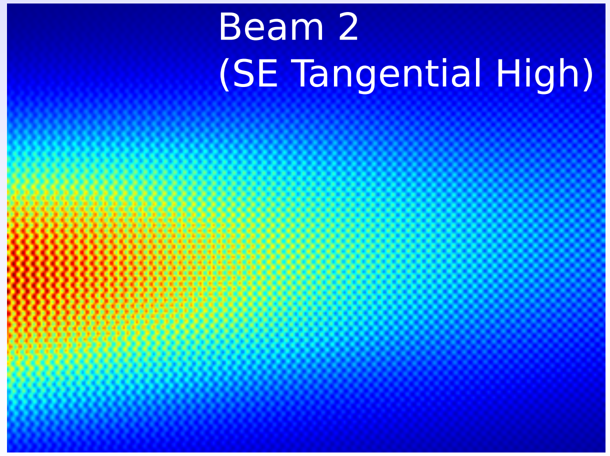


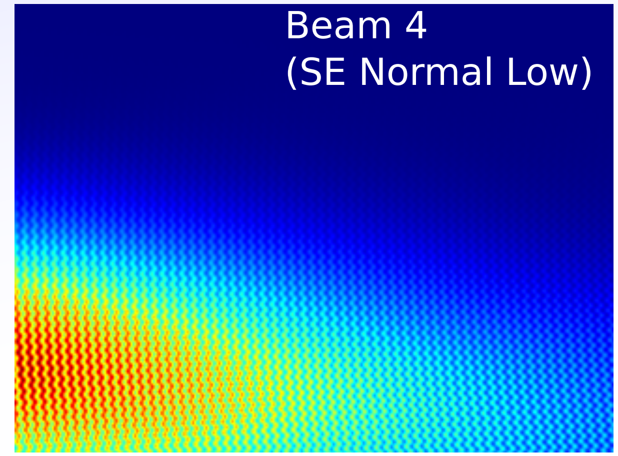


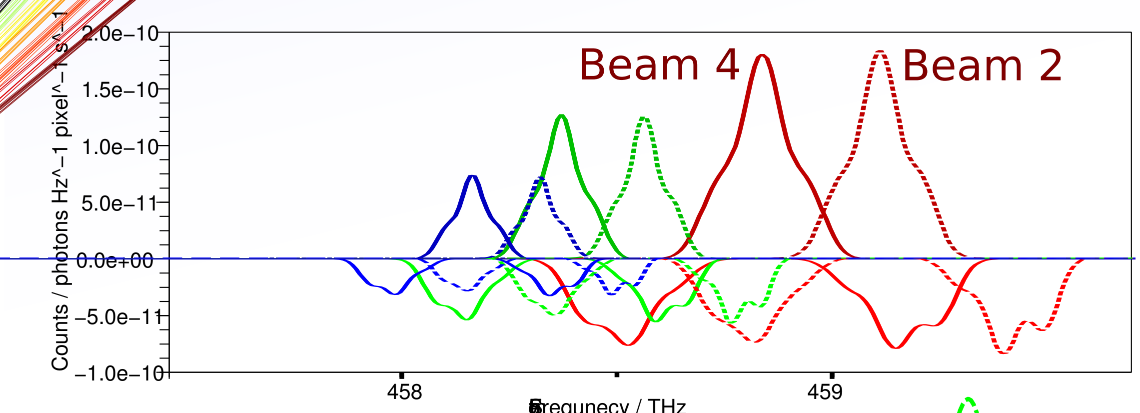

Original
Polarisation Angle Error
Cropped
0
1
Error on Inferred
/ degrees
Cropped
+Smoothed
Gaussian
Window
Original
Cropped
Gaussian Window

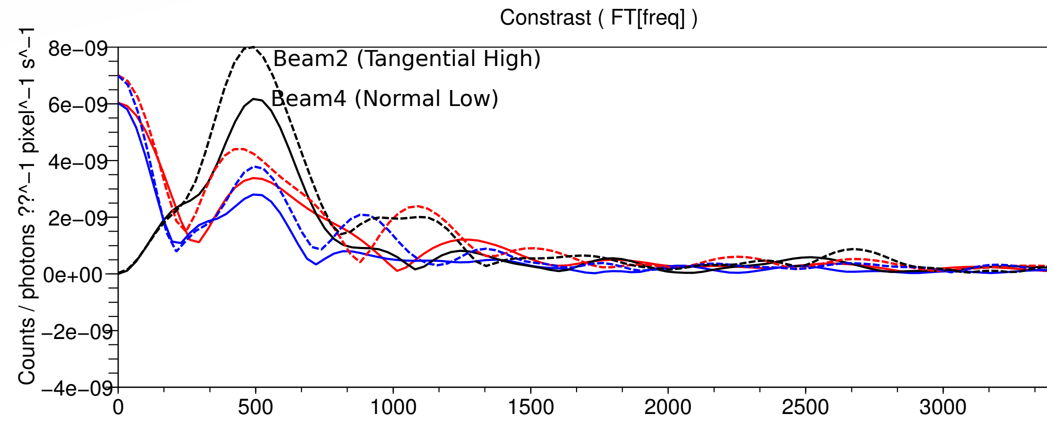
Spectral Contrast Weighted Averages

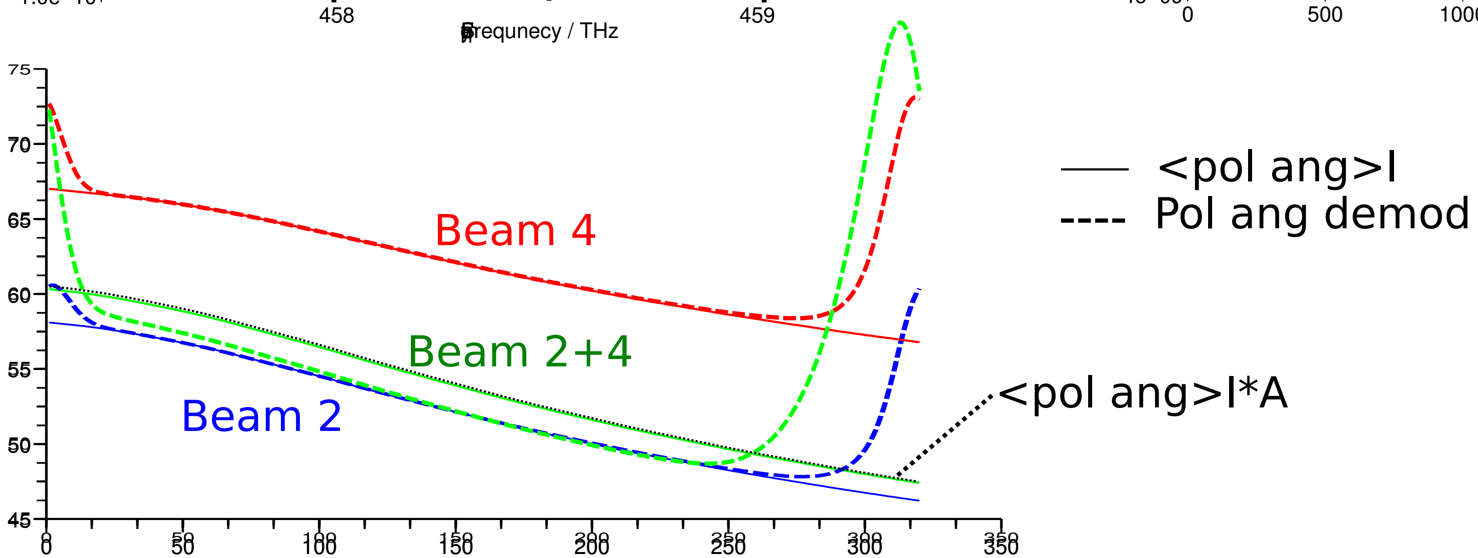












IMSE Design

Variables:

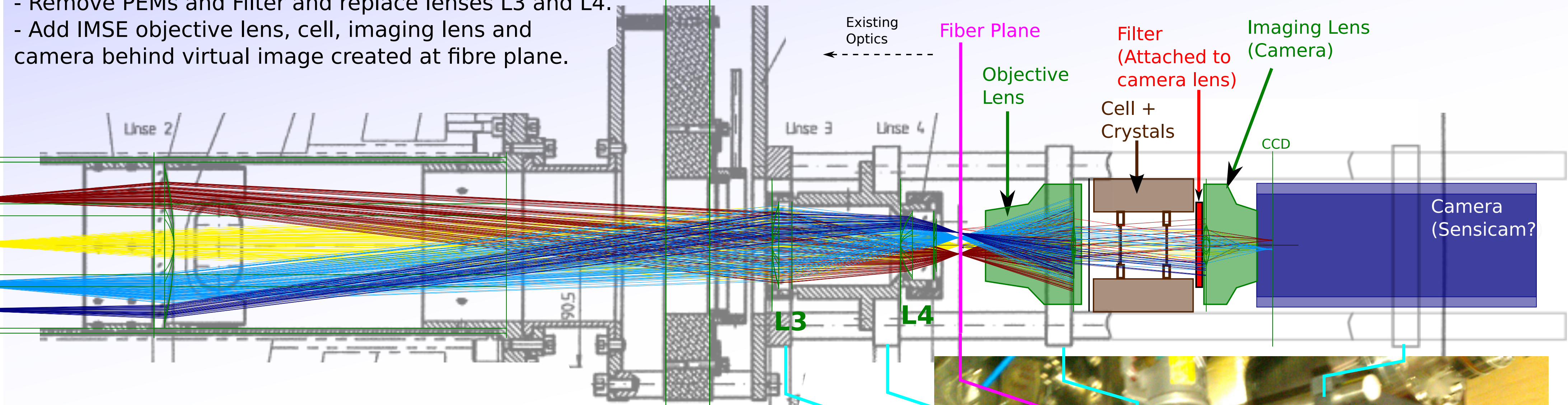
- Focal length and F/# of objective lens.
- Focal length and F/# of imaging (camera) lens.
- Filter.
- Thickness of aBBO delay plate.
- Thickness of aBBO displacer and Savart plate.

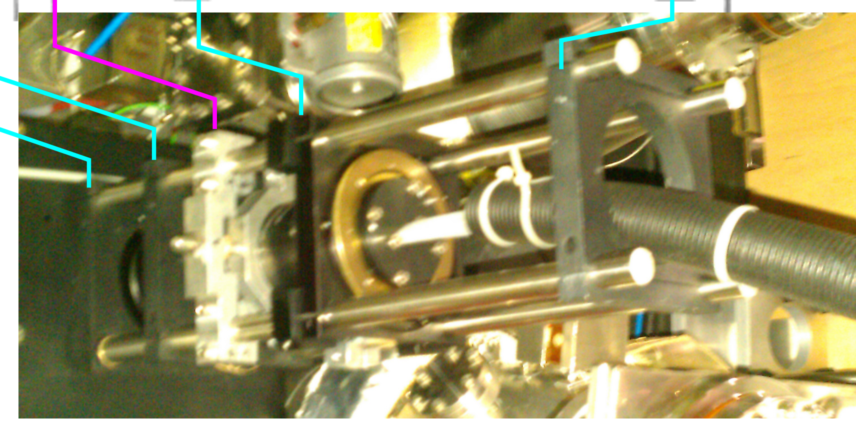
Requirements:

- Image available FOV and all 4 beams onto CCD.
- Set reasonable fringe period (need as much flexibility as possible here!)
- Set overall delay to optimise fringe contrast.
- Keep as much of the light delivered by forward optics as possible.
- Reject as much background spectrum and emit as much useful light as possible.

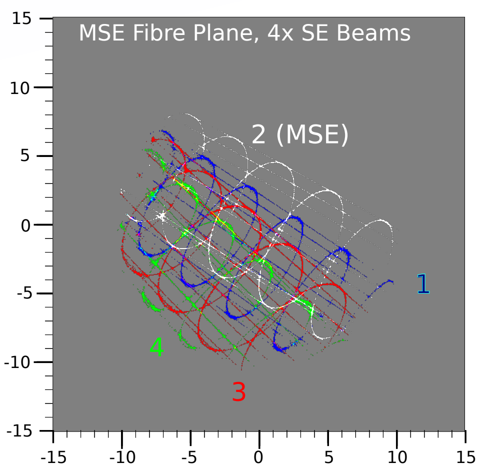
IMSE Design - Imaging

- Remove PEMs and Filter and replace lenses L3 and L4.
- Add IMSE objective lens, cell, imaging lens and camera behind virtual image created at fibre plane.



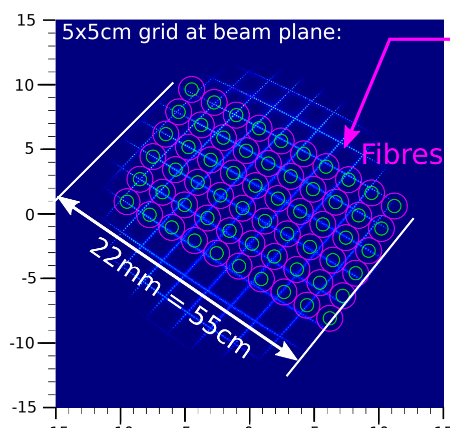


Light delivered by existing optics to fibre plane at f/1.4.
Raytracing 10cm sections of a cylinder for each beam (FWHM=20cm),



Beam 1 : Upper Away/Radial
Beam 2 : Upper Near/Tangential (Primary MSE)
Beam 3 : Lower Near/Tangential
Beam 4 : Lower Away/Radial

According to ray tracing, full viewing diameter is:
~55cm at beam plane
~22mm at fibre plane.

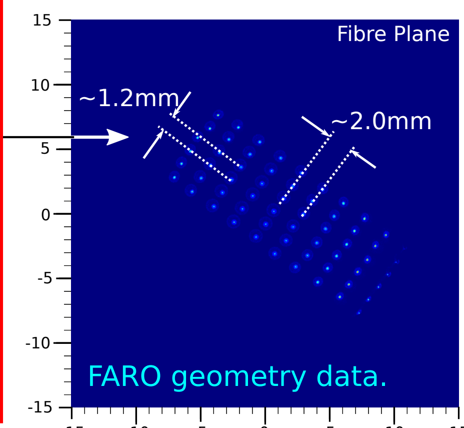


We think the fibres are roughly 10x6 grid of 2mm fibres with 1mm core [T. Löbhard].

Raytracing of FARO data suggests fibres are ~1.2mm apart vertically.

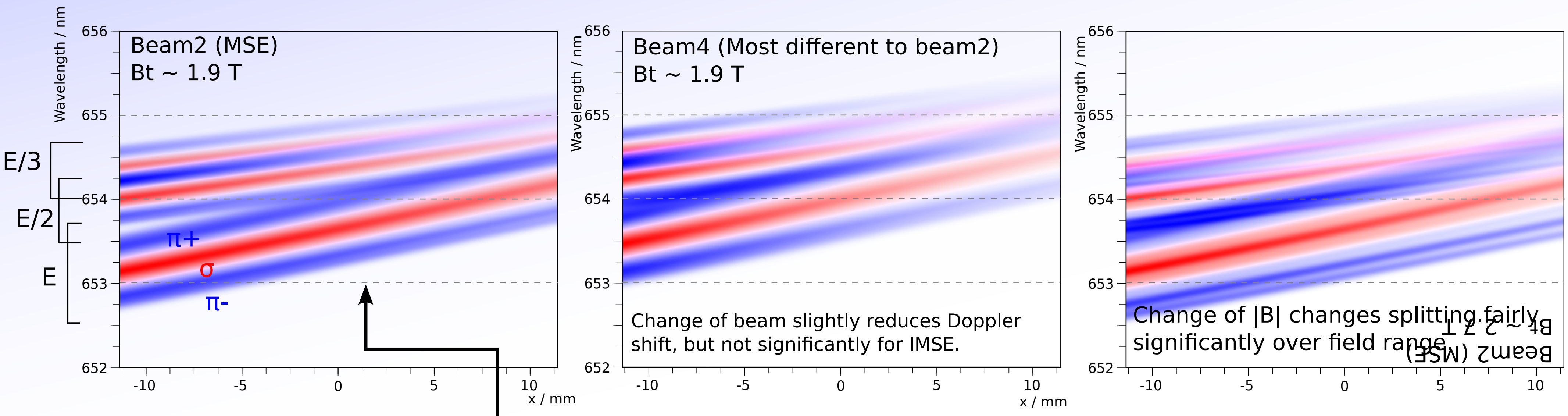
Original paper [R.Wolf] says 12cm height at beam plane. Here it looks like 18cm.

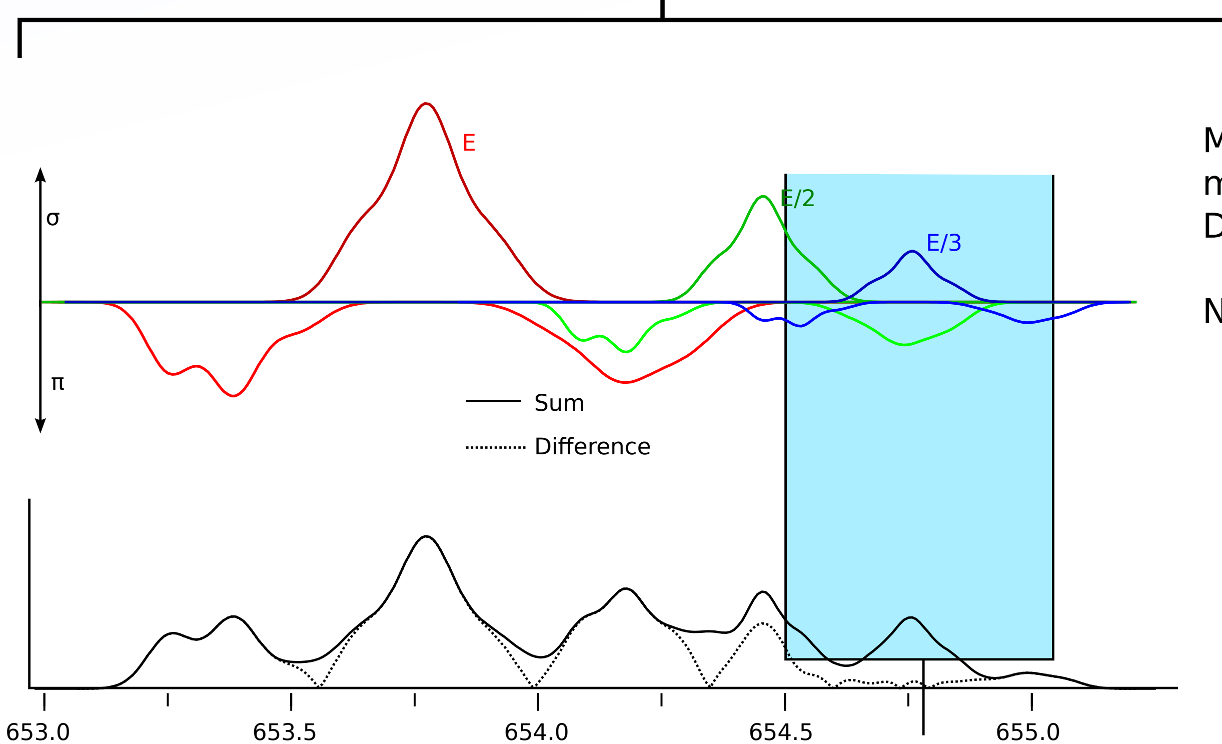
But, the 10 channels cover the expected region of the plasma and this matches the ray traced FOV, which is important here.



IMSE Design - Spectrum

Spectrum across centre of image for high and low fields.



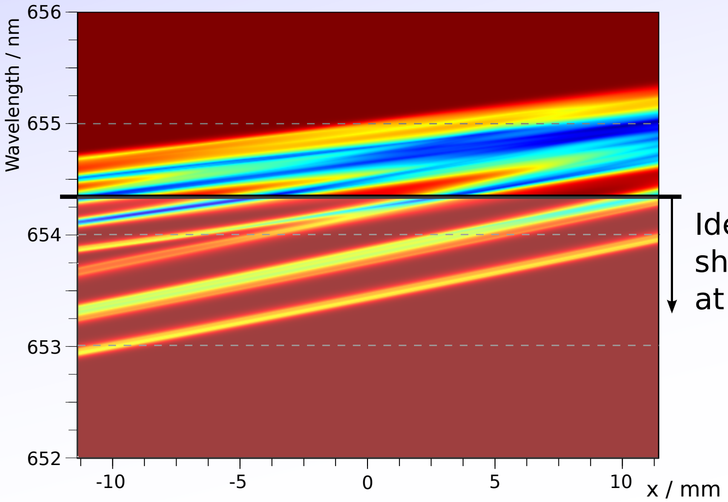


Mixing of pi/sigma from different components makes l > 654.5nm useless. This plus background Da means it just reduces S/N.

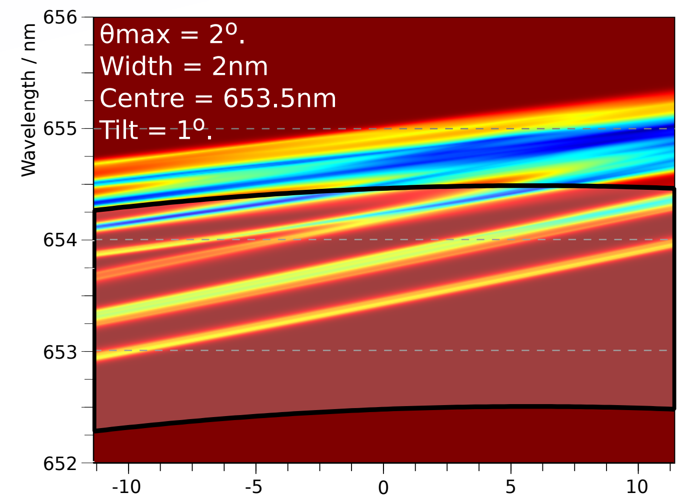
Need a filter to reject this.

IMSE Design - Filter.

To look at where is best to filter, plot |π - σ| / (π + σ) averaged over scenarios (4 x extreme + 1 middle of the road)
This is something like 'generally expected linear polarisation fraction as f(x, λ)':



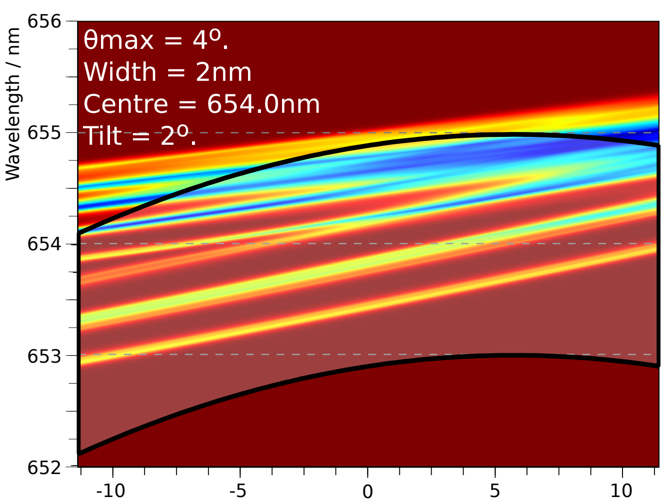
Ideal filter would be sharp high-pass at λ~654.3nm

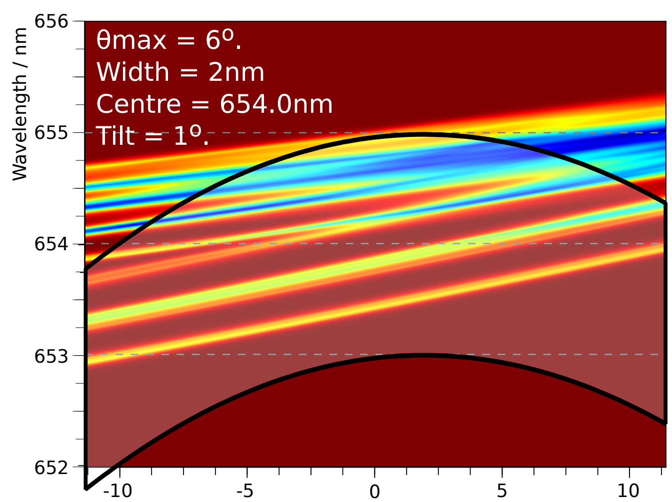


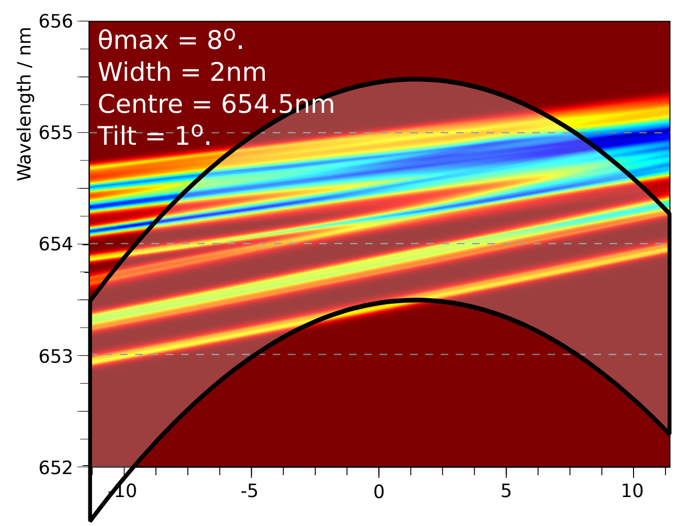
Interference filter passband depends on angle of light, so changes over FOV.

Above θ_{max} ~4º (8º FOV) the filter function moves too much to easily capture edges with also capturing poor regions in centre.

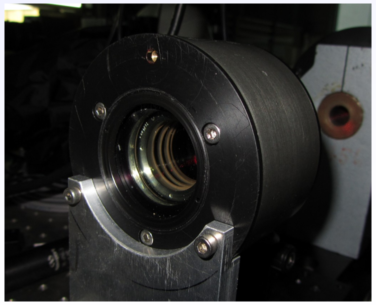
We really need to keep max angle through filter below 8º.





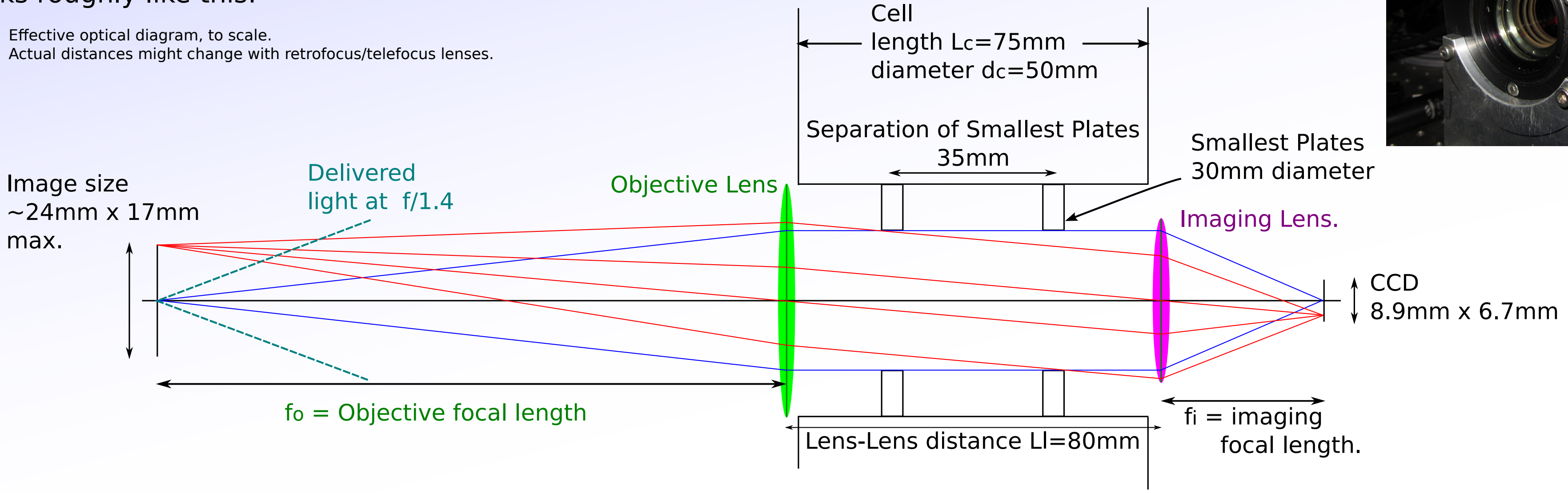


IMSE Design - Lenses.



Without using extra intermediate lenses, angle through the filter is the same as angle through the crystal plates.
Coupling looks roughly like this:

Effective optical diagram, to scale.
Actual distances might change with retrofocus/telefocus lenses.

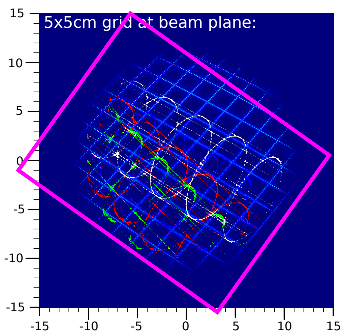


Objective Lens:

Angle of light through plates is set by *fo*: θmax = 24mm / (2 fo)

So that objective lens is not restricting light, it must be faster than the minimum diameter in the cell: f/# > fo/30mm.

So for θmax = 5º, we need 135mm faster than f/4.5.
NB: To accept the whole image, objective must be a 35mm film lens - not the smaller C-mount (CCTV) ones.

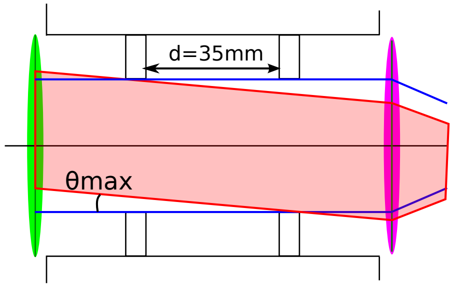


Imaging Lens:

We need to choose *fi* to image 25x17mm of fibre plane completely onto 8.9x6.7mm CCD. That requires *fi < 0.34 fo.*

For the imaging lens to not restrict the light throughput, it needs at least a speed of *fi/30mm.* For θmax = 5o case, we need fi < 43mm/1.4.
35mm or 50mm are nearest, but not great.

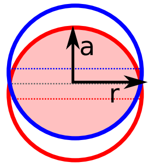
Vignetting:



Roughly (assuming both lenses are fast/close enough):
Aedge / Acentre = (a r)/r^2
= (r - d θmax) / r
= 1 - d/r θmax = 1 - 1.17 θmax.

For θmax = 5o, Ae/Ac = 89%.
Generally, it is never worse than 75%.
If imaging lens isnt fast enough, both Ac and Ae are reduced, vignetting still isn't bad.

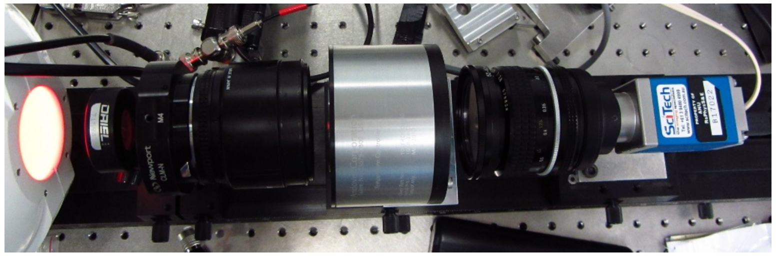
a=r - d θmax
r=30mm



Ac = r^2 /
(fo/1.4)^2

We've tested the setup at ANU:

(and I have here at IPP too)



IMSE Design - Lenses.

Looking around the lab, and around the web for generally available lenses.
Zoom (adjustable focal length) lenses tend to not be fast enough for imaging side.
We can use one for the objective side though, if it's fast enough and sees the full 35mm virtual image area.

Objective:

f	f/#	Req f/#
75	1.4	2.5
85	2.1	2.9
100	1.2	3.3
17.5 - 105	1.8	3.5@105
135	2.0	4.5
180	4.5	6.0
300	9.0	10.0

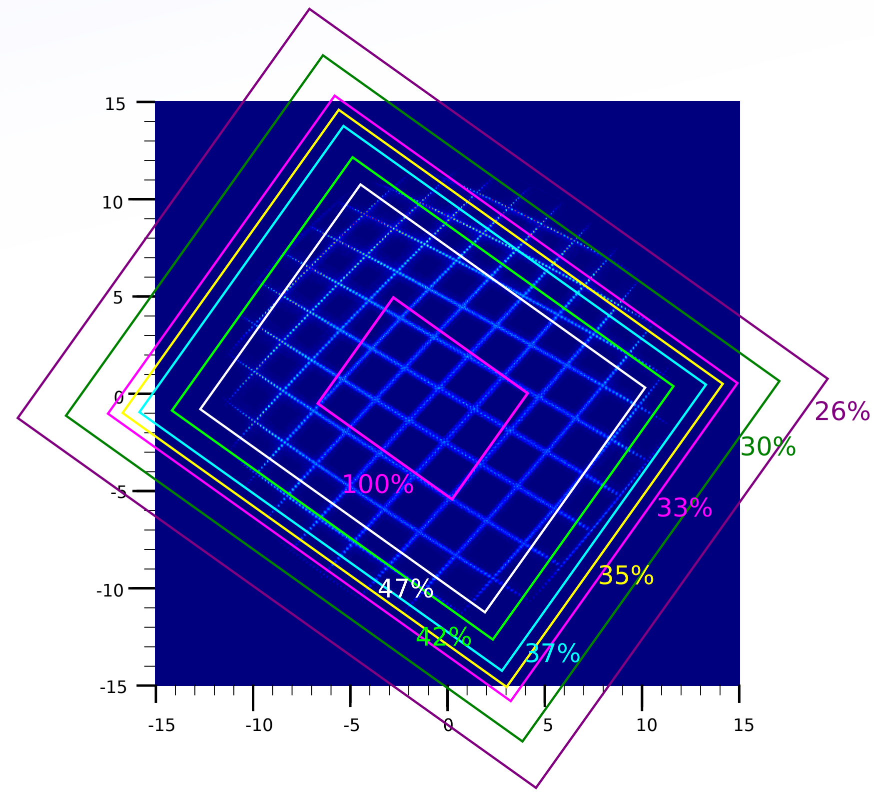
Imaging:

f	f/#	Req f/#
25	0.85	0.83 ← We have a box for this.
25	0.95	0.83
28	1.4	0.93
35	1.2	1.2
50	1.4	1.6
75	1.4	2.5

Things we'd need to buy.
Things which are not ideal.
Things which are really bad.

Some combinations:

fo	fo/#	fi	fi/#	M	θmax	Ac (throughput)		Ae (vignetting)
75	1.4	25	0.85	33%	9.2o	30%		80%
75	1.4	25	0.95	33%	9.2o	24%	Lens speed limited.	78%
85	2.1	25	0.95	30%	8.1o	19%		81%
100	1.2	35	1.2	35%	6.9o	17%		85%
105(Z)	1.8	35	1.2	33%	6.5o	15%		86%
105(Z)	1.8	50	1.4	48%	6.5o	16%		87%
135	2.0	35	1.2	26%	5.1o	9.1%		89%
135	2.0	50	1.4	37%	5.1o	9.6%	Cell limited	89%
180	4.5	50	1.4	28%	3.8o	5.4%		92%
180	4.5	75	1.4	42%	3.8o	5.4%		92%
300	9.0	100	1.2	33%	2.3o	2.0%		95%



Conclusions:
- Vignetting should not be a problem.
- Can change fringe frequency by ~4x without changing plates, but at cost of either bad filter shift or low throughput.
- The 180mm/4.5 lens would be really handy, the 35mm/1.2 necessary.
- 5.1o looks the best middle ground to aim at.

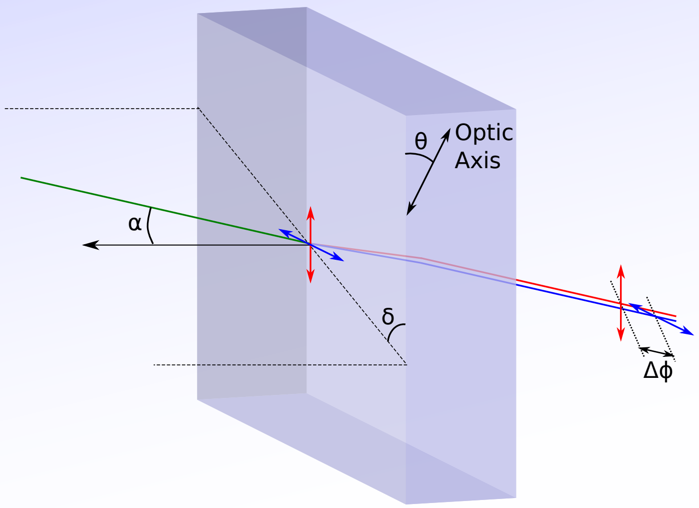
- Throughput for sensible θmax is only 5 - 10%.
  Limited by 30mm apature only for θmax < 5.1o.
  Increasing crystal size to 35mm apature would give:

fo	fi	Ac(30mm)	Ac(35mm)
135	50	9.6% →	13%
180	50	5.4% →	7%
300	100	2.0% →	2.7%

So bigger plates are not worth the price.

IMSE Design - Fringes

From F.E.Veris, phase shift in arbitary crystal.



$$S = n_e^2 \sin^2\theta + n_o^2 \cos^2\theta$$

$$\Delta\phi = \frac{2\pi L}{\lambda_0}\left[\left(n_o^2 - n^2\sin^2\alpha\right)^{\frac{1}{2}} + \frac{n}{S}\left(n_o^2 - n_e^2\right)\sin\theta\cos\theta\cos\delta\sin\alpha + -\frac{n_o}{S}\left[n_e^2 S - \left[n_e^2 - \left(n_e^2 - n_o^2\right)\cos^2\theta\sin^2\delta\right] n^2\sin^2\alpha\right]^{\frac{1}{2}}\right]$$

Generally, n=1 and $sin^2\alpha$ is small .
For waveplate, θ=0:

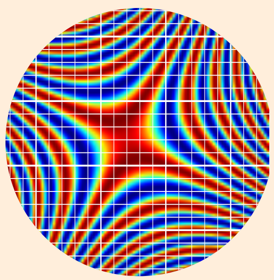
$$\Delta\phi = \frac{2\pi L}{\lambda_0}\left[\left(n_o - n_e\right) - \sin^2\alpha\,\frac{1}{2n_o}\left(1 - \frac{n_e}{n_o}\left[1 - \sin^2\delta\left(1 - \frac{n_o^2}{n_e^2}\right)\right]\right)\right]$$

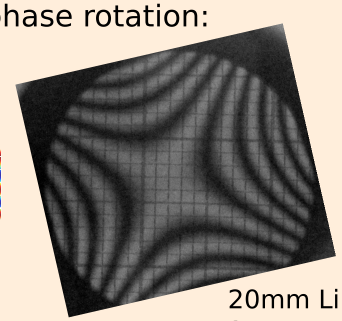
The $\sin^2\alpha$ term gives the fringes due to the delay plate (which bend the displacer fringes).
To quantify, we can calculate αp, the angle at which it gives 1 full phase rotation:

$$\alpha_p \approx \sqrt{\frac{2n_o\lambda_0}{L\left(1-\frac{n_e}{n_o}\right)}}$$

at (δ=0°, 90°, 180° or 270°)

I'll come back to that later.





20mm LiNb
fo=100mm

This all matches what we see in the lab.

For displacer, θ=45°, phase is 'approximately':

$$\Delta\phi = \frac{2\pi L}{\lambda_0}\left[\frac{(n_o-n_e)}{2} + \frac{(n_o^2-n_e^2)}{(n_o^2+n_e^2)}\cos\delta\sin\alpha\right]$$

Fringes run in ~ δ=90° direction.

Contribution to fixed delay is ~1/2 of same thickness waveplate +/- 10%

Setting α to the maximum θ_{max} from earlier (excuse the mixed notation). The number of fringes for the full (2 θmax) image is:

$$N = \frac{2N\Delta\phi}{2\pi} \approx \frac{2L}{\lambda_0}\frac{(n_o^2-n_e^2)}{(n_o^2+n_e^2)}\theta_{max}$$

For αBBO at 653.5nm:
no = 1.666, ne = 1.549

N = 3880 L θ_{max} ~ 4 fringes per mm per degree

Total delay in waves = 1.8x10^5 (Ldelay + Ldisplacer/2) ~ 180 waves per mm of delay