IMSE Design

These slides lay out the design decisions for the ASDEX MSE coherence imaging system. Where possible, this is with first order 'back-of-envelope' calculations so I can get a feeling for the numbers and to cross check the models.

The emphasis is largely on flexibility - so we can cope with errors in input data (e.g. the ray tracing), and to cope, as much as possible, with those pesky 'unknown unknowns'.

I'm not trying to push any boundaries - *yet.* I first want to make it work reliably. The objective of the first phase is to repeatably match the expected polarisation image (or at the very least to a fixed offset) without fudges, hacks or cross calibrations.

The main parameters that need to be decided and the requirements which need to be satisfied are:

Variables:

Focal length and f/# of objective lens.

Focal length and f/# of imaging (camera) lens.

Filter.

Thickness of αBBO delay plate.

Thickness of αBBO displacer and Savart plate.

Requirements:

Image all available FOV of all 4 beams onto CCD.

Set reasonable fringe period
(need as much flexibility as possible here!)

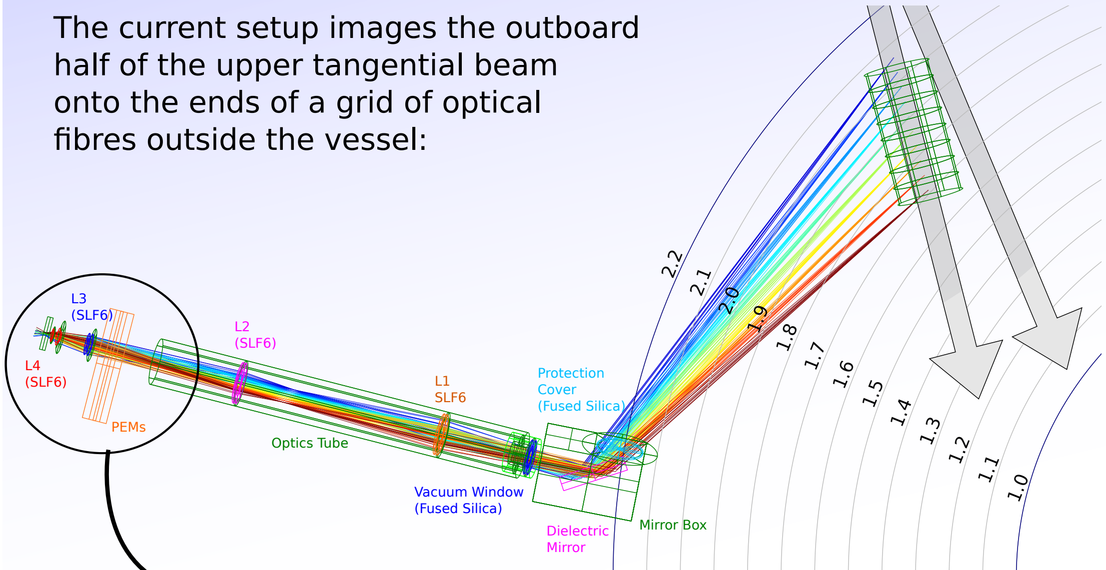
Set overall delay to optimise fringe contrast.

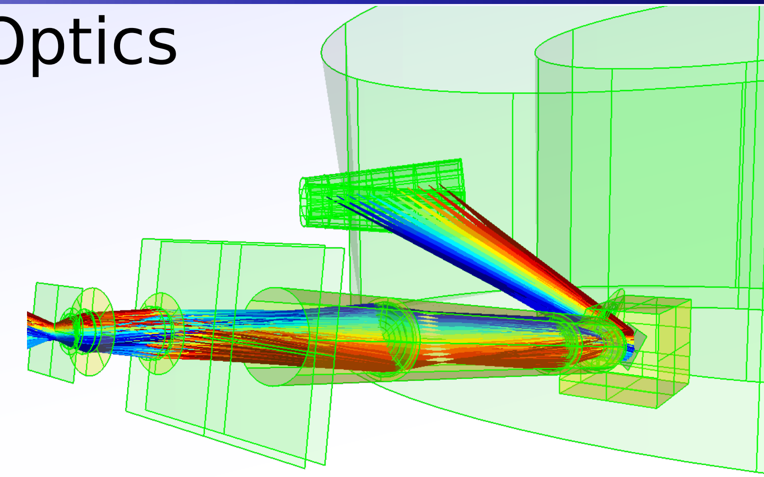
Keep as much of the light delivered by forward optics as possible.

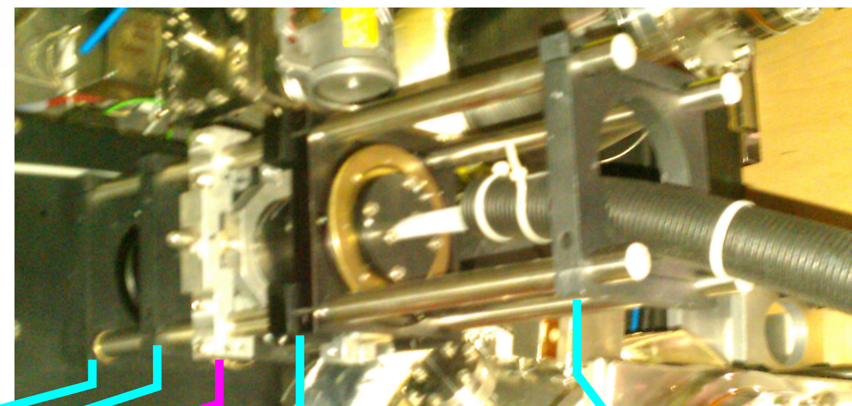
Reject as much background spectrum and emit as much useful light as possible.

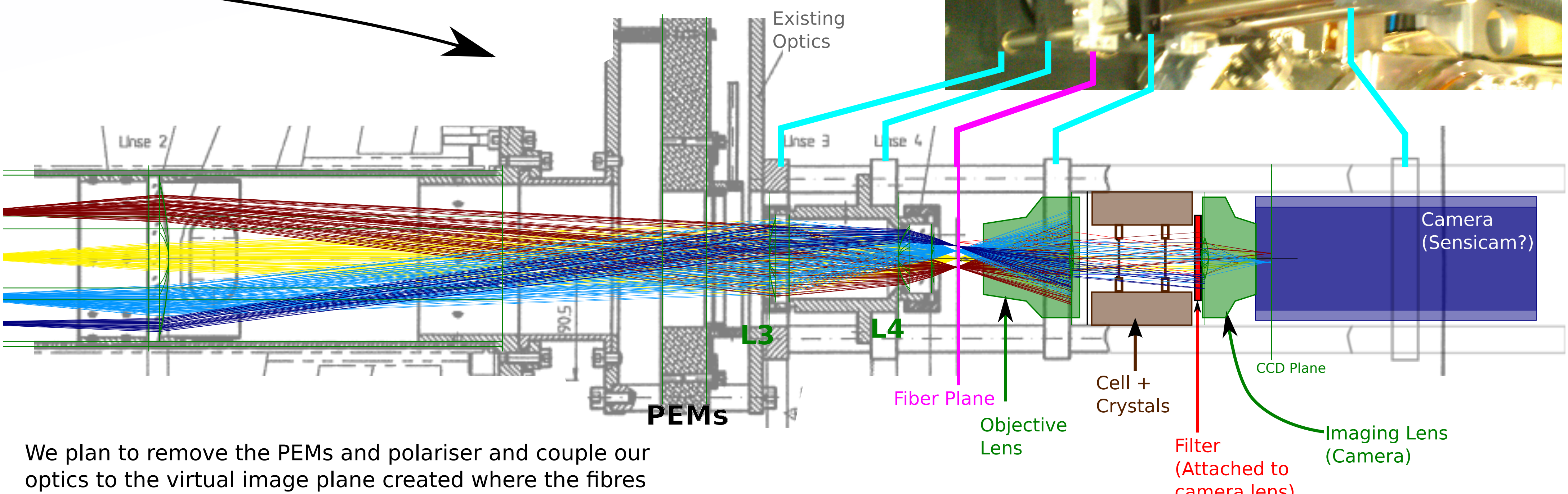
IMSE Design - Existing Optics

The current setup images the outboard half of the upper tangential beam onto the ends of a grid of optical fibres outside the vessel:





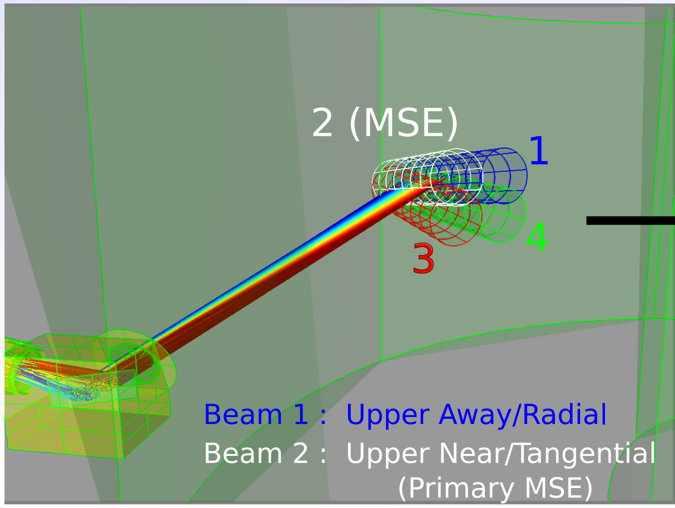




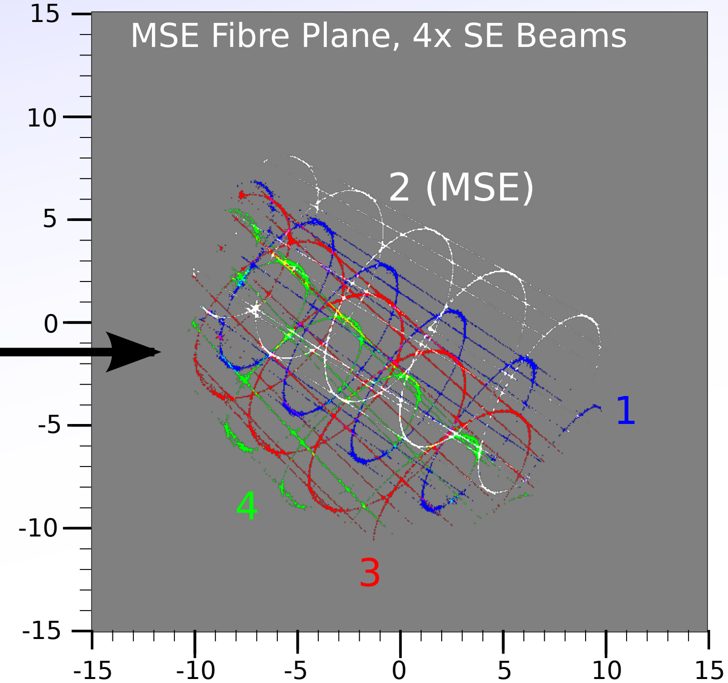
We plan to remove the PEMs and polariser and couple our optics to the virtual image plane created where the fibres are currently held - the 'fibre plane'.

IMSE Design - Imaging

The image of the beams (20cm wide cylinders), at the fibre plane, should look like this:

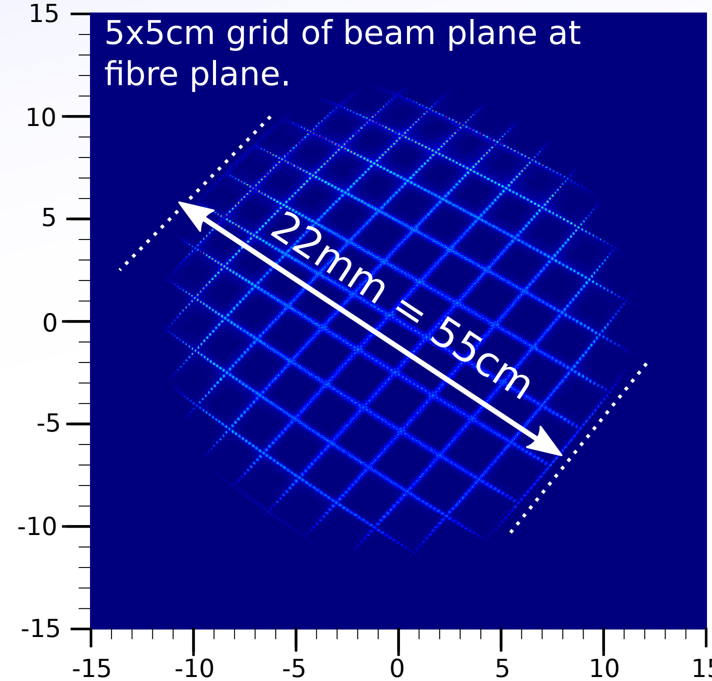


Beam 1 : Upper Away/Radial
Beam 2 : Upper Near/Tangential (Primary MSE)
Beam 3 : Lower Near/Tangential
Beam 4 : Lower Away/Radial

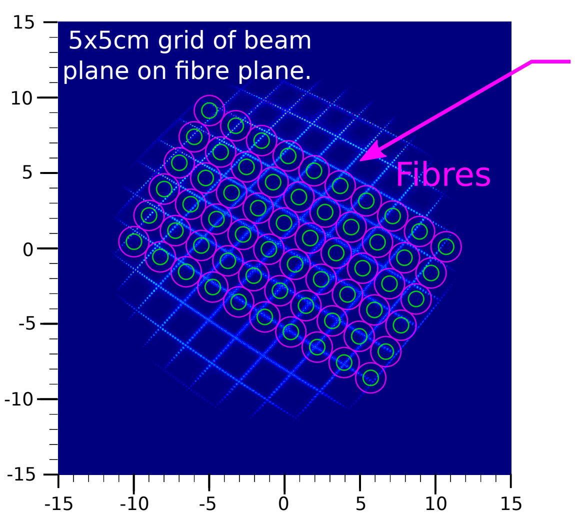


Full FOV: ~55cm at beam plane, ~22mm at fibre plane.

Ray-tracing a 5x5cm cell grid from the beam plane to the fibre plane gives:



We need to demagnify this 22mm onto our 8.9x6.7mm CCD.



There are some discrepancies with what we think we know:

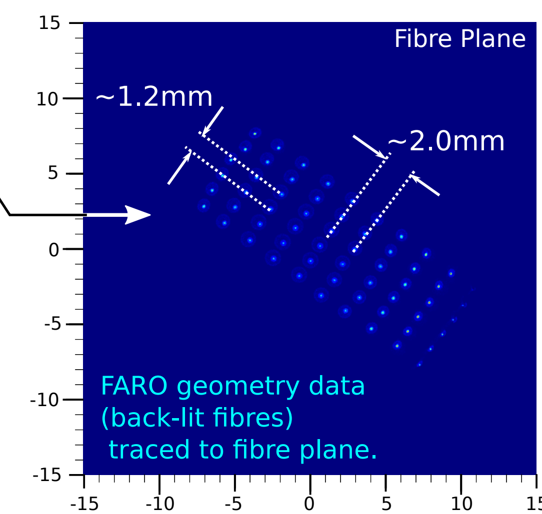
We think the fibres are roughly 10x6 grid of 2mm fibres with 1mm core [T. Löbhard].

Ray-tracing 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.

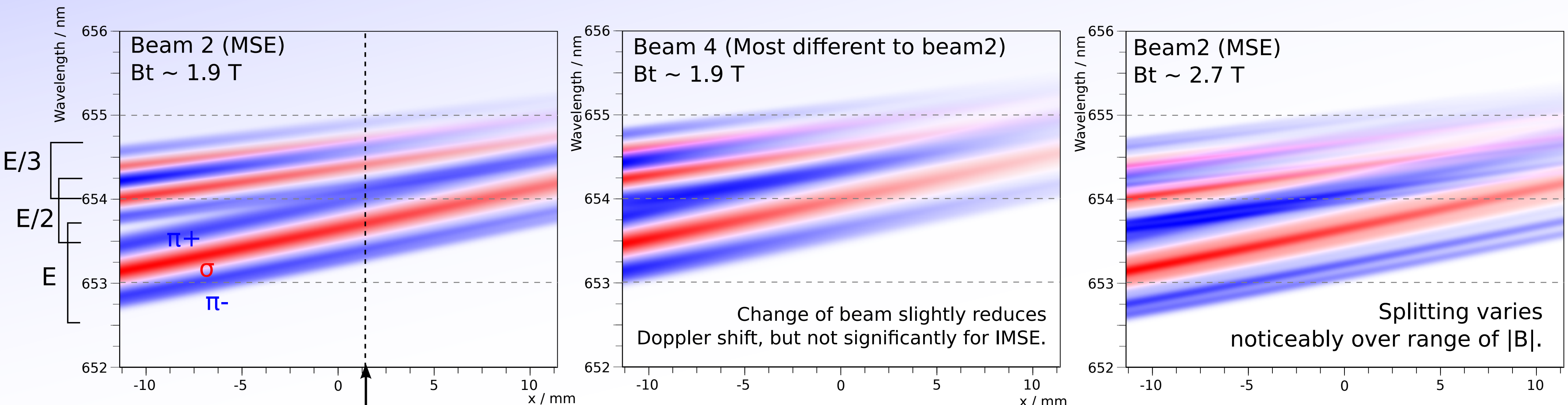
The final lens L4 has an inconsistent focal length and radius. Radius agrees with imaging, but focal length gets light through PEMs parallel.

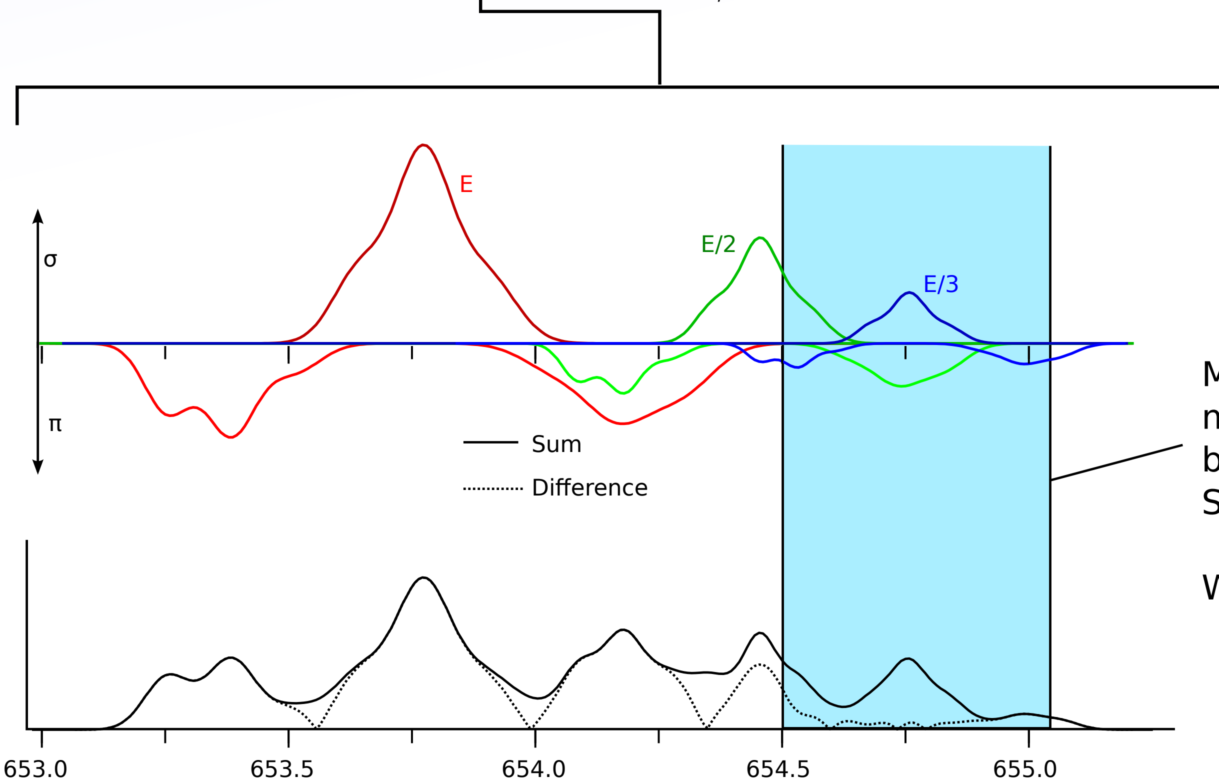
However, the 10 channels cover the expected region of the plasma and this matches the ray traced 55cm - 22mm. This is the only important thing, which appears to be consistent.



IMSE Design - Spectrum

Spectrum across centre of image for high and low fields.



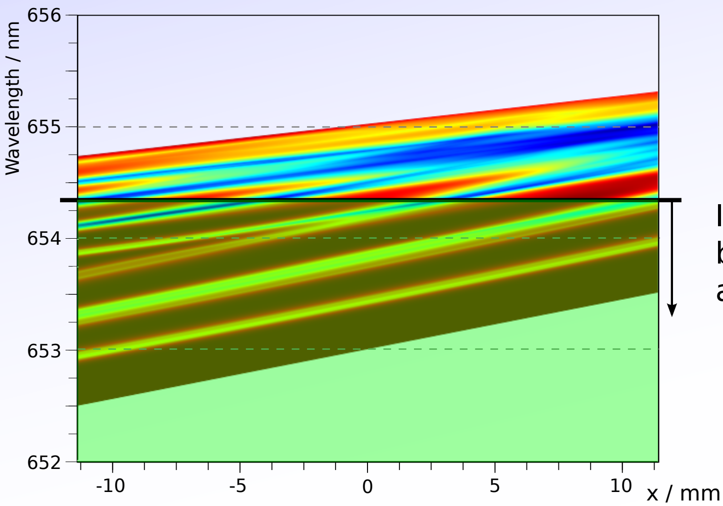


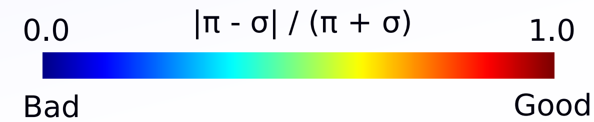
Mixing of *π/σ* from different components makes *λ > 654.5nm* useless. This and the background Dα (at the same end) will reduce S/N.

We need a filter that rejects this.

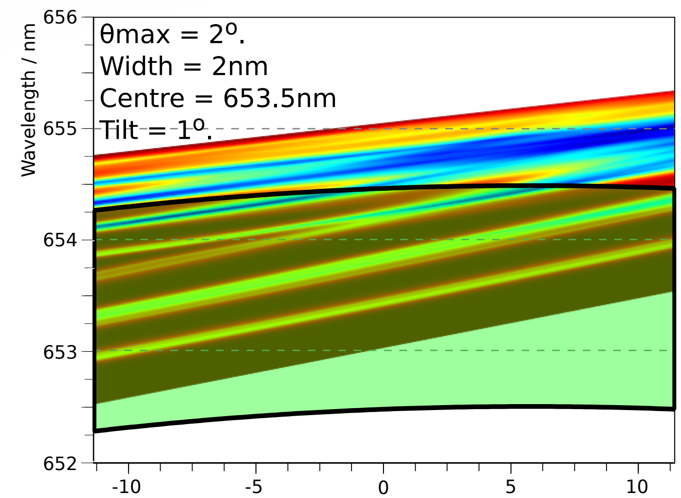
IMSE Design - Filter.

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





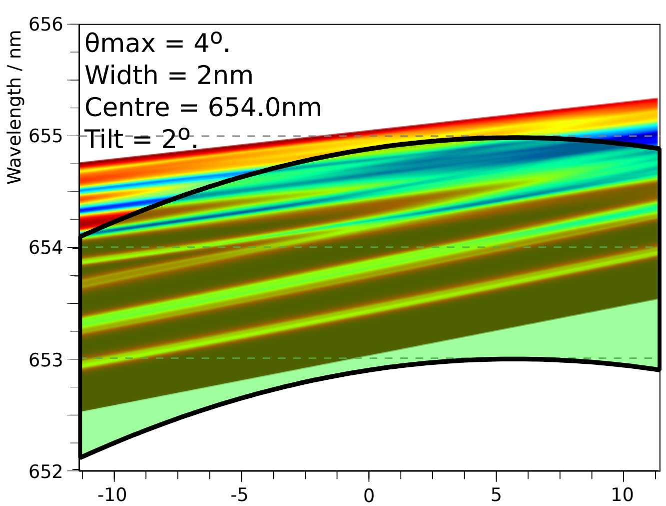
Ideal filter would almost be sharp high-pass at $\lambda \sim 654.3$nm

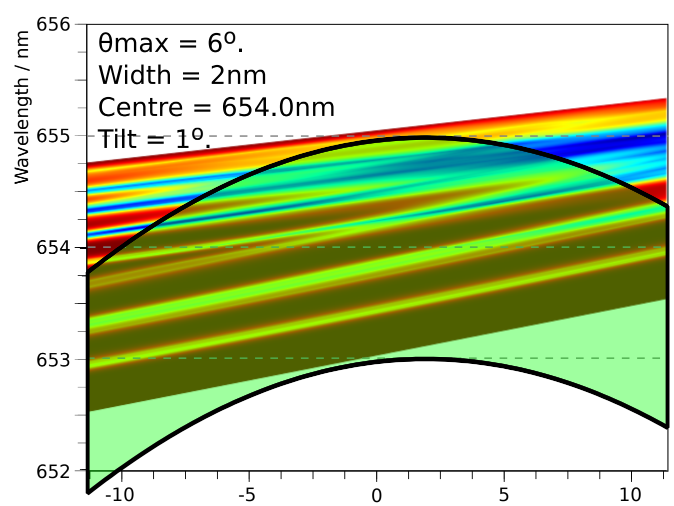


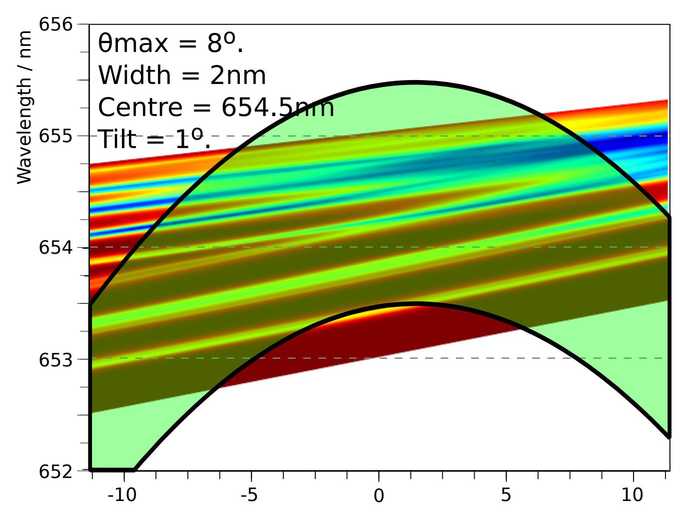
Interference filter pass-band depends on angle of light, so changes over FOV:

$$\lambda \approx \lambda_0 \sqrt{1 - \frac{1}{2}\sin 2\theta}$$

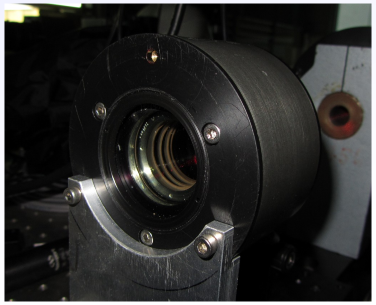
Above θ_{max} ~4° the filter function moves too much to easily capture edges with also capturing poor regions in centre. We really need to keep max angle through filter below 6°.



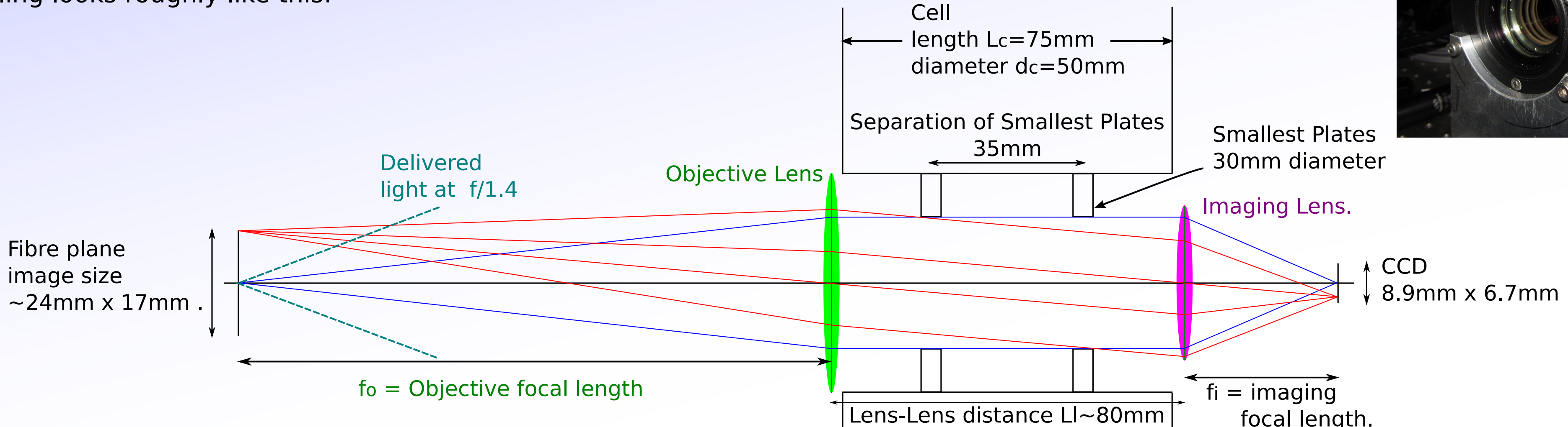




IMSE Design - Lenses.



Without using 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:

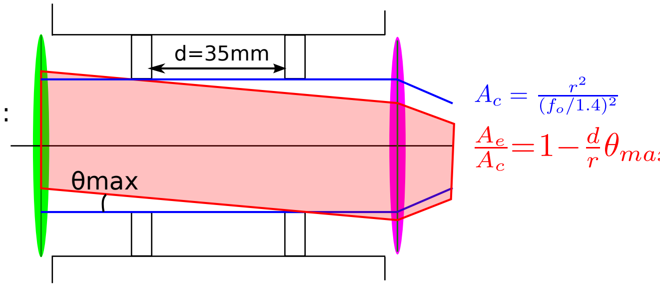
Angle of light through plates is set by f_o: $\theta_{max} = 24mm / (2\ f_o)$

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

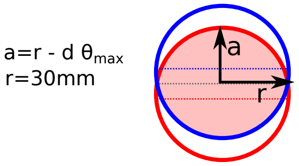
So for $\theta_{max} = 5°$, we need 135mm faster than f/4.5.
NB: To accept the whole image, objective must be a 35mm film lens - not the smaller C-mount (CCTV) ones.

Vignetting:

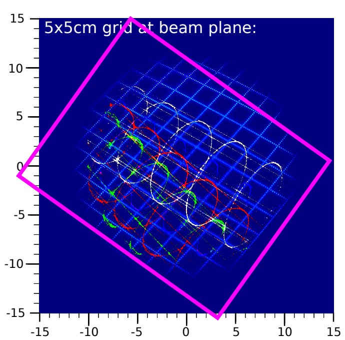
Roughly (assuming both lenses are fast enough and close enough):
$A_{edge} / A_{centre} = (a\ r)/r^2$
$= (r - d\ \theta_{max}) / r$
$= 1 - d/r\ \theta_{max} = 1 - 1.17\ \theta_{max}$.



For $\theta_{max} = 5°$, $A_e/A_c = 89\%$.
Generally, it is never worse than 70%.



If imaging lens isn't fast enough, A_c and A_e are both reduced and *d* is longer (~60mm) so vignetting is worse (~65%), but usually this is because f_i is shorter, so A_e is actually much higher.



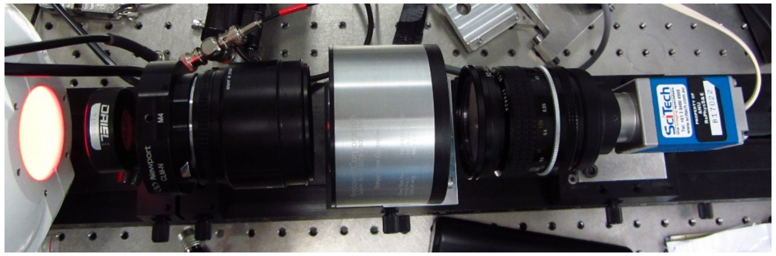
Imaging Lens:

We need to choose f_i to image 24x17mm of fibre plane completely onto 8.9x6.7mm CCD. That requires $f_i/f_o \sim 0.34$.

For the imaging lens to not restrict the light throughput, it needs at least a speed of *fi/30mm*. For the $\theta_{max} = 5°$ case, we need $f_i < 43mm/1.4$.
35mm or 50mm are nearest.

We tested the setup at ANU:

..and I have here at IPP too.



IMSE Design - Lenses.

I've looked 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 24mm virtual image area.

Objective candidates:

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 candidates:

f	f/#	Req f/#
25	0.85	0.83
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

We have a box for this.

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

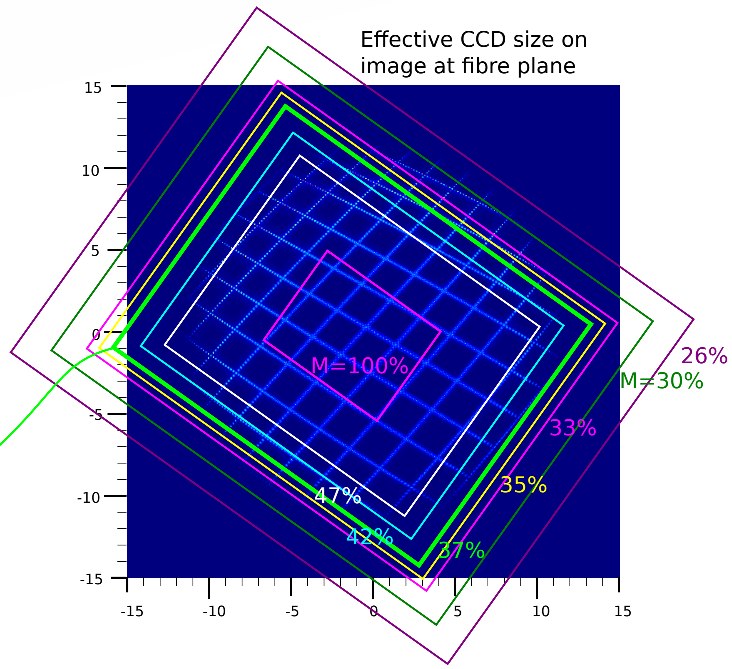
Some combinations:

fo	fo/#	fi	fi/#	M	θmax	Ac (throughput)	Ae/Ac (vignetting)
75	1.4	25	0.85	33%	9.2°	30%	70%
75	1.4	25	0.95	33%	9.2°	24%	67%
85	2.1	25	0.95	30%	8.1°	19%	68%
100	1.2	35	1.2	35%	6.9°	17%	85%
105(Z)	1.8	35	1.2	33%	6.5°	15%	86%
105(Z)	1.8	50	1.4	48%	6.5°	16%	87%
135	2.0	35	1.2	26%	5.1°	9.1%	89%
135	2.0	50	1.4	37%	5.1°	9.6%	89%
180	4.5	50	1.4	28%	3.8°	5.4%	92%
180	4.5	75	1.4	42%	3.8°	5.4%	92%
300	9.0	100	1.2	33%	2.3°	2.0%	95%

Lens speed limited.
Cell limited

Reasonable options

Best choice of lenses
(and we have them already)



NB: θmax is the angle through the plates of the light from the edge of visible beam. It isn't exactly equal to the angle of light to the edge of the CCD. i.e. it is independent of M.

Conclusions:

- Vignetting should not be a problem.
  Ac/Ae is higher for large θmax, but *Ae* itself is actually bigger.
- 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, a 35mm/1.2
  is almost necessary.
- θmax = 5.1° looks the best middle ground to aim at.

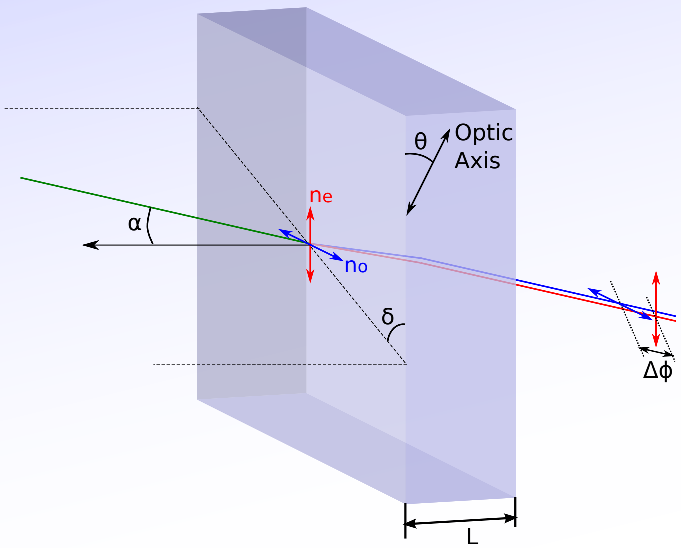
- Throughput for θmax permitted by filter is only 5 - 10%.
  It is limited by 30mm aperture only for θmax < 5.1°.
  Increasing crystal size to 35mm aperture would give:

fo	fi	Ac(30mm)		Ac(35mm)
135	50	9.6%	⟶	13.0%
180	50	5.4%	⟶	7.0%
300	100	2.0%	⟶	2.7%

So bigger plates are not really worth the price.

IMSE Design - Fringes

From F.E.Veiras, phase shift in arbitrary crystal:
NB: α here is the incidence angle - like θ_{max} was before - sorry.



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

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

Generally, n=1 and $\sin^2\alpha$ is small

Waveplate (θ=0):

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

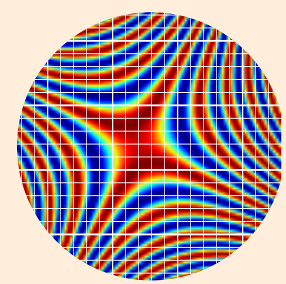
The $\sin^2\alpha$ term gives the fringes due to the delay plate (which bend the displacer fringes).
To quantify, we can calculate α_p, the angle at which it gives 1 full phase rotation:

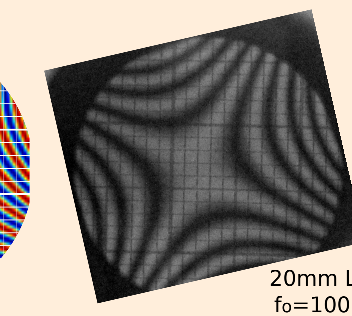
$$\alpha_p \approx \sqrt{\frac{2n_o\lambda_0}{L\left(1 - \frac{n_e}{n_o}\right)}}$$

at (δ=0°, 90°, 180° or 270°)

I'll come back to this at the end.

This all matches what we see in the lab:





20mm LiNb
fo=100mm
SX220

Displacer plate (θ=45°):

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

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

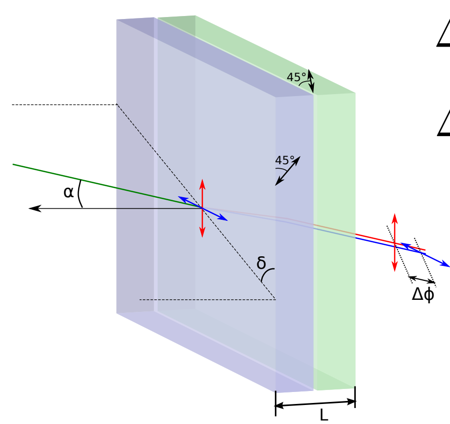
The maximum α is θ_{max} from earlier.
So the number of fringes for the full (2x *θmax*) image is:

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

For αBBO at 653.5nm:
$n_o = 1.666$, $n_e = 1.549$

$N = 2.2\times10^5\ L\ \theta_{max}$ ~ 4 fringes per mm per degree

Savart plate (2 displacers at 90°):



$$\Delta\phi_s = \Delta\phi\left(\frac{L}{2}, \delta\right) + \Delta\phi\left(\frac{L}{2}, \delta - \frac{\pi}{2}\right)$$

$$\Delta\phi_s = \frac{2\pi L}{\sqrt{2}\lambda_0}\frac{(n_o^2 - n_e^2)}{(n_o^2 + n_e^2)}\sin\left(\delta + \frac{\pi}{4}\right)\sin\alpha$$

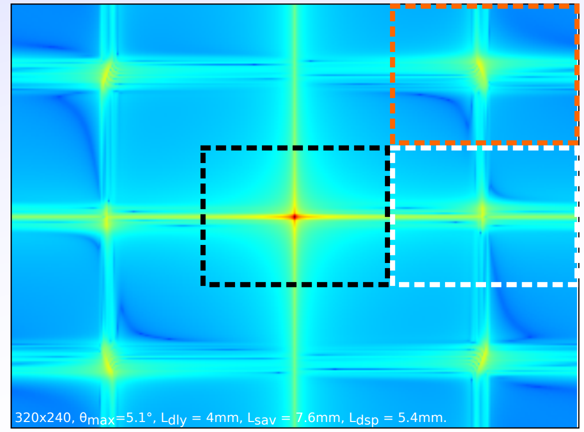
Has no zero-order delay and produces fringes running at 45° to the first plate axis, of the same frequency as a displacer plate of thickness L / √2. (i.e. The Savart plate is √2 thicker)

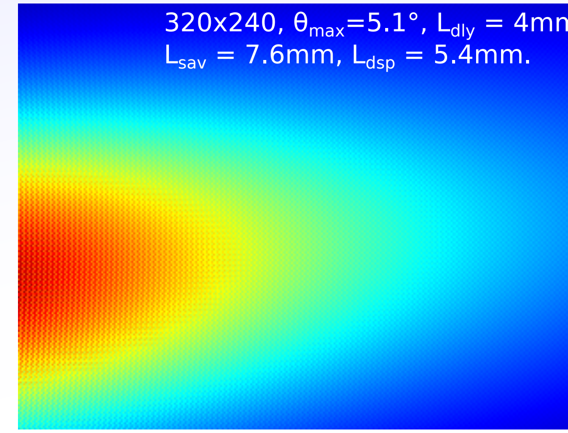
For αBBO at 653.5nm:
N = 5.5 fringes per mm per degree

IMSE Design - Fringes 2

How many fringes do we want?
This is the bit I'm least sure about....

When analysing the image, we take the FFT and isolate components. High frequency information moves away from component centres and where they overlap, contaminates the other components. Any space on the high frequency side of the fringe frequency is effectively wasted. So, central frequencies should be at 2/3 of the Nyquist frequency - i.e. 3 pixels per fringe.





However...

a) We don't yet know what resolution we'll want - it will depend on the time resolution and light level. We can say, that the minimum resolution will be limited to 3x the number of fringes.

b) The highest properly resolvable frequency will be lower than the Nyquist frequency due to imperfect focusing of the fringes by the final imaging lens - i.e. the blurring attenuates high frequencies.

c) Such a high frequency 'feels' like a bad idea, why? Mathematically, $\Delta\phi$ for the plates (from Veiras) has higher order terms only in $\sin^2 \alpha$ and in (n_e-n_o). Since it is all linear in L, there should be no detrimental effects.

Linearity in L also tells us that increasing the fringe frequency by increasing L is better than by increasing θ_{max}.

Max resolution for sensicam, pixelfly etc is 1376x1040. Take 1/4 of that to be very safe and make minimum resolution images easier to handle: 320x240.

Using αBBO at 653.5nm, N_{pixels} =320 and the standard case of θ_{max} = 5.1° (135-50):

Displacer: L_{dsp} = 5.4mm
Savart: L_{sav} = 7.6mm

Put these into the full forward model to check all of this - works as expected.

At this thickness, our middle and extreme cases give:

θ_{max}	~ # fringes across beam	Demodulation resolution at plasma	Min image size
9.2° (75-25)	190	6mm	688x520 (½)
5.1° (135-50)	100	11mm	344x260 (¼)
2.3° (300-100)	50	22mm	172x130 (⅛)

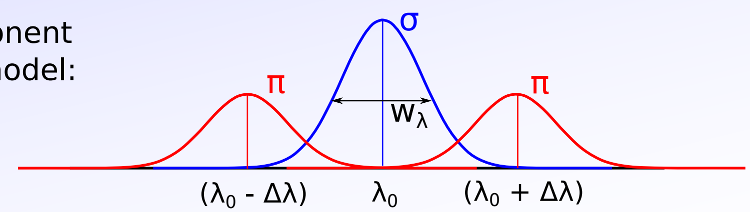
θmax was calculated for the edge of the visible beam, which always covers 55cm of beam, regardless of M. The # fringes here also used θmax, so is technically #fringes across the beam, not necessarily exactly across the image.

Considering that the LOS integration gives us a resolution of ~20mm at best, this is good.

IMSE Design - Delay (Simple Calculation)

The final thing to be decided is the thickness of the delay plate.

Take just the full energy component and the very simple splitting model:



λ_0 = 653.5nm
$\Delta\lambda \sim$ 0.4nm (see right)
w_λ: FWHM ~ 0.25nm,
$\sigma_\lambda \sim$ 0.1nm (from spectrum, page 3)

Each gives interference pattern with amplitude:

$$A \propto \exp\left(-\frac{\sigma_\lambda^2}{2\lambda_0^2}\Delta\phi^2\right)\cos\Delta\phi(\lambda)$$

Phase shift is always $\Delta\phi = \frac{2\pi L}{\lambda}(\ldots)$, so $\Delta\phi(\lambda_0 \pm \Delta\lambda) = \Delta\phi(\lambda_0) \pm \frac{\Delta\lambda}{\lambda_0}\Delta\phi(\lambda_0)$

Sum of interferograms from each component σ - π^+ - π^- gives:

$$A \propto \underbrace{\exp\left(-\frac{\sigma_\lambda^2}{2\lambda_0^2}\Delta\phi^2\right)\left[1-\cos\left(\frac{\Delta\lambda}{\lambda_0}\Delta\phi\right)\right]}\cos\Delta\phi$$

This thing is the 'net contrast' and varies slowly with $\Delta\phi$ i.e. only the zero order $\Delta\phi$ terms matter (no *sin α*)

Maximum is at *L ~ 4.1mm* for a single delay plate. At the field extremes the max is *L =4.8mm* at *B=1.9T* and *3.6mm* at *B=2.7T.*

We already have a L_{dsp} = *5.4mm* displacer plate, which gives an effective delay of a 2.7mm delay plate. With the (surface projected) optic axes aligned, the delays add and the delay plate needs to be only 1.4mm. With the plates at 90°, the delay subtracts and the delay plate must be 6.8mm.

Splitting, very roughly....
B = 2.3T (1.9 to 2.7 is range)
Full beam energy = *60 keV* (Deuterium = 2 x m_p)
Angle between *B* and *v* ~ *62°* in centre.
λ_0 = 653.5nm

$$v = \sqrt{\left(\frac{2\times 60keV}{2m_p}\right)} \approx 2.4\times 10^6 ms^{-1}$$

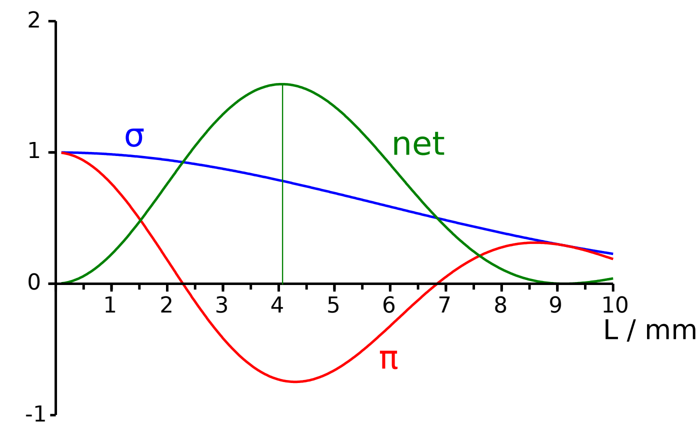
$$E = \underline{v}\times\underline{B} \approx 4.9\times 10^6 Vm^{-1}$$

$$\Delta E = 3\times\frac{3}{2}ea_0|E| \approx 1.3\times 10^{-3}eV$$

$$\Delta\lambda = \frac{\lambda_0^2}{hc}\Delta E \approx 0.4nm$$

Ranges from 0.32nm at 1.9T to 0.46nm at 2.7T.

Put this into google: sqrt(2*60keV/(2*m_p)) * 2.3T * sin(62 degrees) * 3 * (3/2) * electron charge * 5.29e-11m * (653.5nm)^2 / h /c



From 2 slides ago, the angle at which the 2nd order delay plate terms start to really bend the fringes α_p:

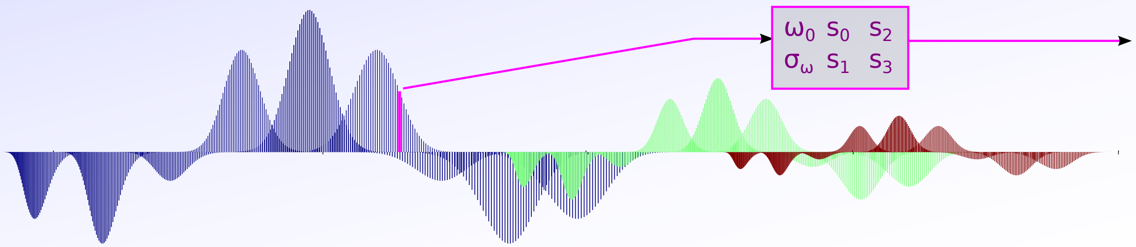
$$\alpha_p \approx \sqrt{\frac{2n_o\lambda_0}{L\left(1-\frac{n_e}{n_o}\right)}}$$

For L_{dly} = 1.4mm: α_p = 8.5° - nicely outside our 5.1° standard case.
For L_{dly} = 6.8mm: α_p = 3.9° - things start to bend.

We should use the thinner delay plate and align it with the displacer.

IMSE Design - Delay (Modelling)

That delay calculation might be a bit *too* crude, since the spectrum is considerably more complex, it changes over the FOV with different beams, we need to include dispersion etc.
The virtual camera model (the medium level one) works by adding the DSH equation for each stokes spectral component vector:



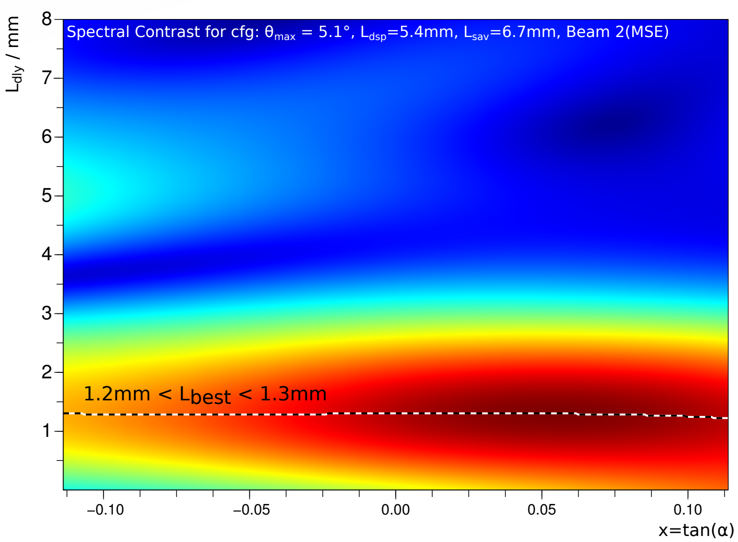
$$I = \sum \left(s_0 + \exp\left(-\tfrac{1}{2}\sigma_\omega^2\tau^2\right)\begin{bmatrix} -\, s_1 \sin(\omega_0\tau_2)\sin(\omega_0\tau_1) \\ -\, s_2 \cos(\omega_0\tau_2) \\ +\, s_3 \sin(\omega_0\tau_2)\cos(\omega_0\tau_1)\end{bmatrix}\right)$$

With all the τ calculated at the component's ω_0 - i.e. includes dispersion.

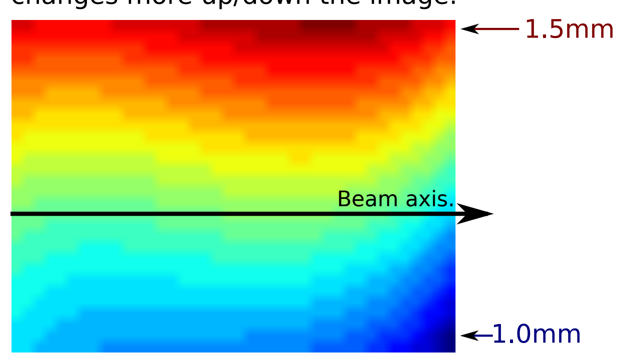
We calculate the net spectral contrast *C*, by building 4 images of the oscillating terms with shifted phases and adding them in quadrature:

$$C^2 = A(\omega_0\tau_1,\, \omega_0\tau_2)^2 + A(\omega_0\tau_1 + \tfrac{\pi}{2},\, \omega_0\tau_2)^2 + A(\omega_0\tau_1,\, \omega_0\tau_2 + \tfrac{\pi}{2})^2 + A(\omega_0\tau_1 + \tfrac{\pi}{2},\, \omega_0\tau_2 + \tfrac{\pi}{2})^2$$

For a scan across the beam, plotted vs delay plate thickness L_{dly}:

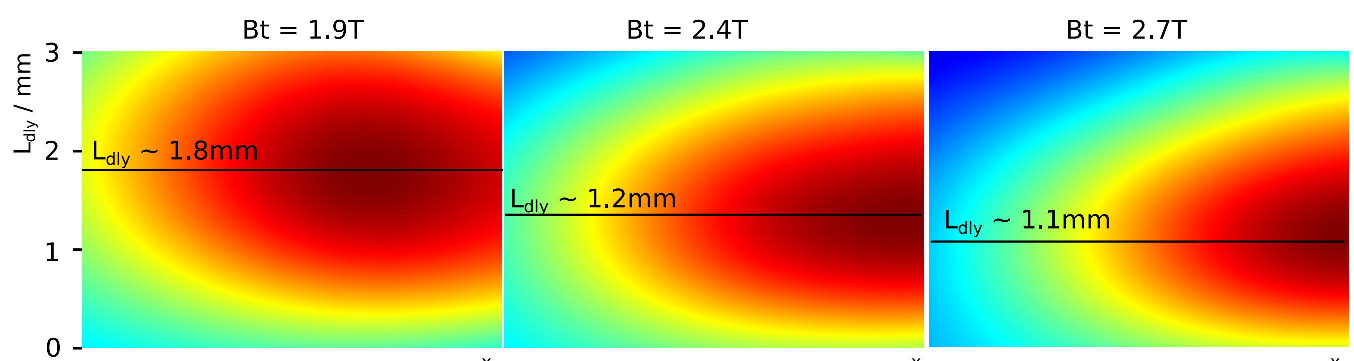


We can also plot the optimum L over the 2D image, which shows that it changes more up/down the image:



Optimal here is slightly lower than simple calculation, at 1.2mm instead of 1.4mm. The region of high contrast is broad and doesn't change much between configurations. Changes to the filters, which beams are in use, etc don't really make a big difference either.

Best all round average:
L_{dly} = 1.2mm



IMSE Design - Summary

Variables:

Focal length and f/# of objective lens.................. *135mm f/2.0*

Focal length and f/# of imaging (camera) lens.... *50mm f/1.4*

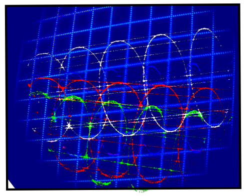
Filter.. λ_{max} = *654.5nm*, tilted at 1° and > *2nm* width.

Thickness of αBBO displacer and Savart plates... L_{dsp} = *5.4mm*, L_{sav} = *7.6mm*

Thickness of αBBO delay plate............................ L_{dly} = *1.2mm*

Requirements:

Image all available FOV of all 4 beams onto CCD...........



θ_{max} = 5.1°

M = 37%

Set reasonable fringe period
(need as much flexibility as possible here!)........... Can in principal range from 50 to 190 fringes.

Set overall delay to optimise fringe contrast................. Easy, this is pretty insensitive.

Keep as much of the light delivered by forward.............
optics as possible. Only about 10% in standard case, we can try pushing it up to 30% later, but we might have to do something different with the filter.

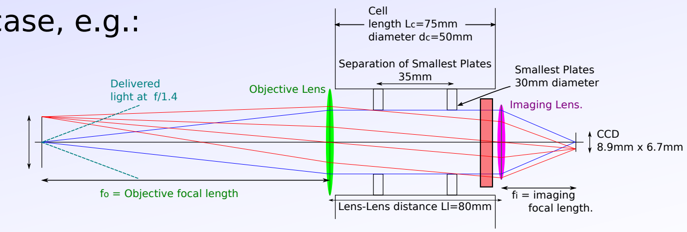
Reject as much background spectrum and emit as........
much useful light as possible. If we can get the filter flat, this is quite good.

Things to come later: Alternative filter positions, Absolute light at camera, Exposure time

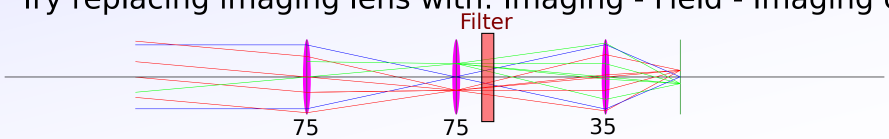
IMSE Design (Additional) - Alternative configs for filter?

What about a 3+ lens system for dealing with the filter angle so that we can use the higher throughput lens configs?

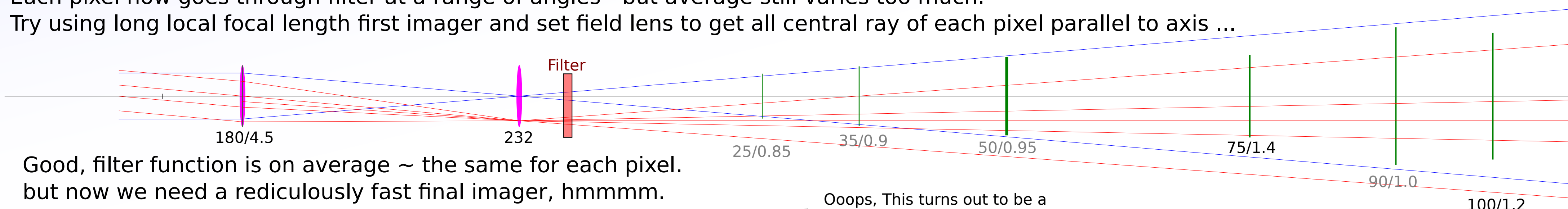
Starting with a standard case, e.g.:
5.1° (135-35)



Try replacing imaging lens with: Imaging - Field - Imaging combination ...



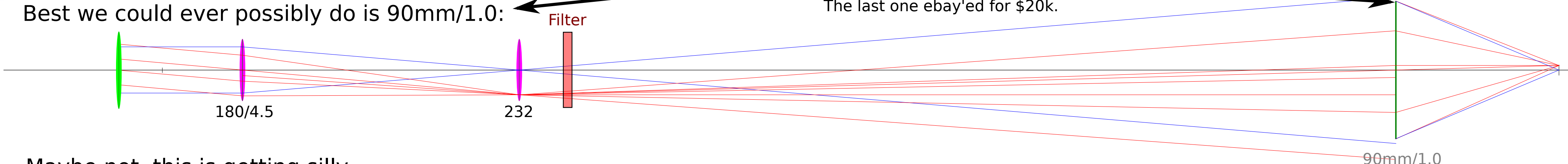
Each pixel now goes through filter at a range of angles - but average still varies too much.
Try using long local focal length first imager and set field lens to get all central ray of each pixel parallel to axis ...



Good, filter function is on average ~ the same for each pixel.
but now we need a rediculously fast final imager, hmmmm.

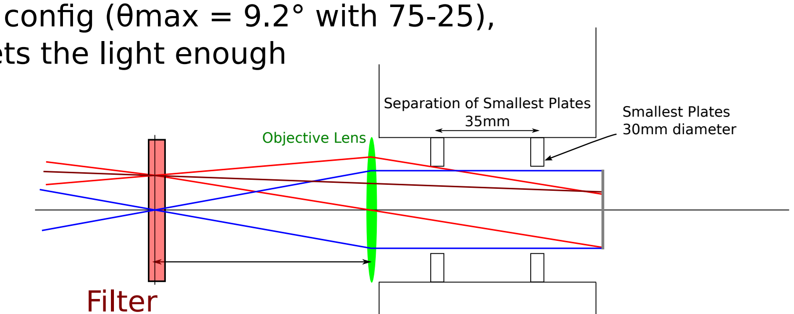
Ooops, This turns out to be a very rare lens Leica made for the military. The last one ebay'ed for $20k.

Best we could ever possibly do is 90mm/1.0:



Maybe not, this is getting silly.

Interestingly, for the strongest config (θmax = 9.2° with 75-25), the 25/0.95 imaging lens vignets the light enough for all pixels to have the same average angle at the fibre plane, so the filter can just go there instead:



Vignetting is now Ae/Ac = 67%, but since throughput is now Ac=24%, which is 2.5x in 5.1° standard case, the edge light is Ae=*2x* the 5.1° case.

So it is worth modelling what putting the filter in an image plane actually does.

* Need to work out for the general, or at least the 100/35 case (6.9°), what field lens at the fibre plane is required to achieve the same result.