Motional Stark Effect Imaging on ASDEX Upgrade:

Notes from Jan 2013 -

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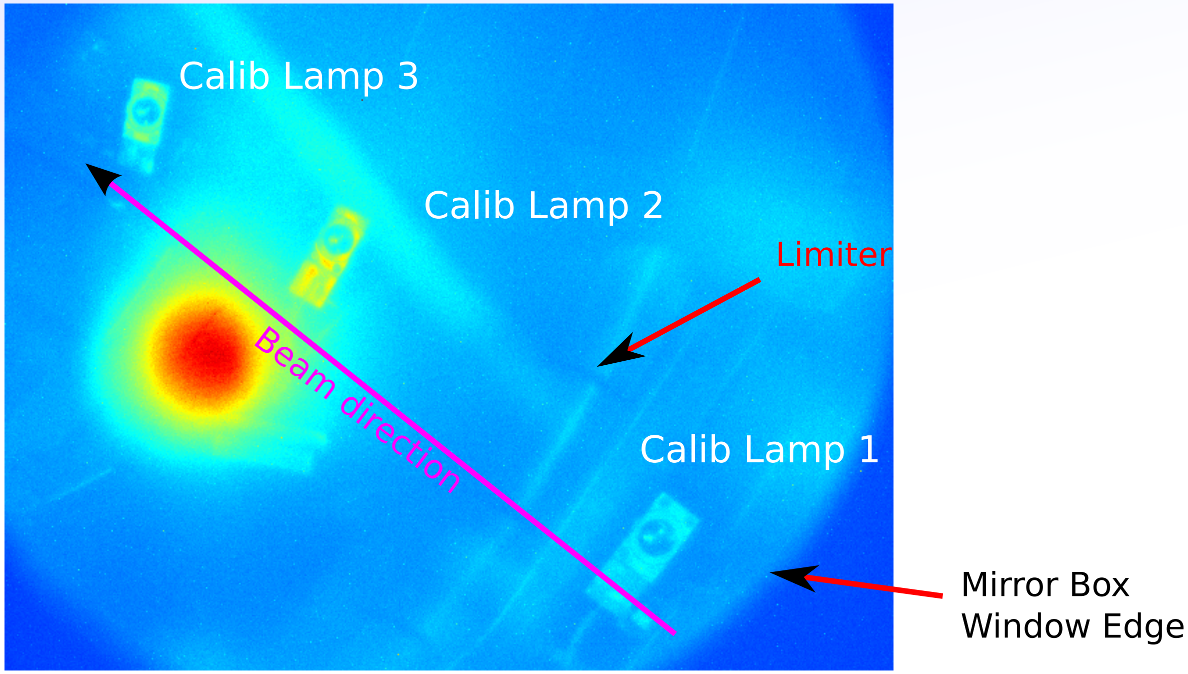
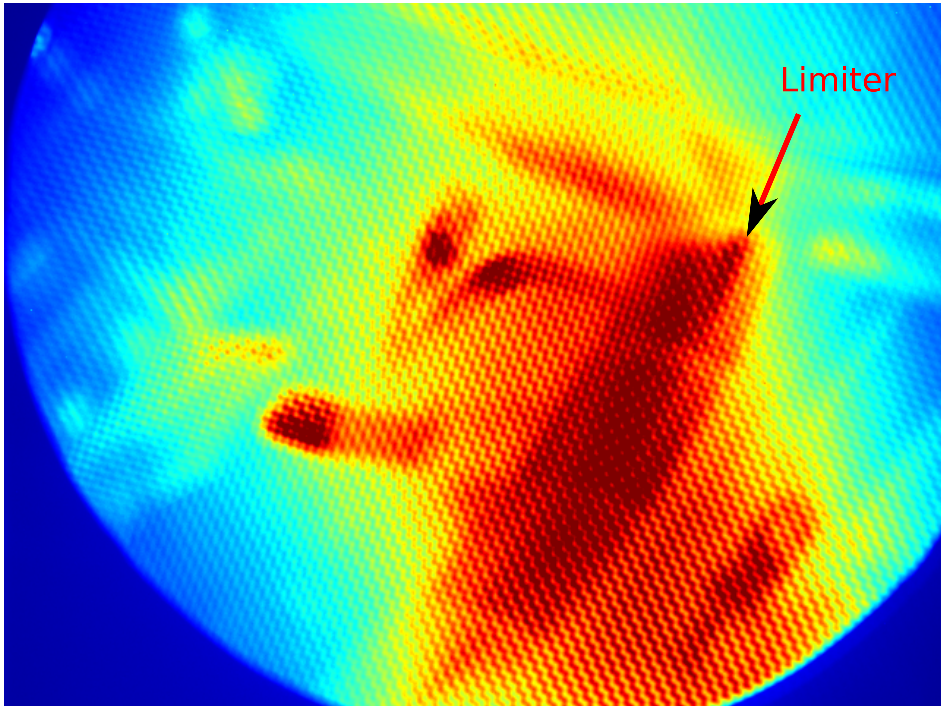
Jan 2013 analysis.
AUG Operations Meetings:
28/01/2013 (Jan 2013 mid)
22/04/2013 (April 2013 pre)
29/04/2013 (April 2013 post)
April 2013 analysis.

Very very early results.

Oliver Ford
IPP Greifswald
gmds/AUG/75-97

Wednesday night, fitting camera.
No filter, big lamps in torus:





First image of beam emission.
Thursday 24th Jan 2013, 08:55:06

Guessed at 50ms expsoure, which was too much.

For 2.5MW beam source 3, require 2-10ms exposure.

Up to 30ms in low-density, lower power/voltage.

Very very early results (Today)

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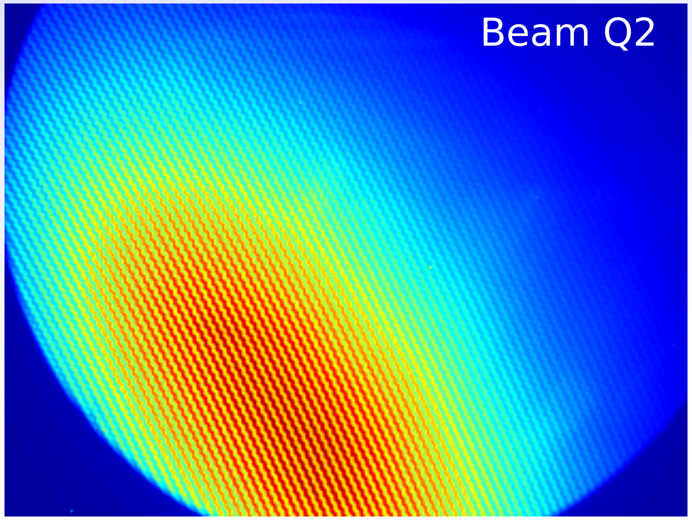
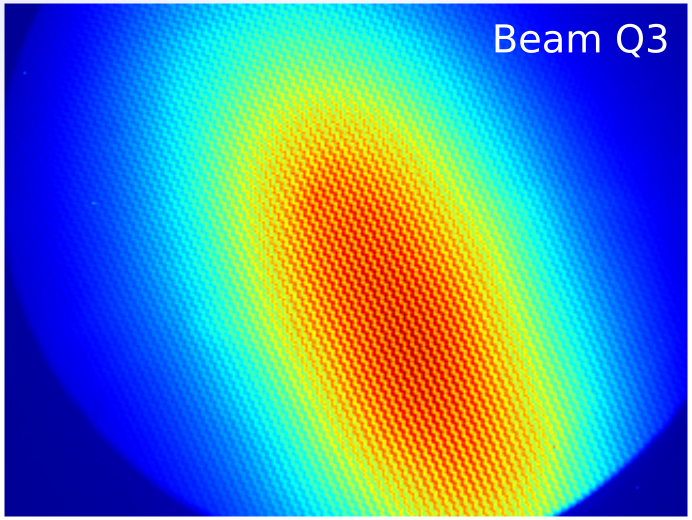
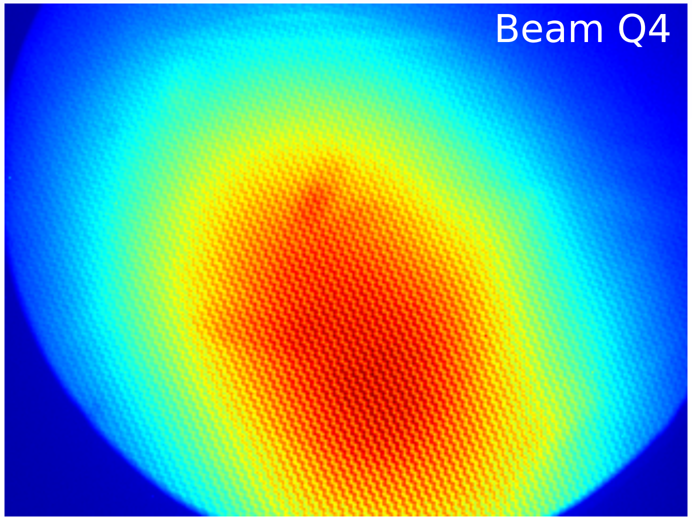
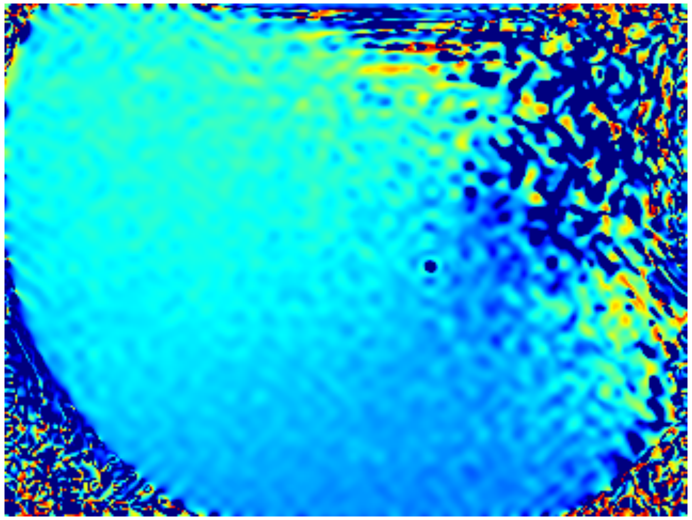
Different beams, all seem to work, but give different angles (as expected).

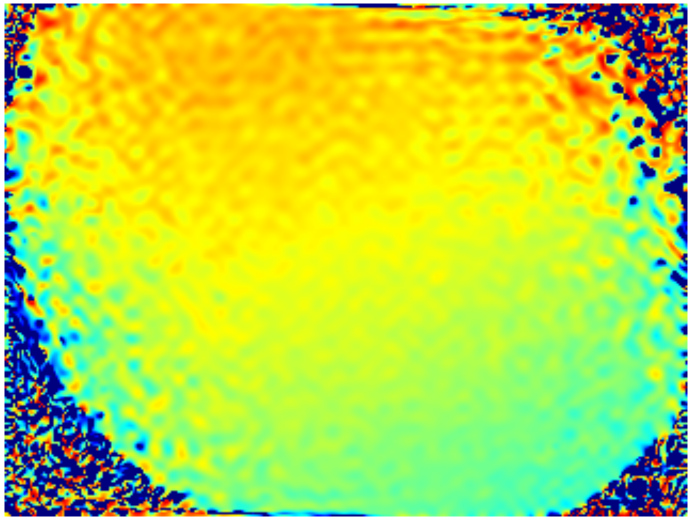


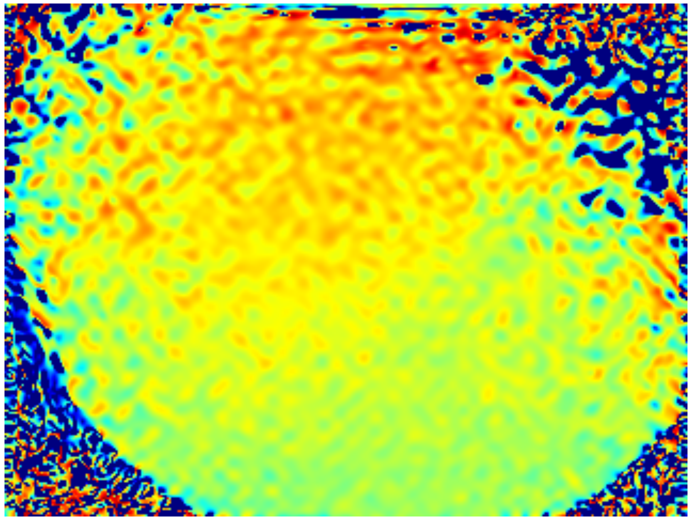




~Polarisation angle:







Early current ramp results

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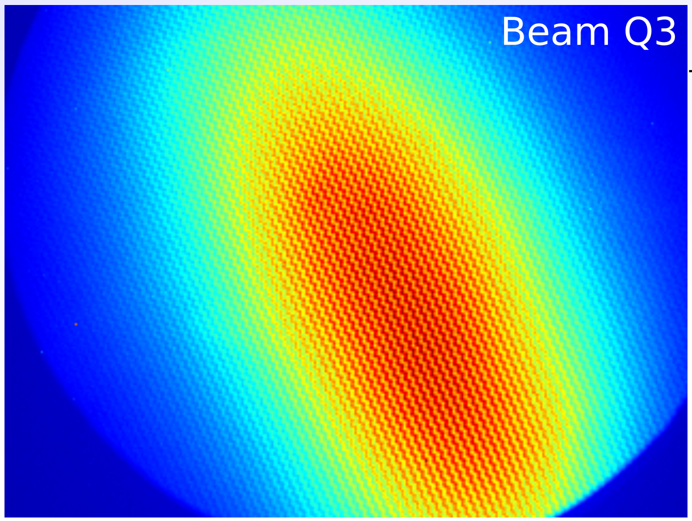
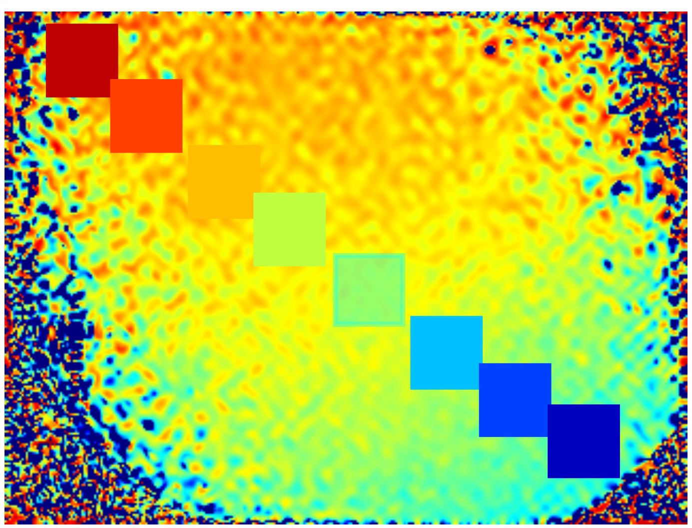
gmds/AUG/29317

Q2 (beam source 2) and mostly Q3 fired during current ramp, and H-mode on first plasma day.
Looks interesting, but I haven't begun to think whether it's sensible or not.





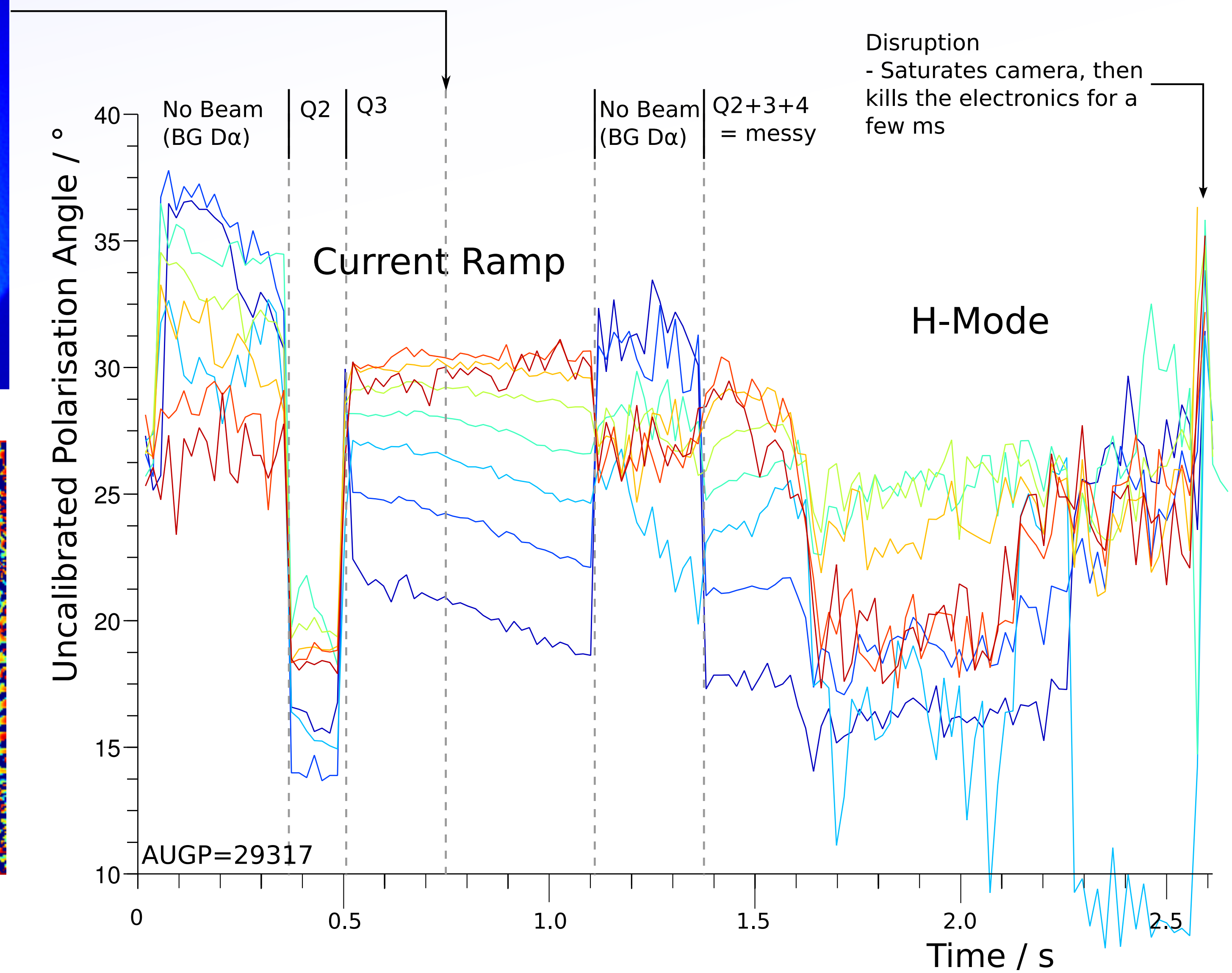


Image Transform

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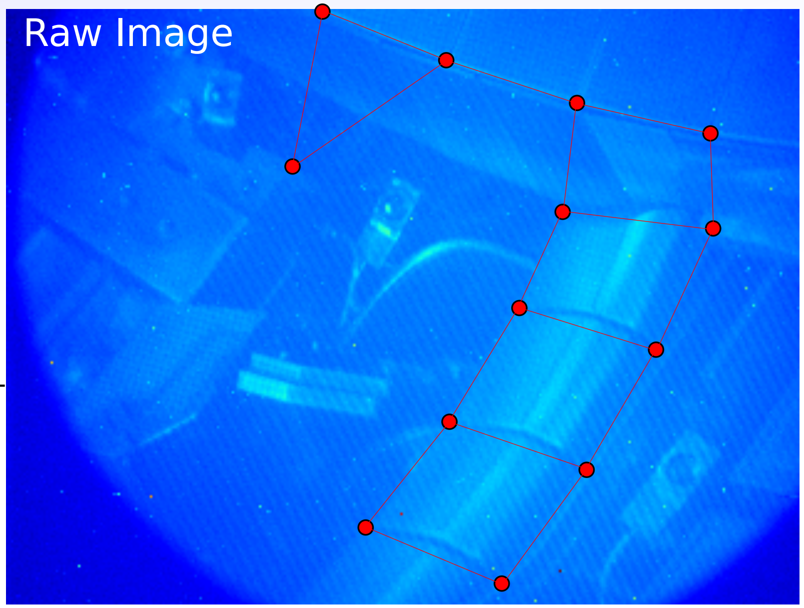
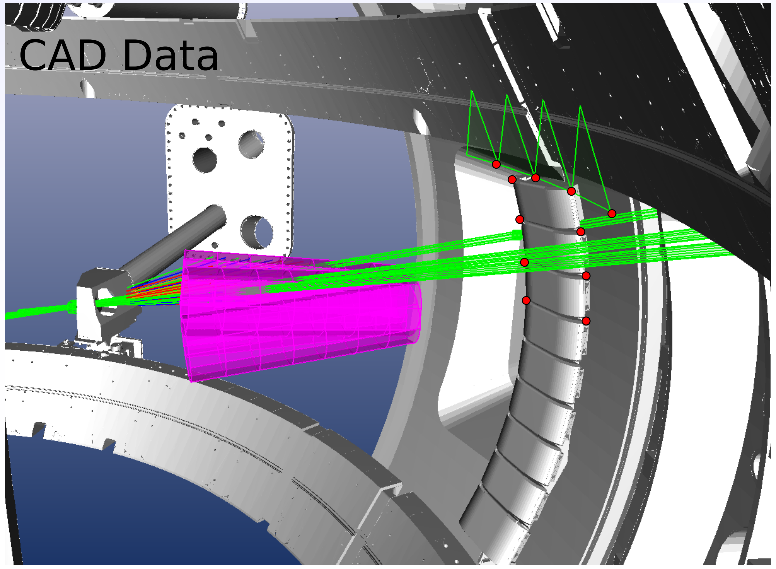
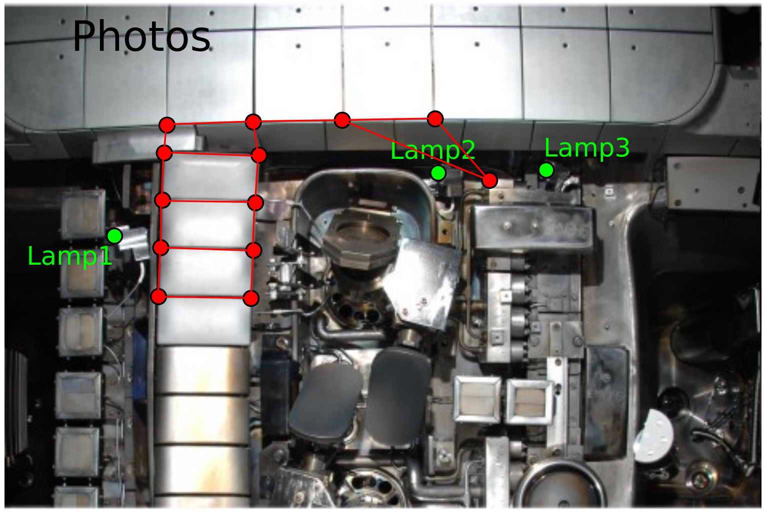
To convert image coordinates to plasma relevant (R,Z) coordinates:

1) Use background and locate the related points in 3D from CAD data.
2) Take (R,Z) of point at closest approach to beam axis on line from camera to object.
3) Fit Affine/Cubic transform to points.



Project in (R,Z)





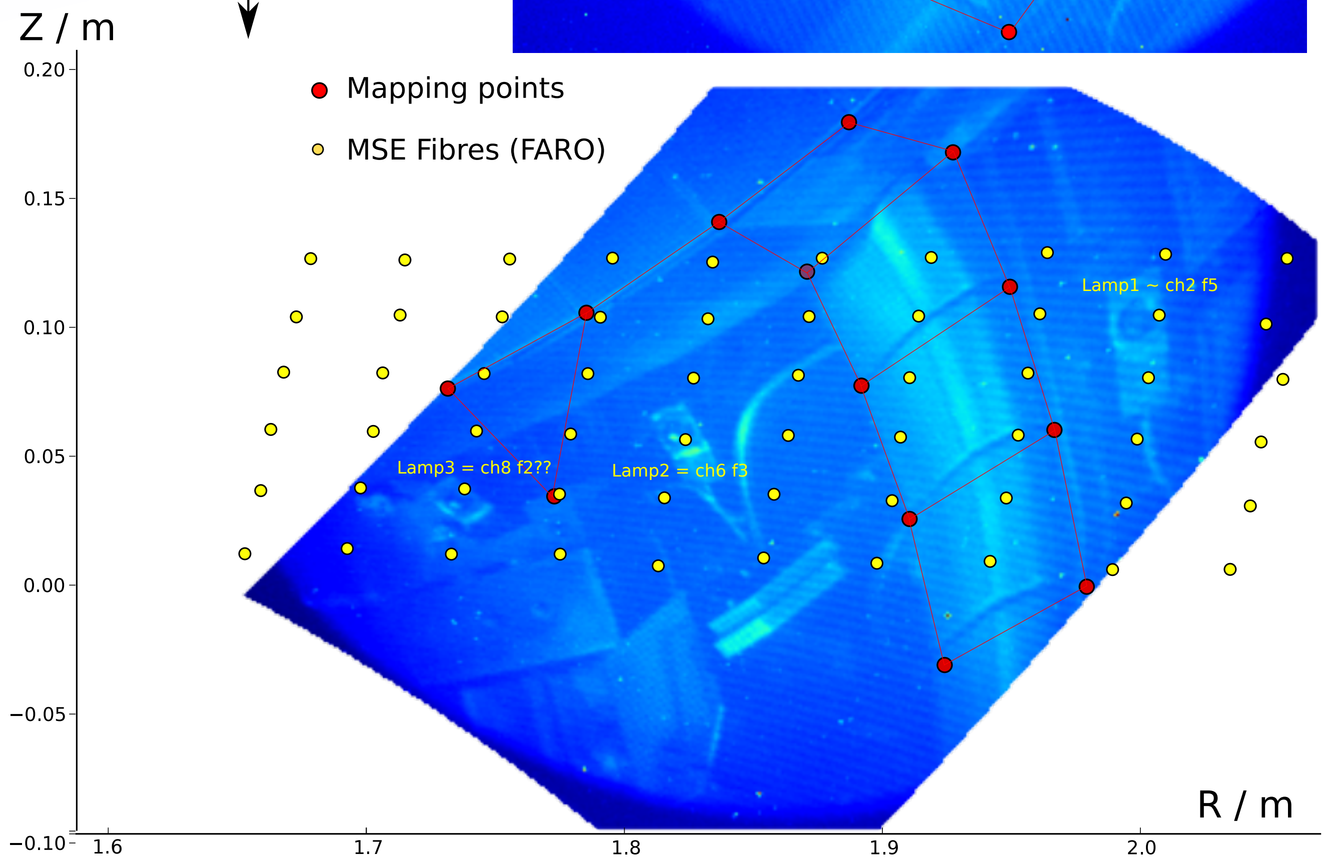


Image Transform 2

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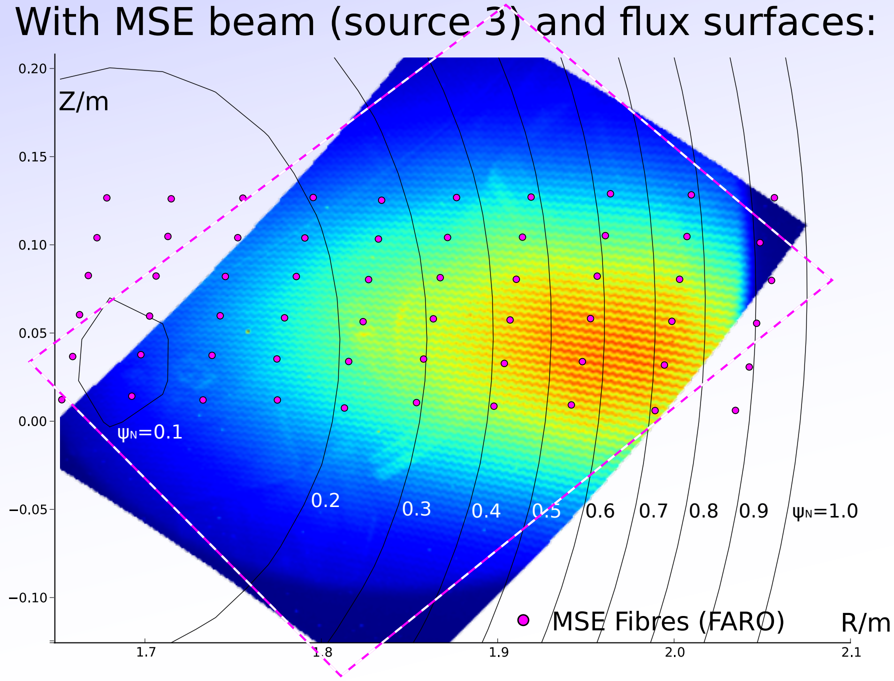
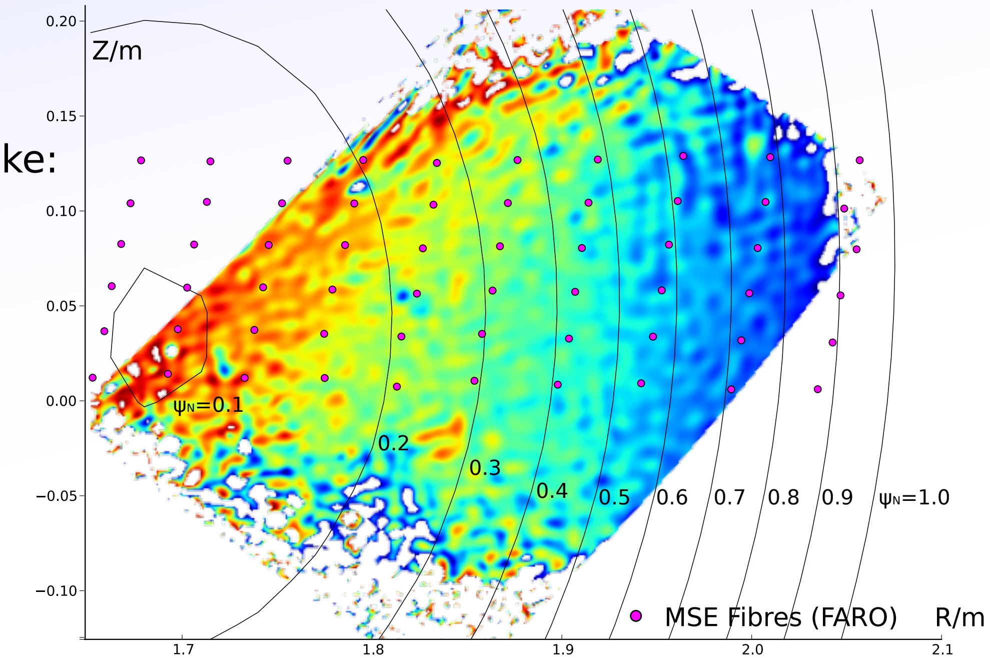
With MSE beam (source 3) and flux surfaces:

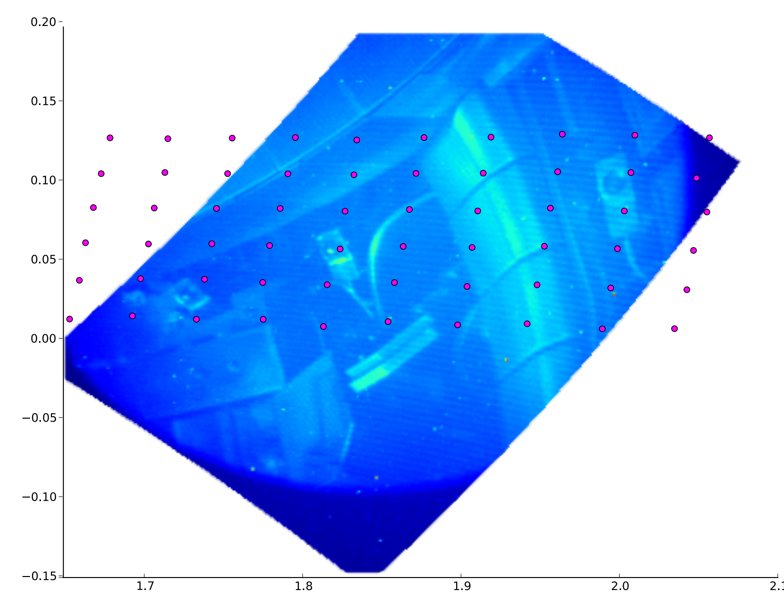


Transformed polaristion angle looks like:



*April2013: Rotated and moved camera to get better view of core and edge.

Ideally would rotate camera ~22° clockwise, but can only get 10° due to physical restrictions.



Intrinsic Contrast Calibration

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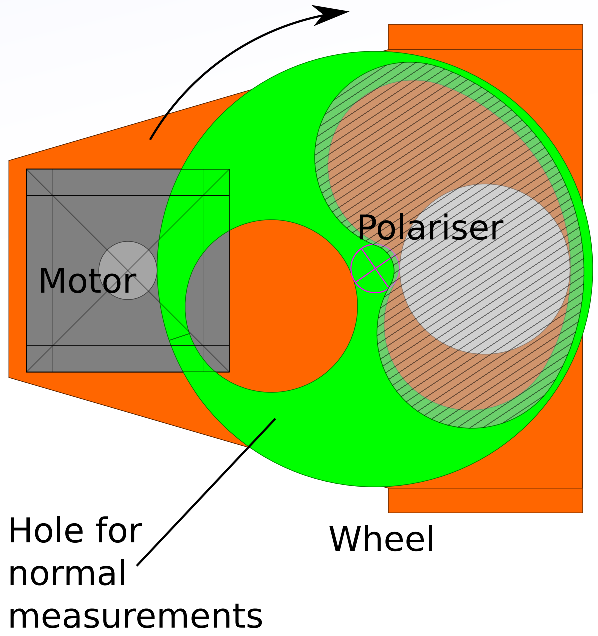
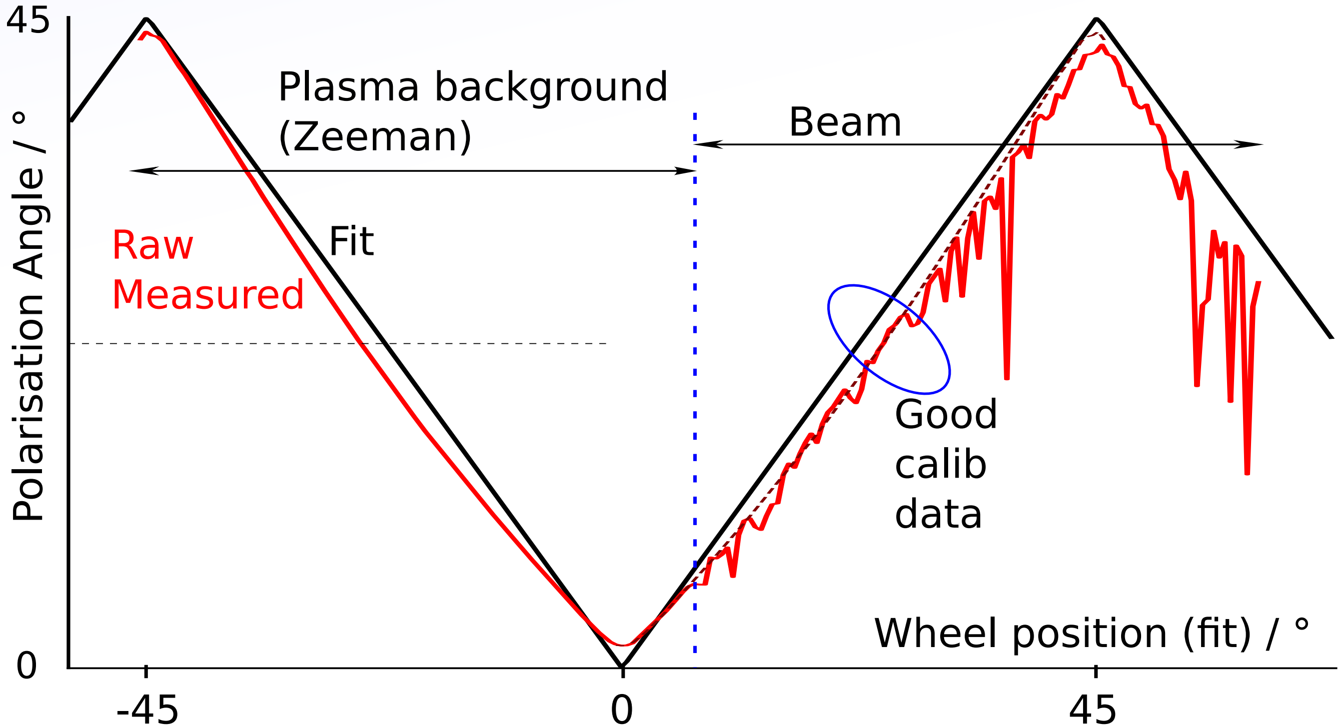
To first order, the system shouldn't require calibration. However, there is a ~3° non-linearity due to intrinsic constrast of the Savart plate. It varies with polarisation, across the image, and with input light cone.

System has a built in polariser on a wheel to provide the calibration for this. Best is a ~100° scan of polarisation angle using full spectrum of beam light but sometimes motor didn't run during pulse.



1) Full rotation with any light source needed to calibrate stepper motor positions against absolute measured angle:



*April2013: Doubled motor voltage and can now run full scan during all pulses.
Primary calibration for Friday 19th missed due to water leak.

2) Record images with beam light at known absolute angle (near 22.5° is best).
In some cases this was a complete scan as above, in other cases a whole pulse at a fixed angle.

Intrinsic Contrast Calibration

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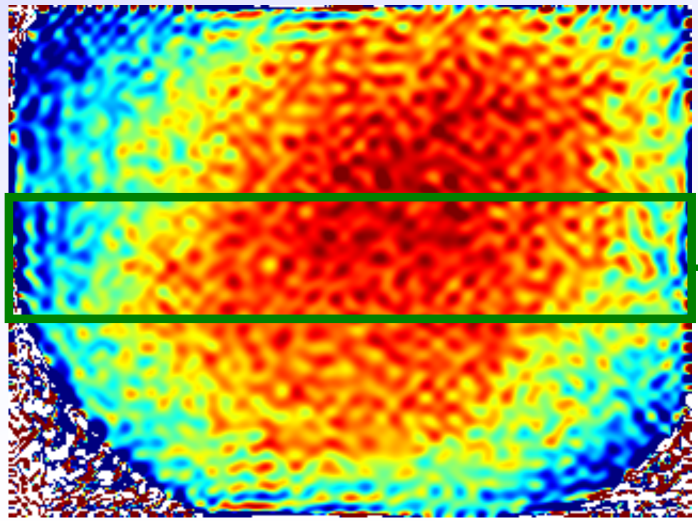
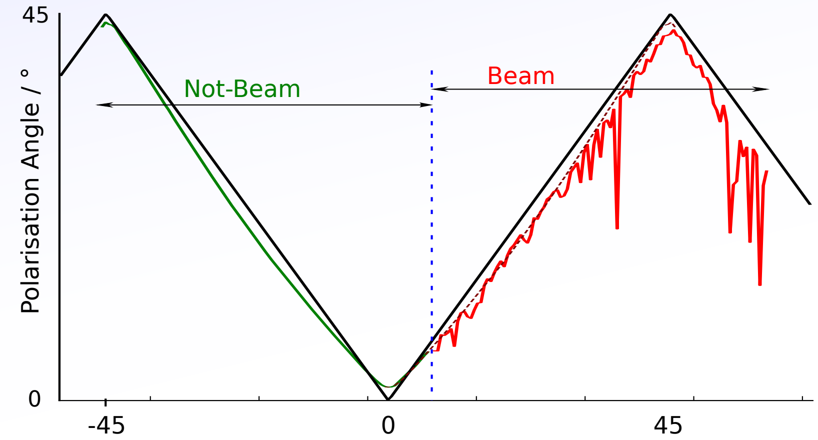
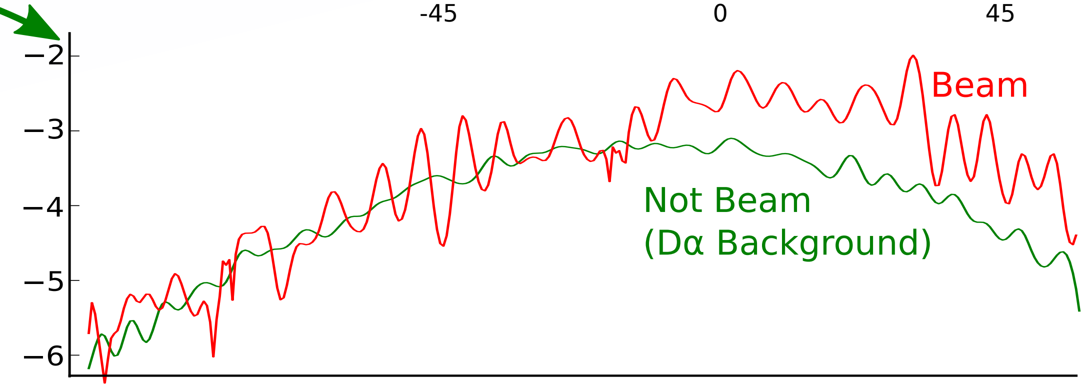
Recorded image gives correction maps:

Not-Beam

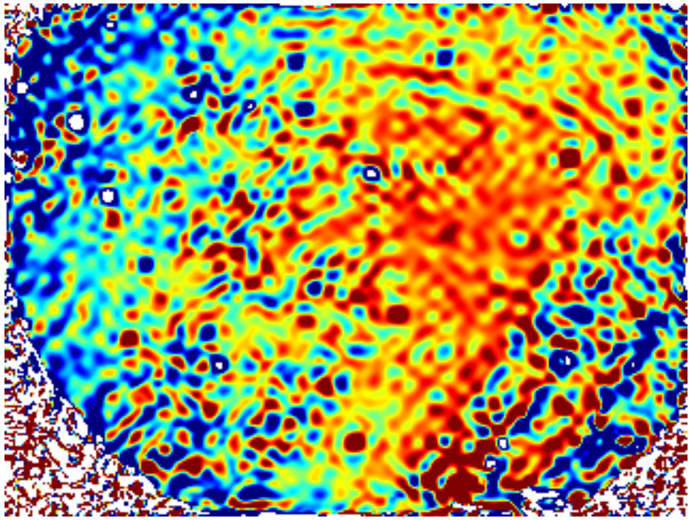


Not-Beam gives much cleaner image, but not necessarily exactly the same as the beam calibration, since light source is at a slightly different focus (distance from lens).

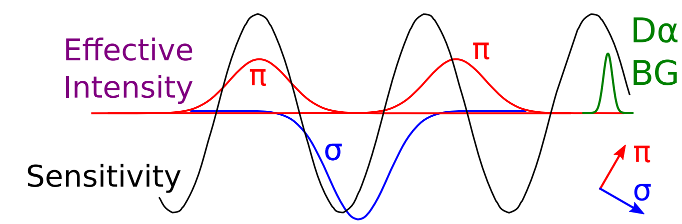




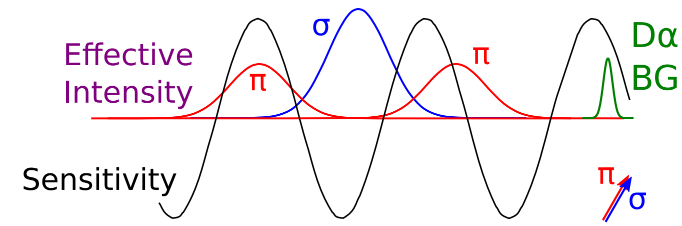
Beam



Beam image has very low contrast, and almost 0 in some areas, because the system delay is set so that contrast adds when σ and π are 90° apart:



With the polariser, σ and π now 0° apart, so system delay makes them subtract while background remains strong.

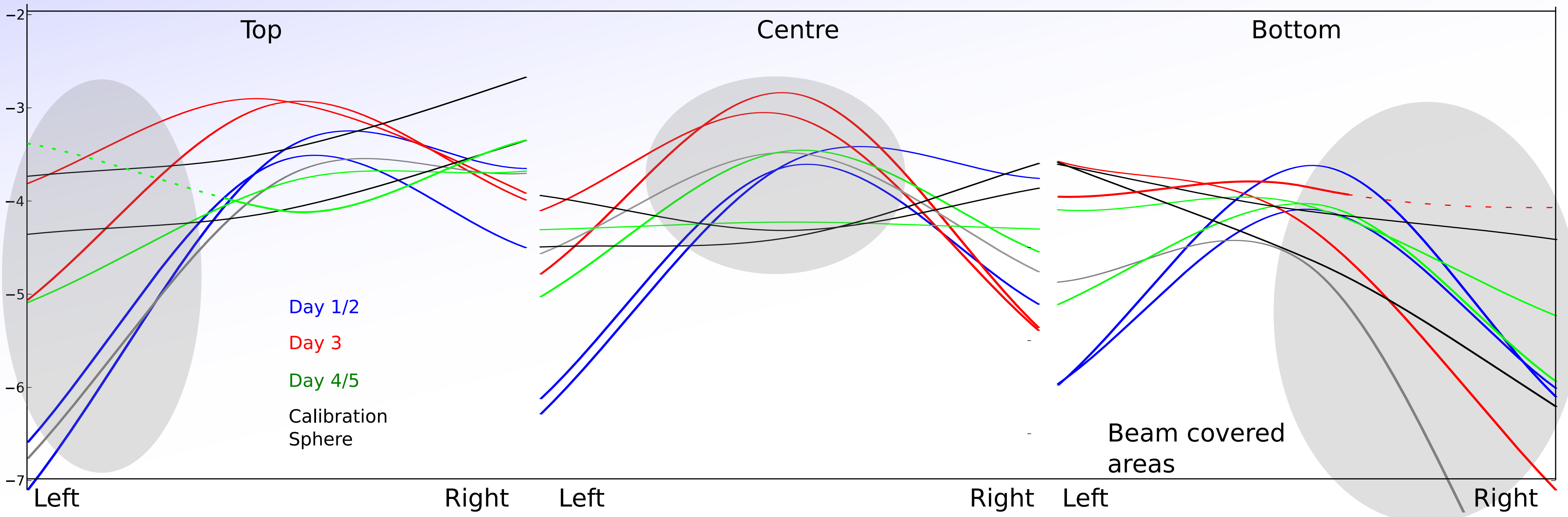


This can be partially mitigated by aligning the polariser to preferentially select σ or π.

Intrinsic Contrast Calibration

Oliver Ford
IPP Greifswald

Fitting 3x3 cubic to good parts of image gives calibration images.



- Variation between days is expected, since the camera and cell were refitted inbetween.
- Calibration sphere is expected to show a different curve, since acceptance angle for image edges is very different to the vignetted beam light.
- ±0.2° of offset is expected due to uncertainty in calibration wheel position (Improved for April experiments).
- Systematic error here is unacceptably large, so calibration needs improvment.

The biggest problem, particularly in the lower right of the image (plasma edge), is that the calibration is almost entirely dominated by reflections since the plasma light is optimised away by the delay plate.

So, for April:

1) Improve calibration wheel reproducibility or knowledge of position (mouse sensor). Done
2) Better filter to reduce Dα background. Arriving now (10am Monday)
3) Several positions over 90° range to preferentially select σ and/or π. Try tomorrow.

Faraday Rotation

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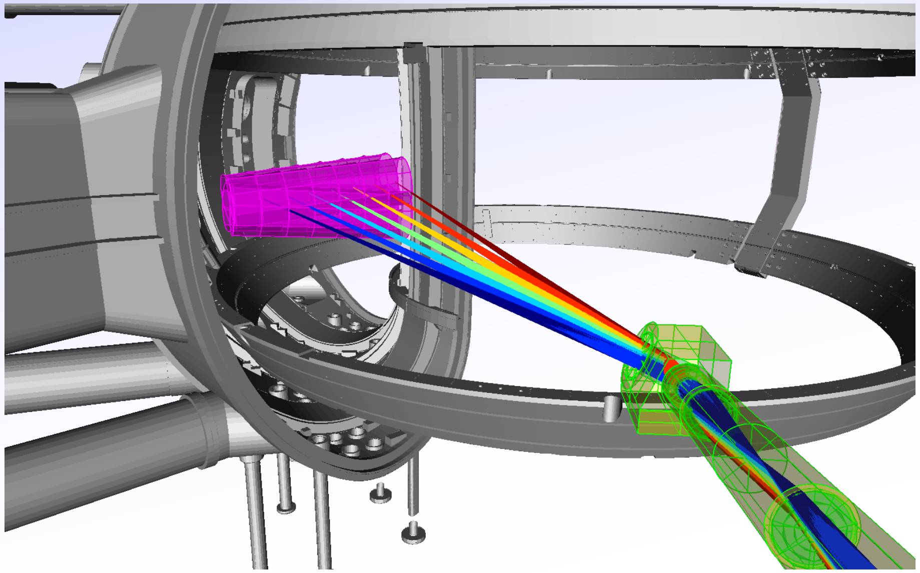
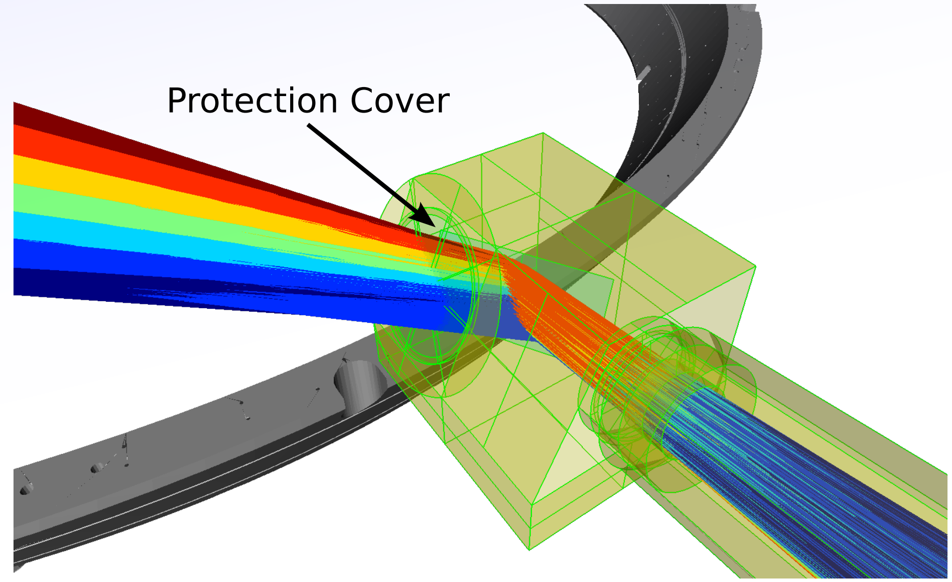
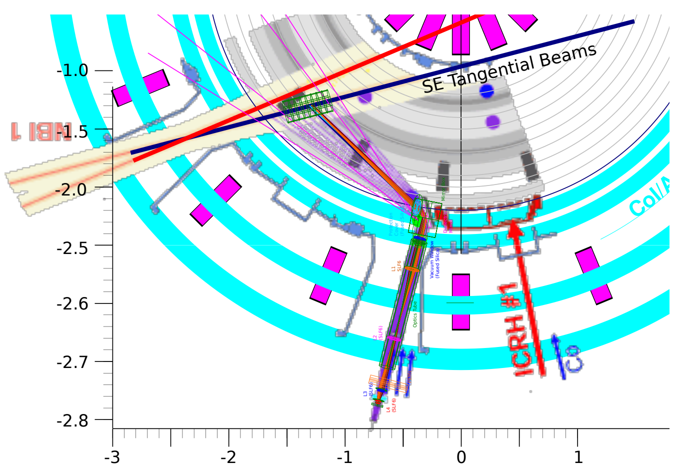
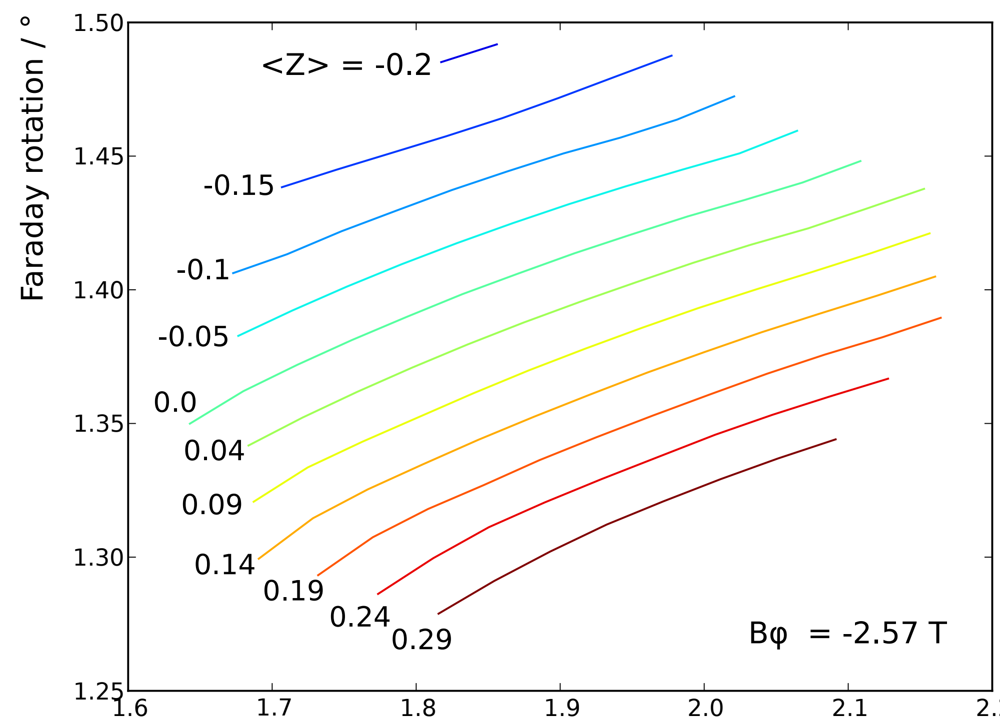
Faraday rotation in the forward optics significant, particularly in the 3.5mm Fused Silica protection cover.





Cover is roughly perpendicular to toroidal field.
Rays vary in angle through glass and to toroidal field dramatically with source/image position
but also slightly with position across glass (i.e. the collection cone angle).





Reflections - Background Dα

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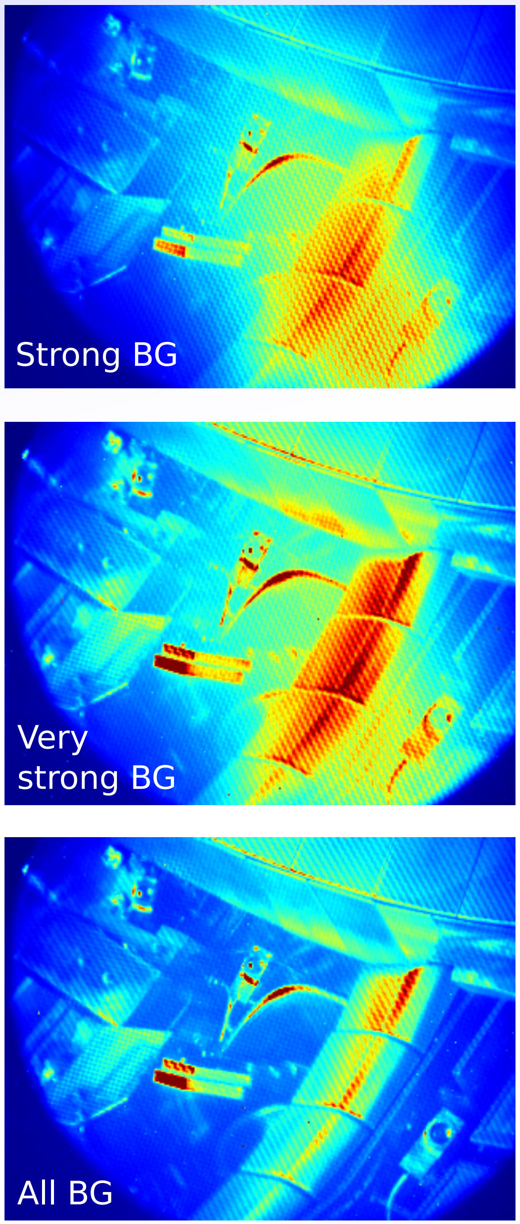
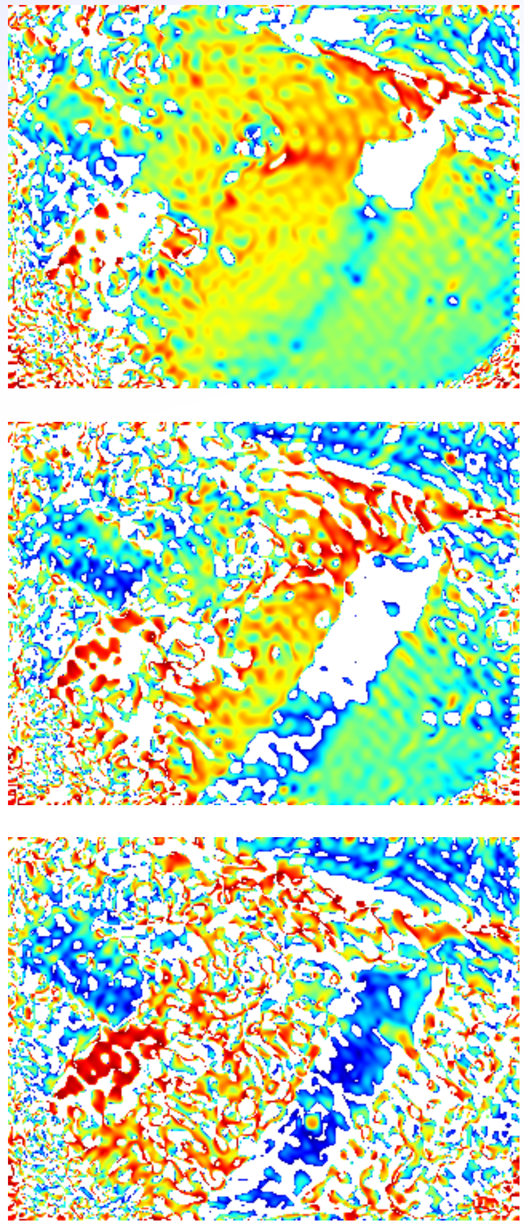
gmds/AUG/29317

During H-Mode / high density operation, background light reflecting from limiter etc significantly contaminates the signal:

Image

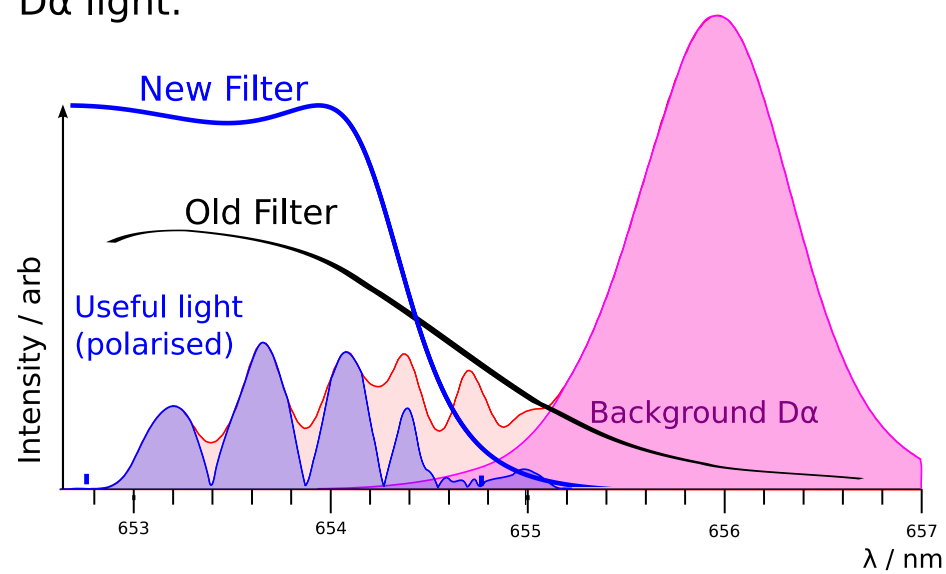


Polarisation:



(This is a particularly bad case during a detachment experiment)

This is suspected to be because the filter used is too wide and catches the abundant edge Dα light:



Meanwhile, Dα reflections could be used to track drifts in forward optics, if reflections from limiter maintain polarisation direction.

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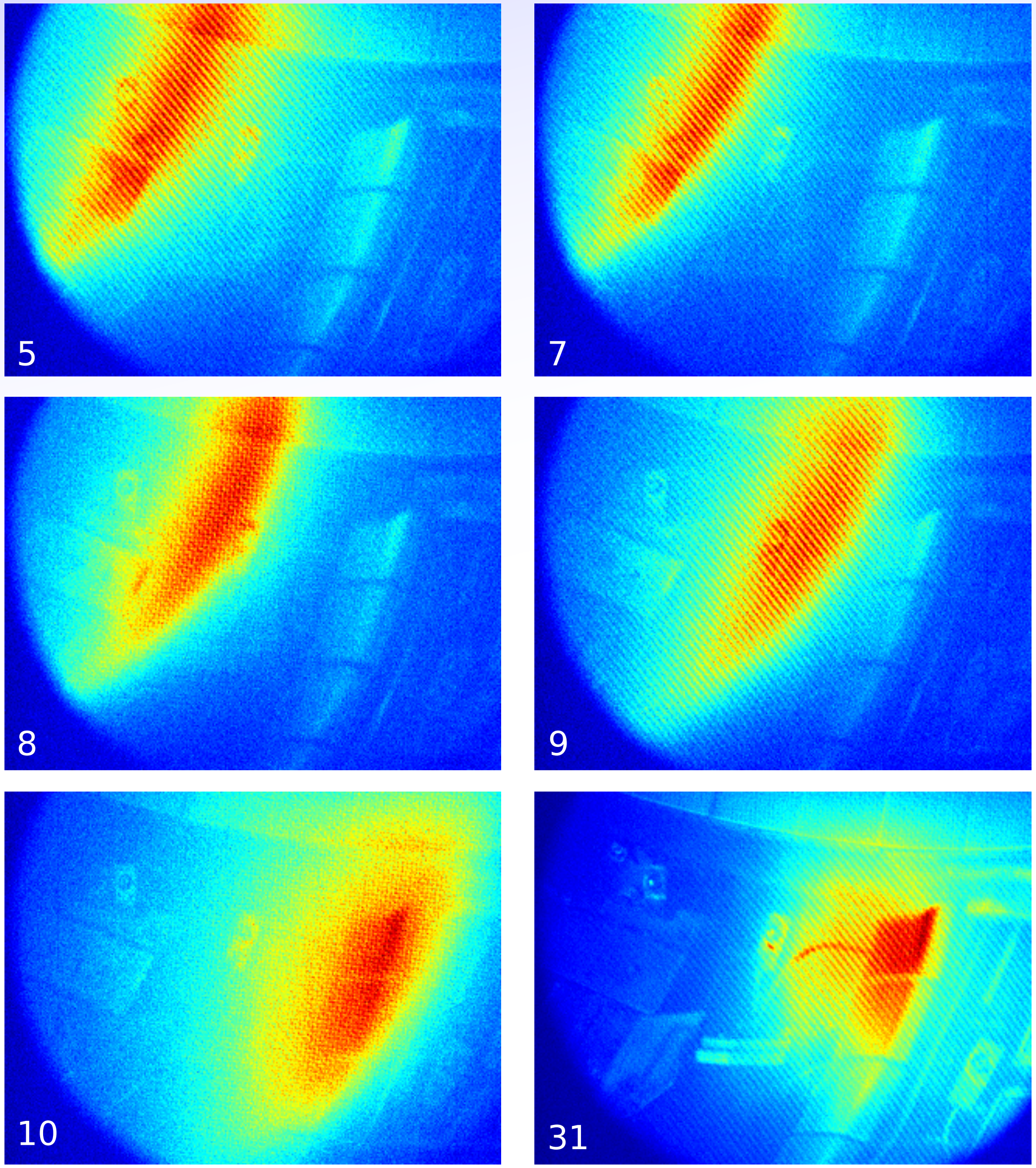
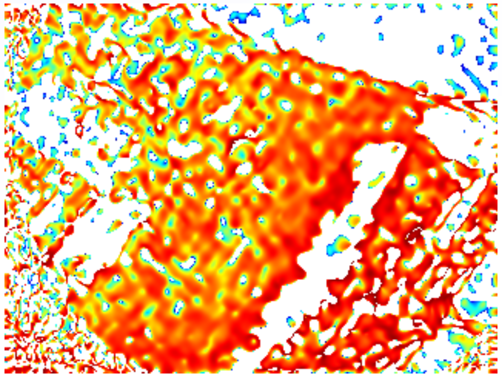
Other background - Zeeman split Dα??

During plasma startup (no beam), background plasma light is polarised (shows fringes).



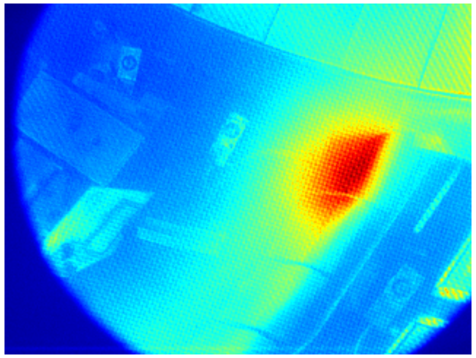
Emission starts near centre and migrates out. Eventually it comes brightest from plasma immediately in front of limiter. Finally it almost disappears at separatrix formation.



Polarisation very elliptical, with a direction that changes as the current ramps up.

It seems to be consistent with Zeeman splitting of Dα peak from recycling neutrals.

To check, used a Dα filter on Thursday (no beam day) and signal is still present:



As field direction during startup, and in front of limiter are both well known, it could be used as cross-check or calibration of diagnostic.

We're also considering what can be measured with a system designed specifically to see it.

Direct MSE - IMSE comparison

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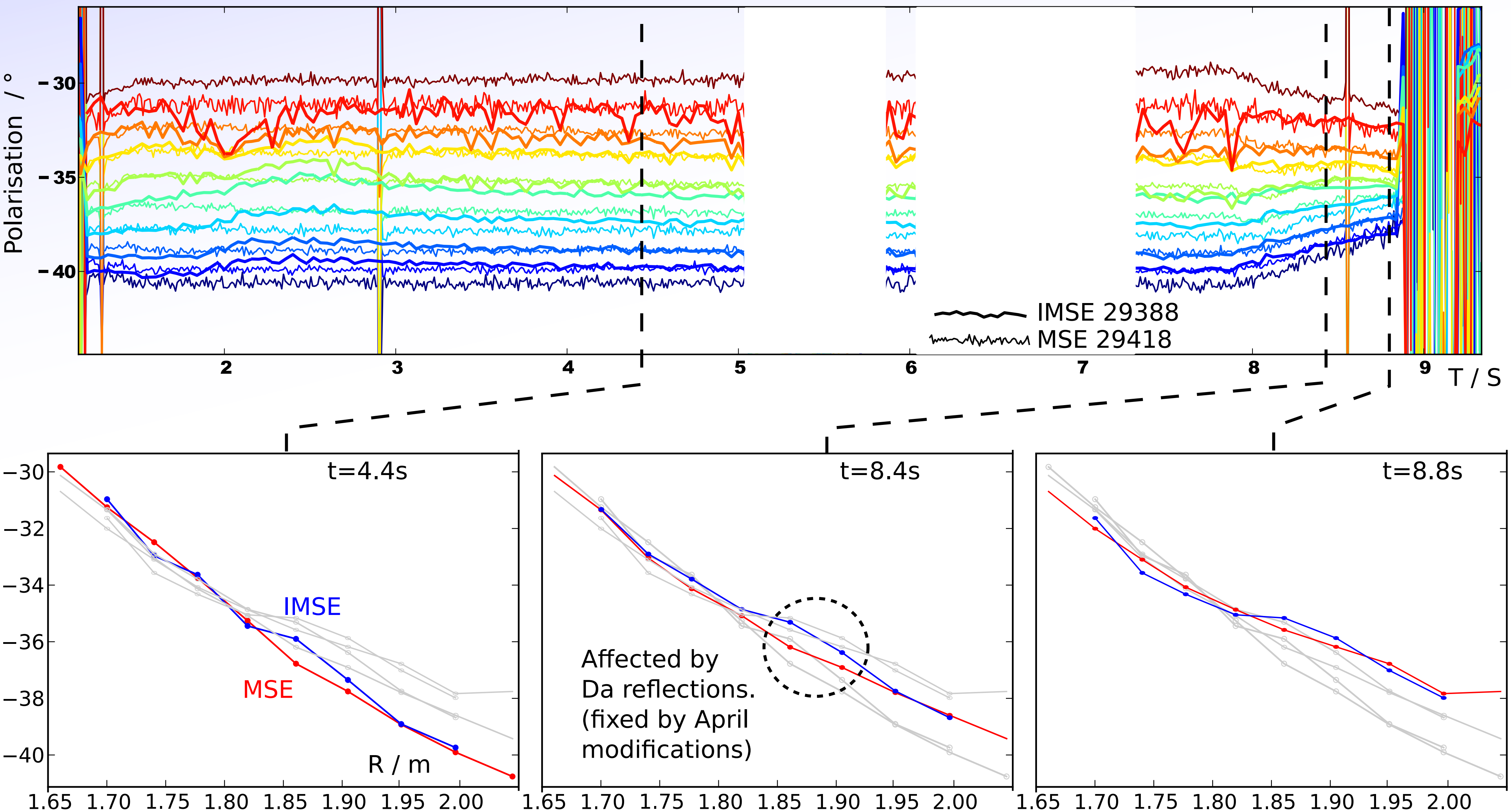
To compare the IMSE/MSE systems directly, the same pulse was run the following week with the MSE system.

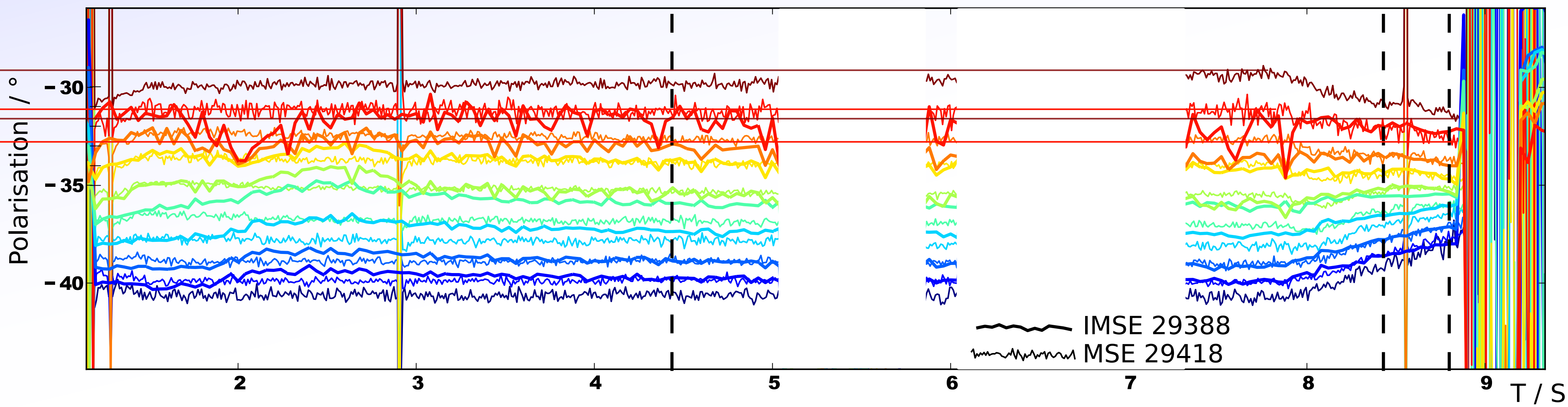


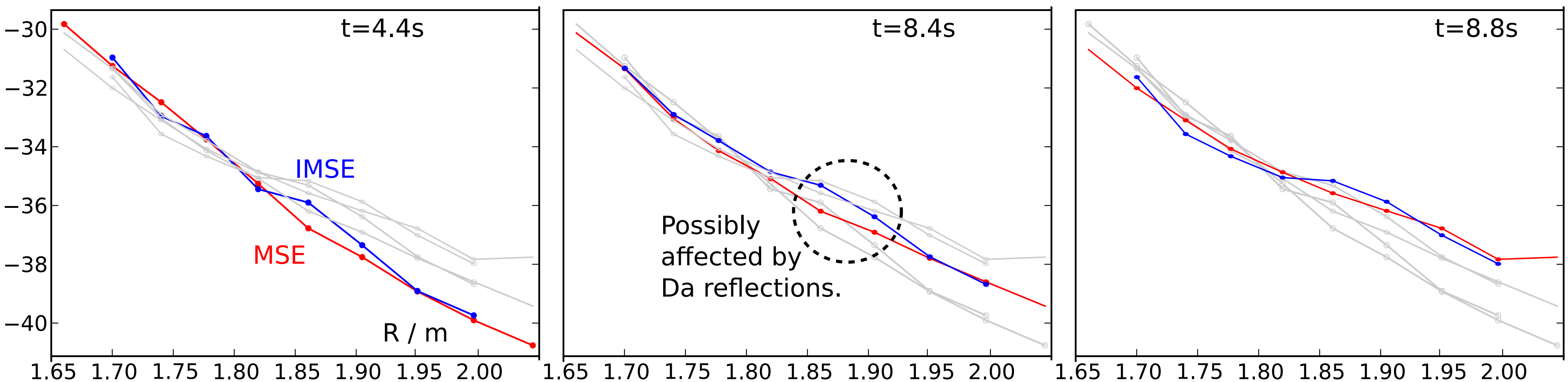
Temporal evolution agreement is very good, spatial agreement is reasonable and was improved recently.
An unidentified offset of 1.1° is still required, but is constant for the whole image.

Direct MSE - IMSE comparison

Oliver Ford
IPP Greifswald
gmds/AUG/29317

To compare the IMSE/MSE systems directly the same pulse was run the following week with the MSE system back in place. There is a polarising wheel in the MSE forward optics which can be used as a common zero reference between the two systems, so the offset *should* also be correct (however, 1.1° is added here)





So far, temporal evolution agreement is very good, spatial agreement is reasonable and should be improved by changes in April. An unidentified offset of 1.1° is still required.

Edge fields.

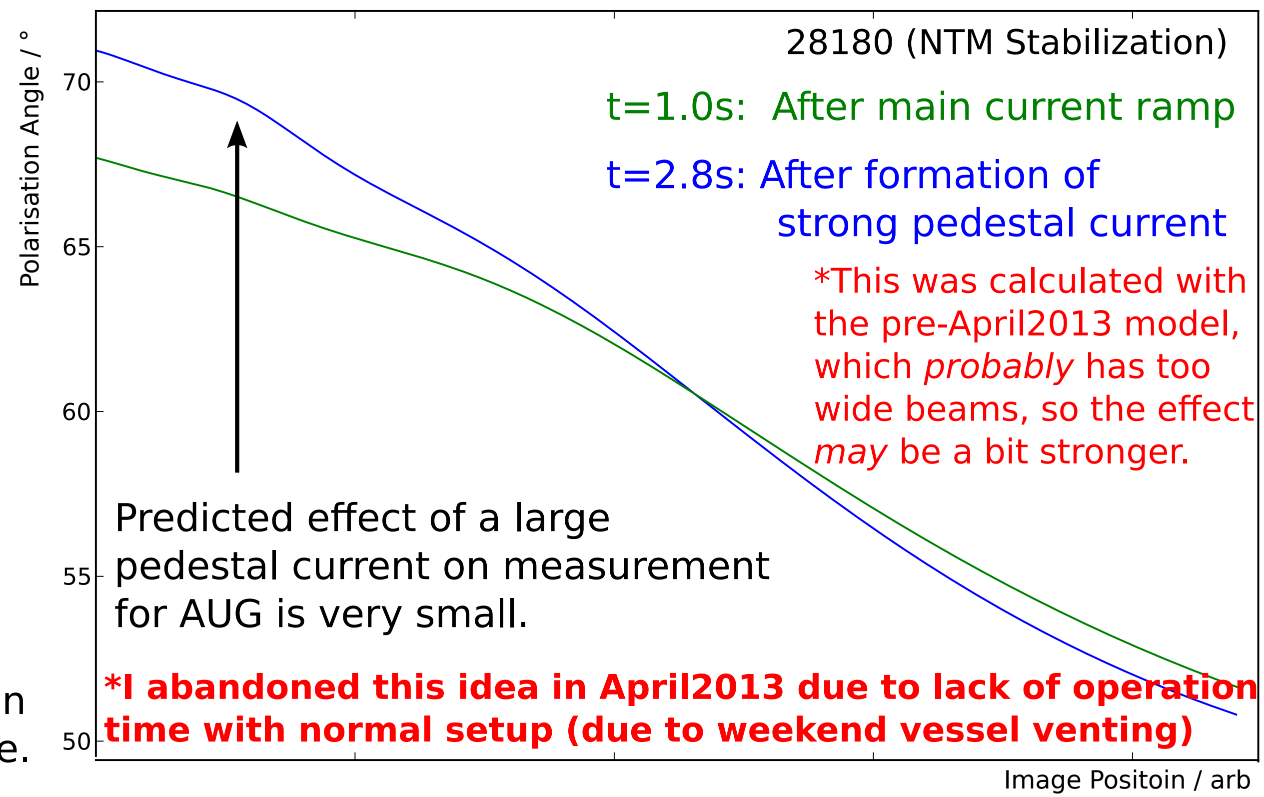
Preliminary (very) results from the IMSE system on K-STAR show some interesting extreme effect at edge [John Howard]:

L-Mode: H-Mode

Clearly see:
- No edge feature in L-Mode.
- Small pedestal ridge in H-Mode.

So, if we see something, it's either;
- Effect of radial electric field (which we can cross-check)
- Extremely large anti-parallel pedestal currents.

To do this we would need to move the MSE mirror on Thursday and run an H-mode pulse with one beam during L-H transition and as much pedestal current as possible.



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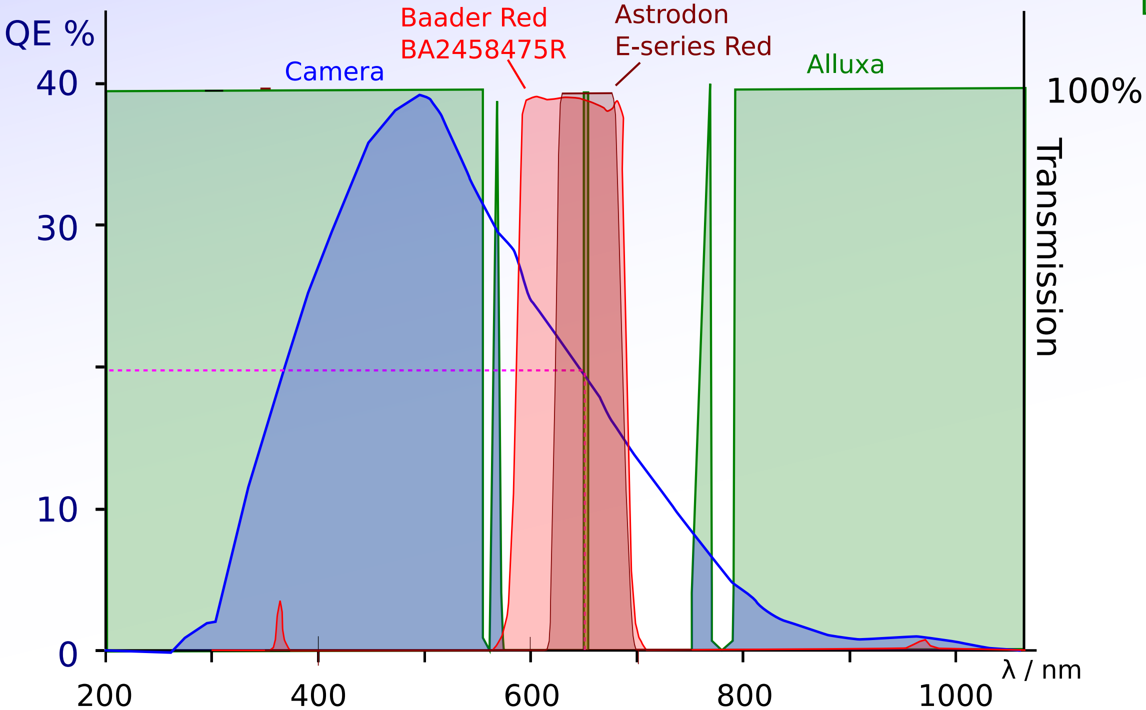
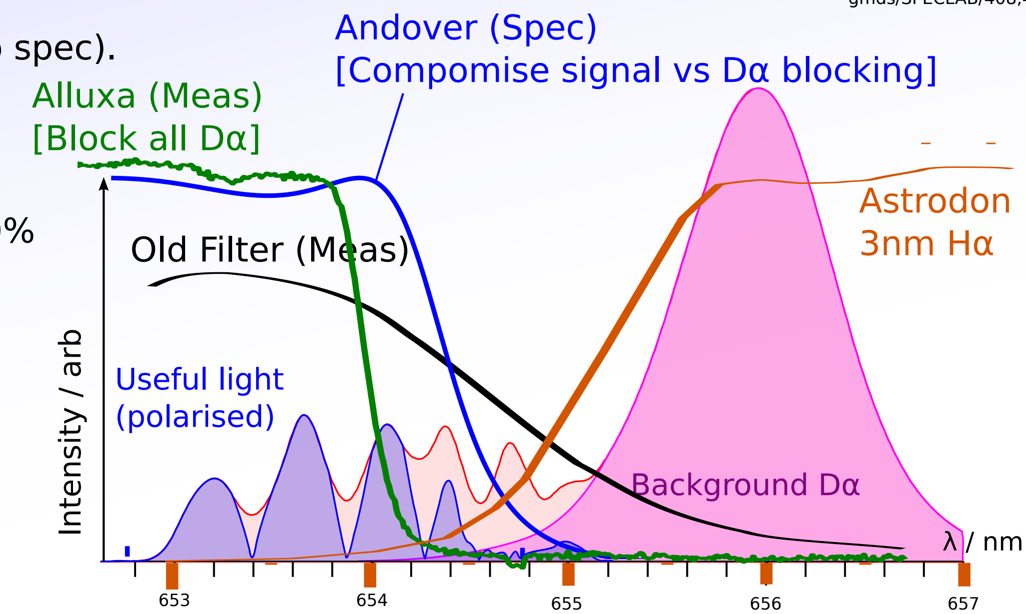
gmds/SPECLAB/408,409

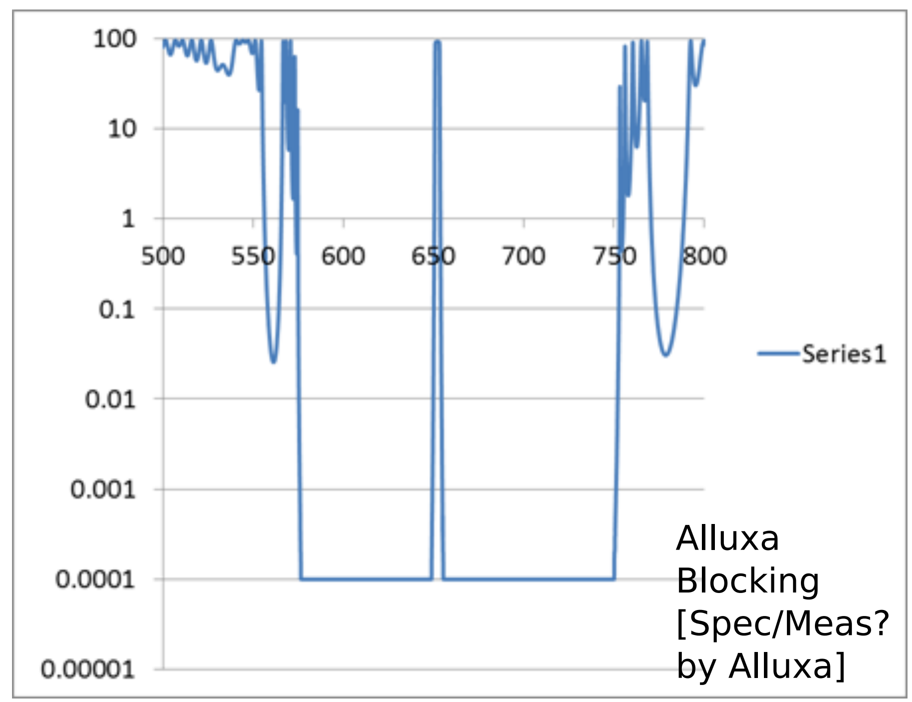
Infrared / UV Filters

Alluxa filter blocks to OD4 from 400nm to 700nm (according to spec).
Camera sensitivity is:





Alluxa filter doesn't block IR.
Temporarily put Omega filter in too (which does)
but need to find something else to block 700-1100nm
(and in principle 200-400nm, although that might
already be done by the glass)



I don't yet know that there is any IR coming up the MSE optics that needs to be blocked, this was just to be safe since there wasn't much operational time left (April2013)
Need an IR filter to block 750 - 1100nm and UV 250 - 580nm
Baader Red 2" BA2458475R Astronomy filter gets almost everything, only a few blips in the UV missing, and possibly a blip at 980nm, but that could be noise on spec. - needs lab test.

An alternative would be CVI Melles Griot F40-650.0-4-50.0M but is only 50% Tpeak gaurenteed.

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April 2013 initial results.

(AUG OPS meeting 29/04/2013)

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2: Plasma Research Laboratory, Australian National University, Canberra

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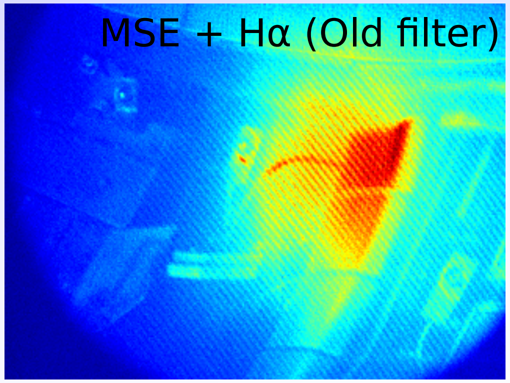
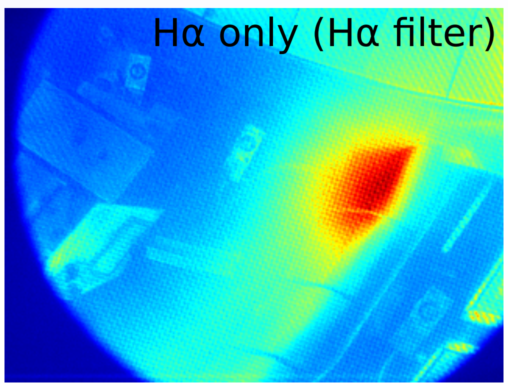
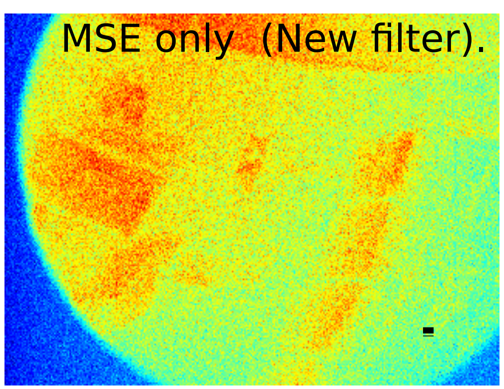
Background - Zeeman split Hα





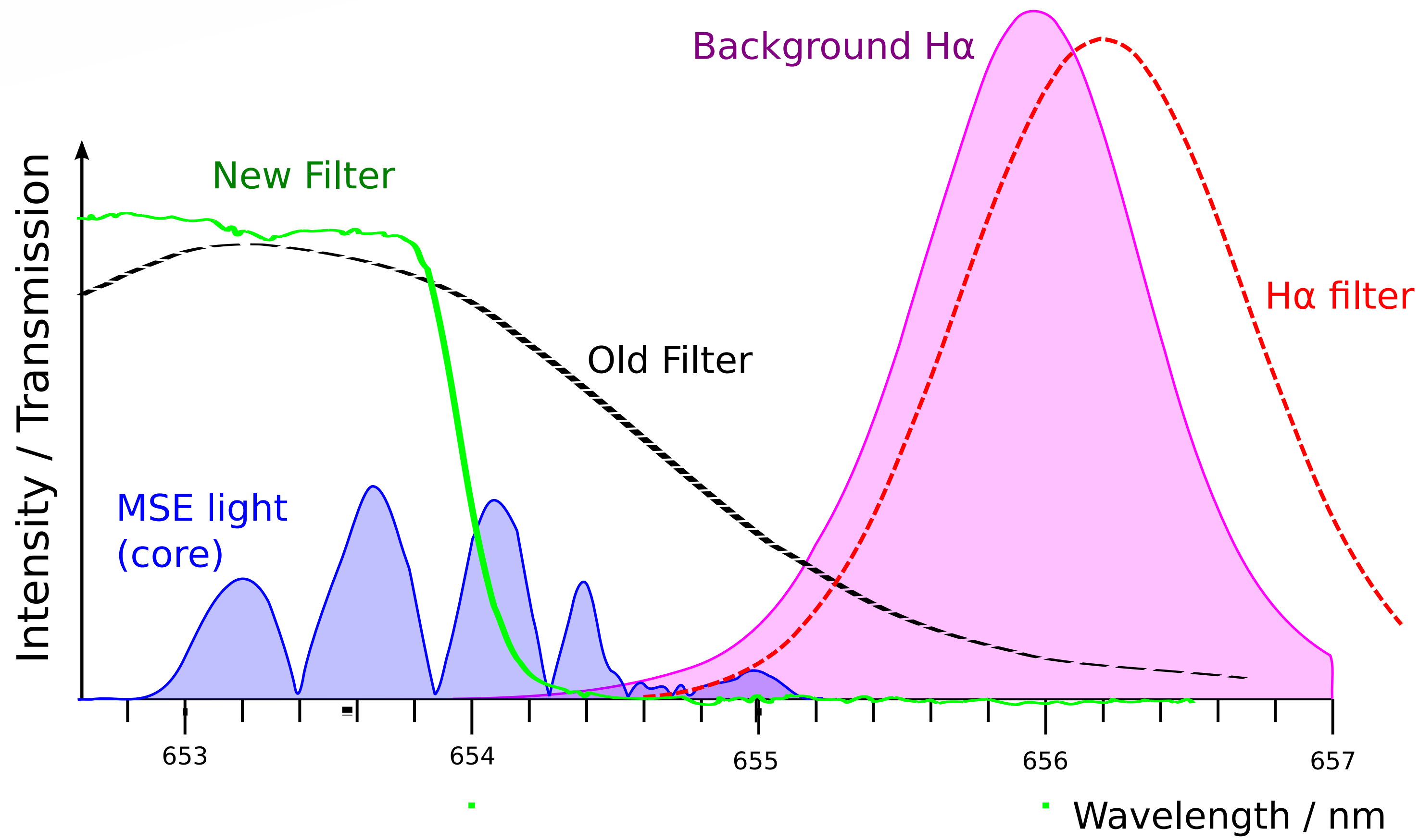


(examples from *different* shots)

Thursday 18th: No beams, so fitted Hα filter to check polarised background is acutally Hα.

Polarised signal is still present with Hα filter and is almost completely excluded by the proper MSE filter (which blocks Hα).

So it probably is Zeeman split Hα and the new filter sucessfully stops it contaminating the MSE measurements.



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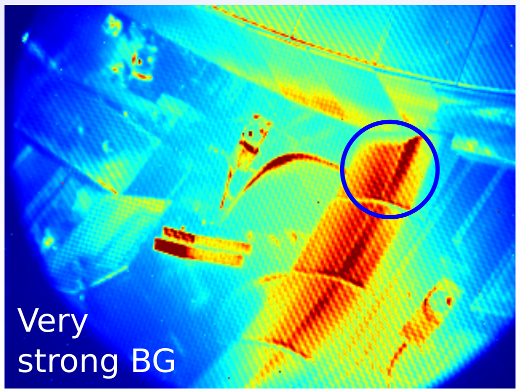
Reflections - Background Dα

The new filter also successfully removed the reflections contamination of the MSE data.

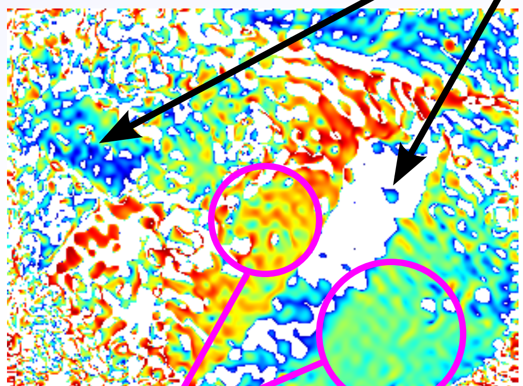
The worse case previously was during pellet injection:

Contaminated by reflections.

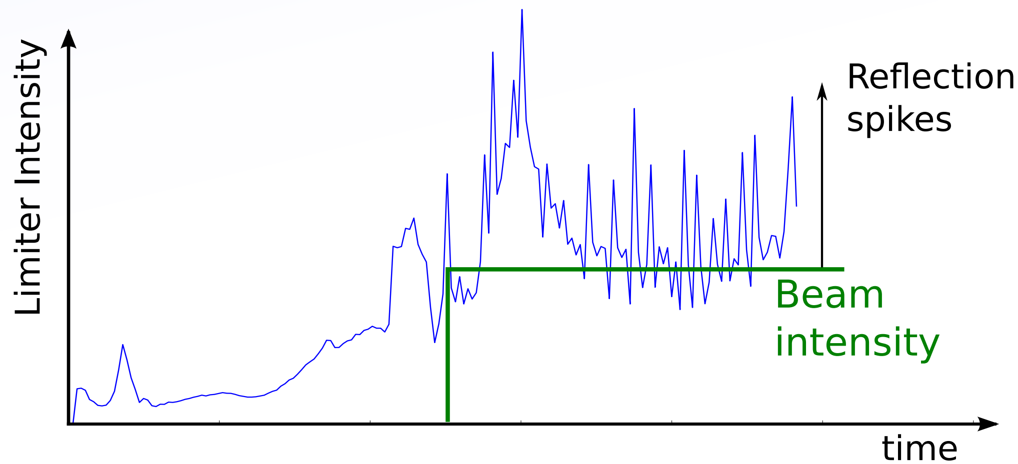
Image:



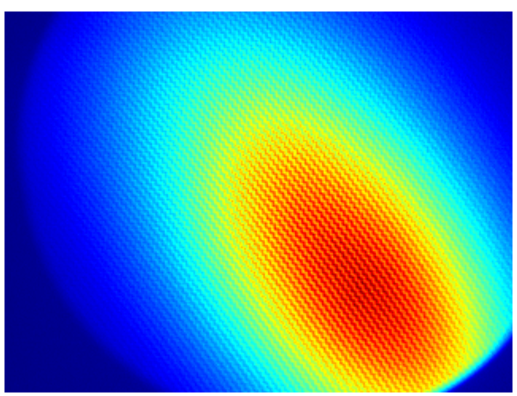
Polarisation:

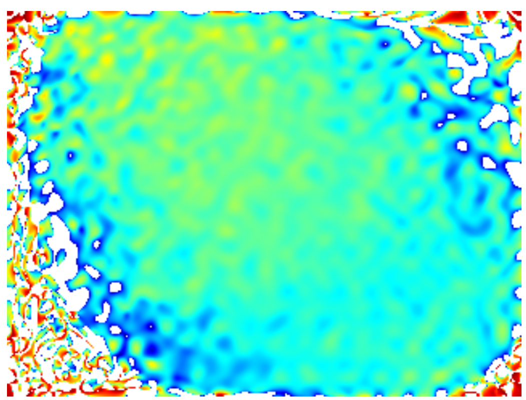


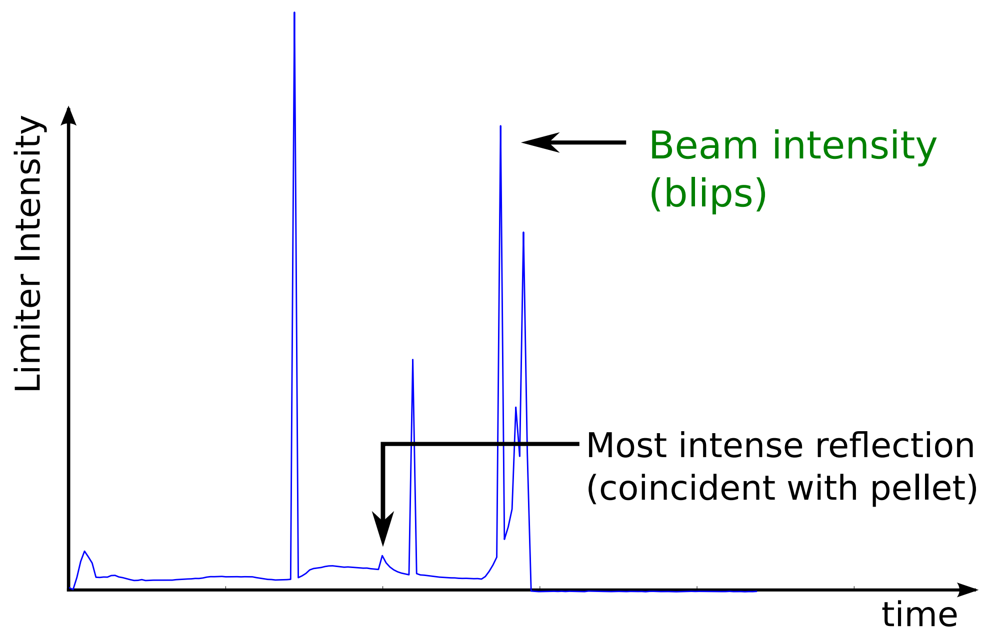
Good data from beam.



With new filter:







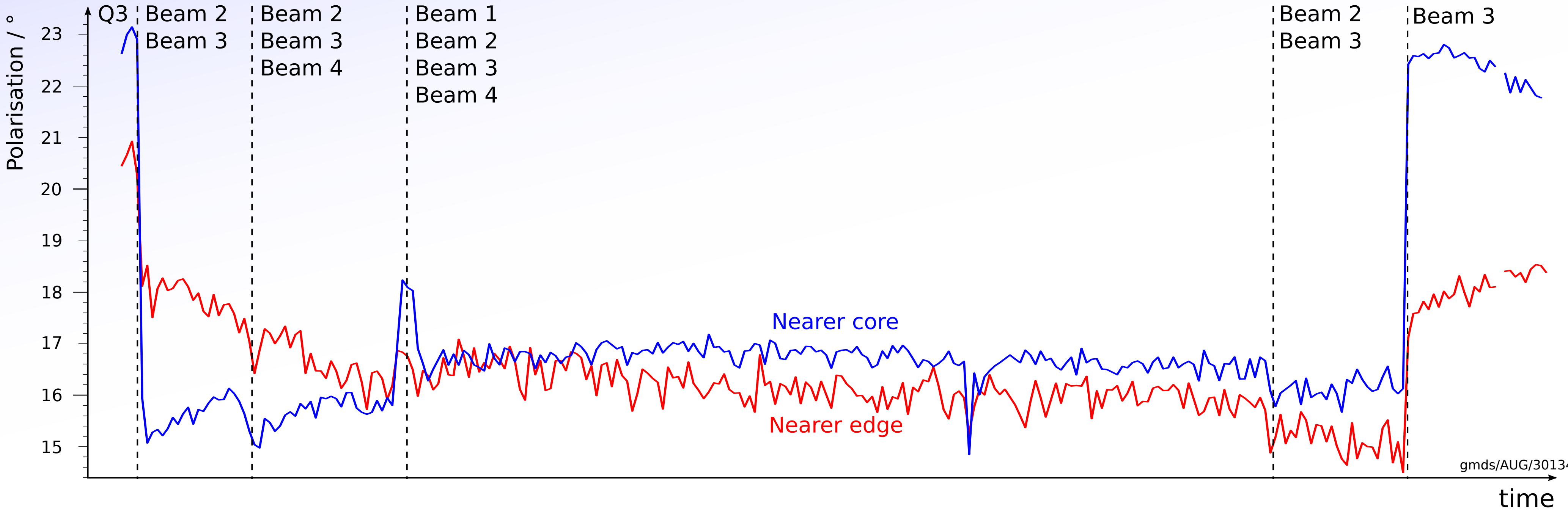
Data quality is much better. It now gives good measurements in all conditions whereas H-mode, pellets, detachment etc were all difficult before.

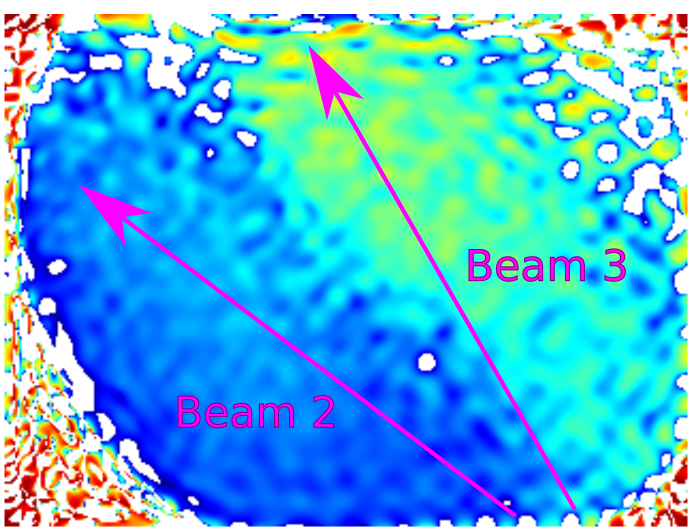
MSE data from last week

Oliver Ford
IPP Greifswald

Used failed NBI assisted breakdown shots on Wednesday to understand and fix calibration problems. NBI was vary early in Ip ramp up, so the data may also help with the absolute calibration (later).

Collected a lot of good data during W-melting experiments on Thursday:





All H-Mode data is unfortunately mixed-beam.

In principle, it's still possible to use but it will take much longer to analyse as it requires knowing the beam geometry and attenuation accurately.

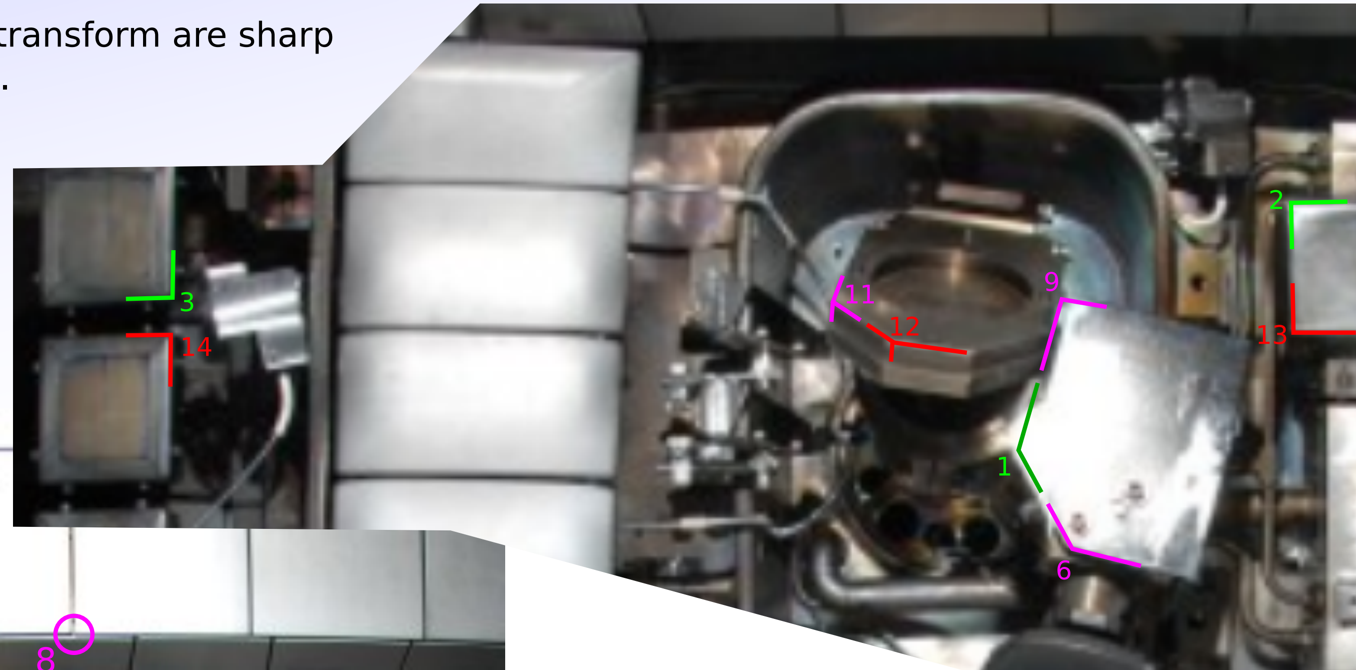
The beam information is actually much better separated than my model predicted - so need to improve the beam model and fit the beam waist and divergence.

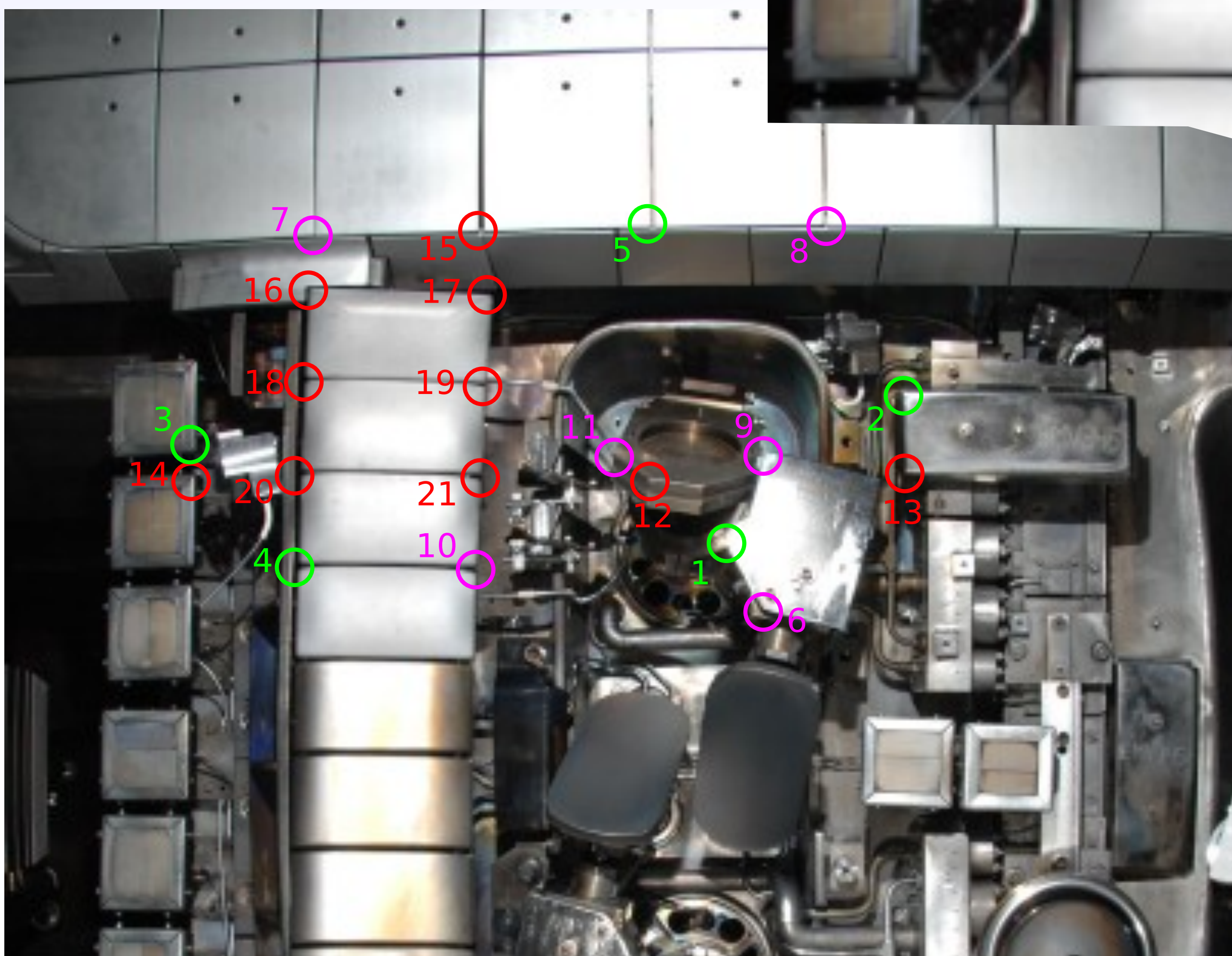
Useful FARO measurements for Image Transform

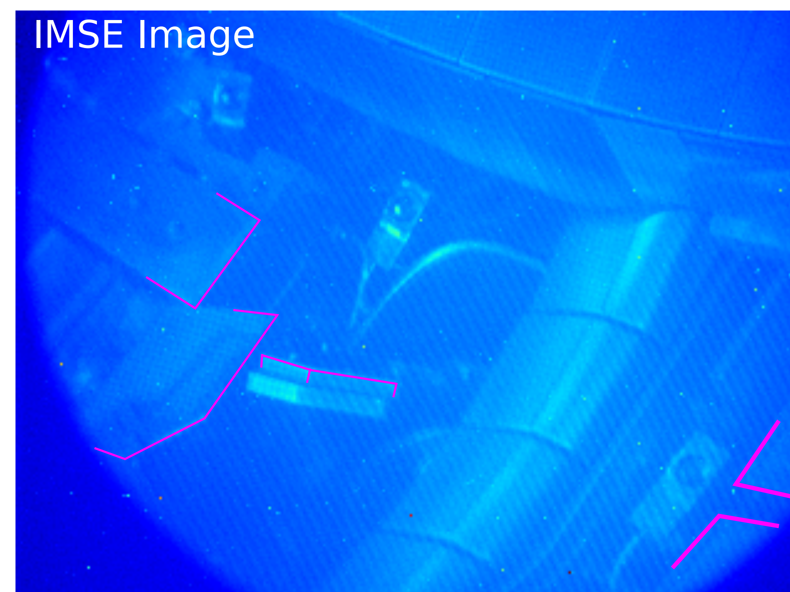
Oliver Ford
IPP Greifswald

The most useful points to constrain the IMSE transform are sharp corners/edges visible during bright Dα events.
21 points in order of usefulness:

- 1-5: Most useful
- 6-10 Useful
- 11-21 For extra accuracy
  (some known already)



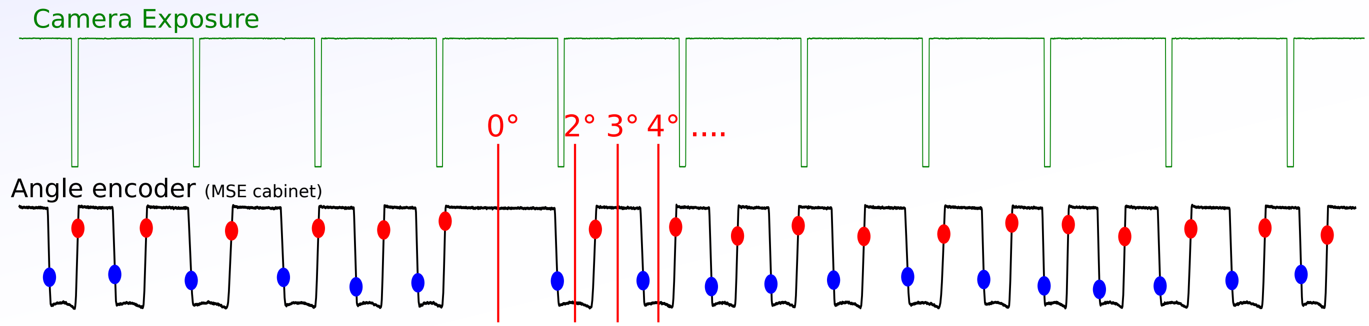




MSE ex-Vessel calibration.

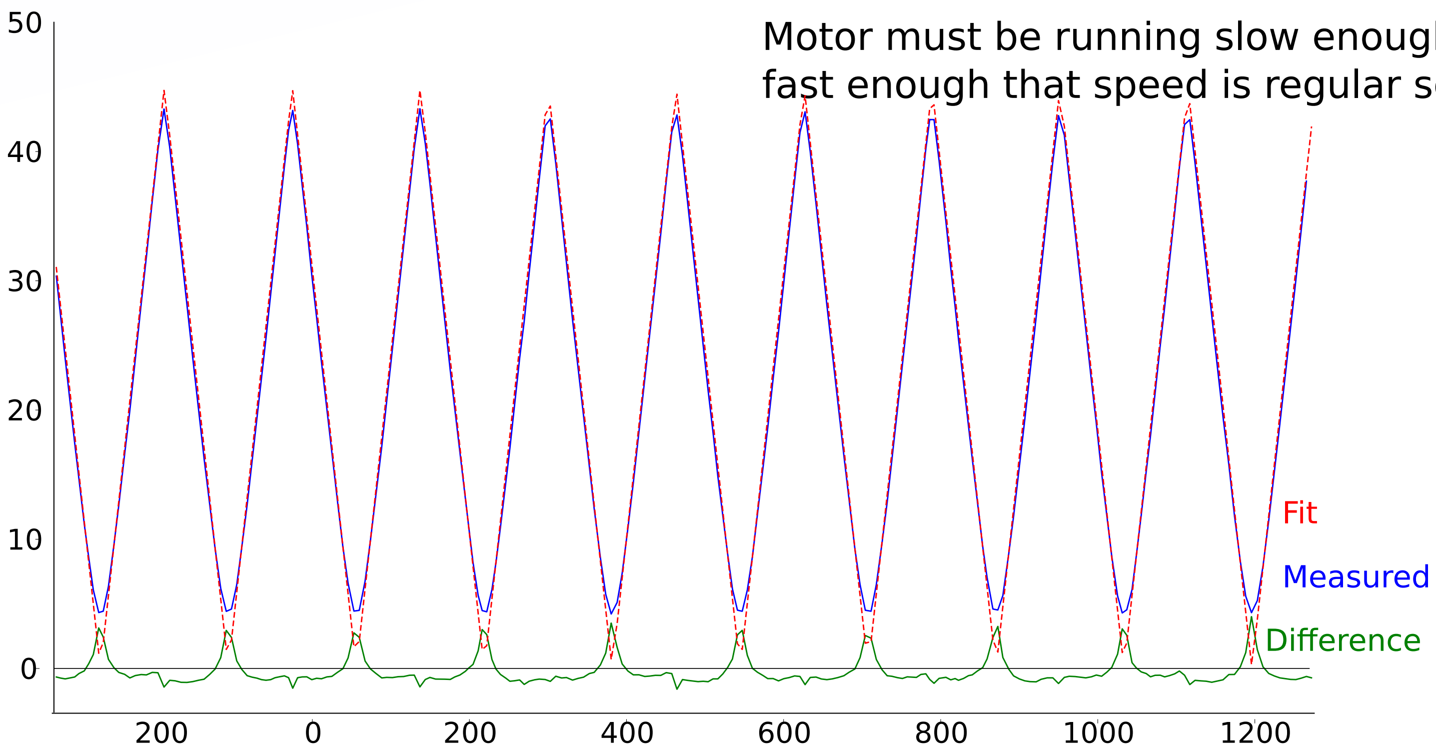
Oliver Ford
IPP Greifswald
gmds/SPECLAB/186-188
gmds/SPECLAB/363-368

The MSE system has a motor driven polariser with angle encoder just before the PEMS.
This can also be used with the IMSE so gives a reference polarisation to compare the systems.



Record camera exposure **output** of camera and angle encoder signal on ADC and work out angle at **centre** of exposure relative to **centre** of the missing notch (Alex's definition) - mseExVessle.py.

Motor must be running slow enough that IMSE doesn't average too much fast enough that speed is regular so the zero notch can be identified.



Triangle wave fitted gives λ and fitted θa at θ(MSE-EX) = 0° is:

Jan2013 [gmds/AUG/186]:
λ = 89.999°,
$\theta a(0)$ = 23.4°
with μ~79%

Apr2013 [gmds/AUG/368]:
λ = 90.008°,
$\theta a(0)$ = 24.99°
with μ~57%

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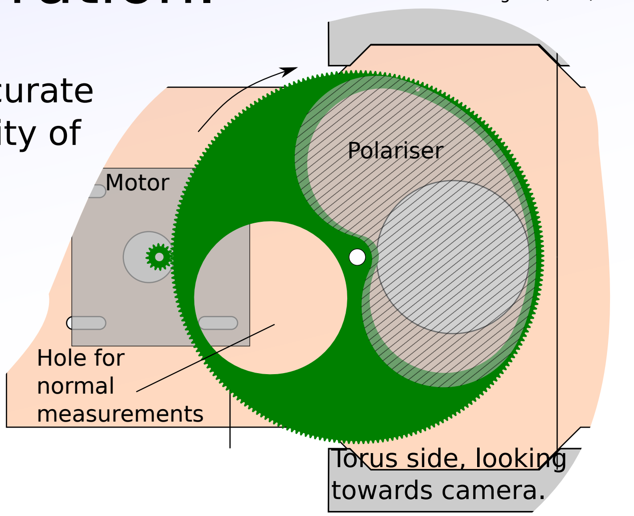
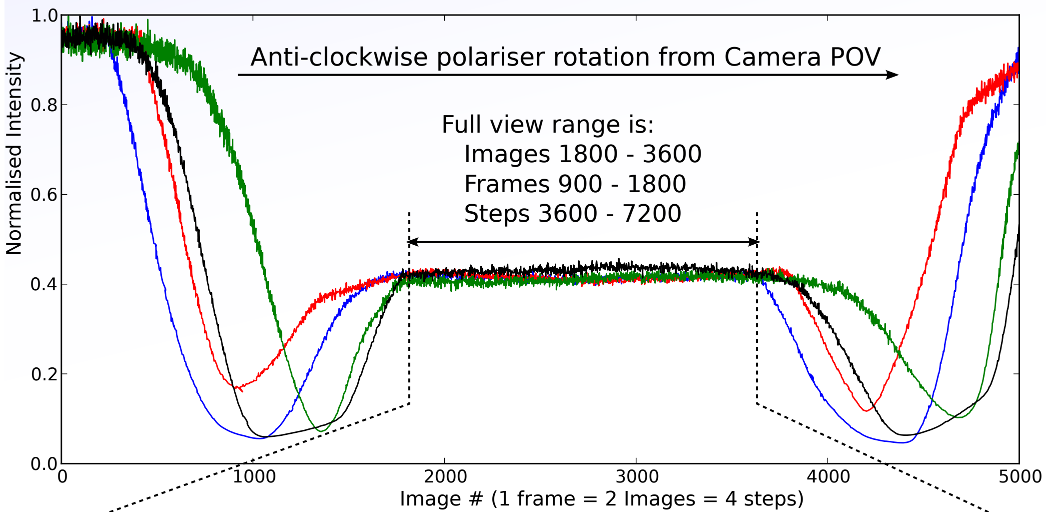
IPP Greifswald
gmds/AUG/362

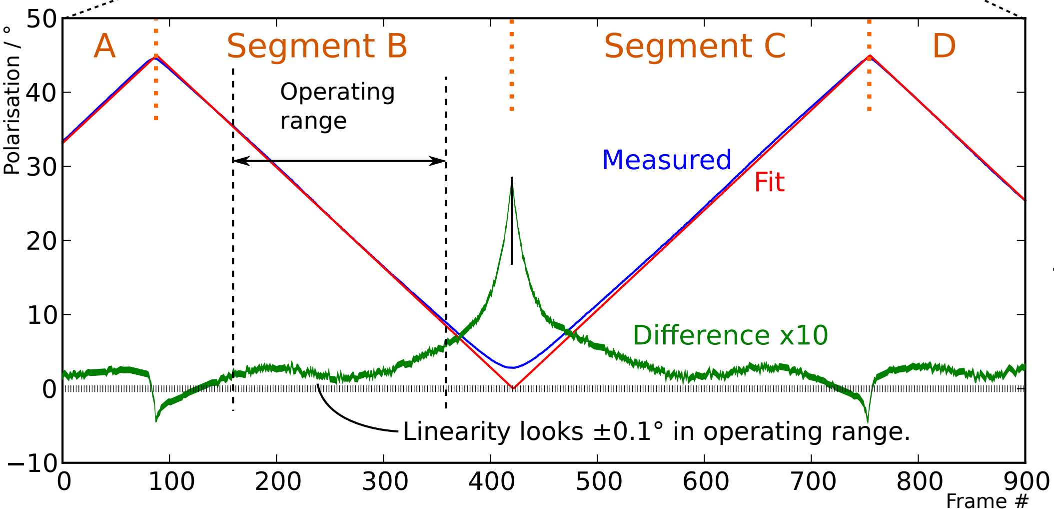
Ne Lamp calibration wheel calibration.

The IMSE's in-built polariser wheel is used for beam-light μ calibration. It has a fairly accurate light barrier switch (returns to ~0.13°) but the zero position is not known and the linearity of angle vs step might not be great as the motor is on springs.

To calibrate the calibration, Ne lamp was put in PEMs box and a 2500 frame full FLC interlaced scan of the wheel was made [gmds/AUG/362]







Use range where aperture is completely open with polariser. FLC off images (odd images, why???) give polarisation. μ~74% gives best fit. (higher than with MSE ex-vessel because Ne lamp is more point-like source in PEMs box).

Fit gives λ=10644.3 steps for 360°, should be ~ 10670±5 according to light barrier position (diff is 0.8° !!!). Fixing λ=10670 only moves offset by 0.02°.

Fit gives first 45° at step 3946, **0° at 5279.8** and next 45° at 6613. This gives our calibration polariser relative to the actual (μ corrected) incoming polarisation. This means polariser home is -133.14 ± 0.08° and the step toθc conversion (for μ calibration) is:

$$\theta c = |\ \mathrm{STEP\#} - 5279.8\ | * 360/10670 \quad (\pm 0.1°)$$

This defines the global θc: Positive for anti-clockwise from camera POV with θc=0 at the θm=0 that aligns with the polariser at step 5279. θa actually the same, but technically without the sign and periodic on 90°:

$$\theta a = -|\ (\theta c\ \%\ 90°) - 45°\ |$$

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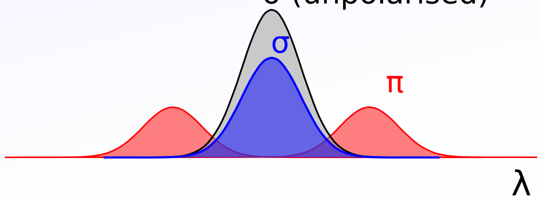
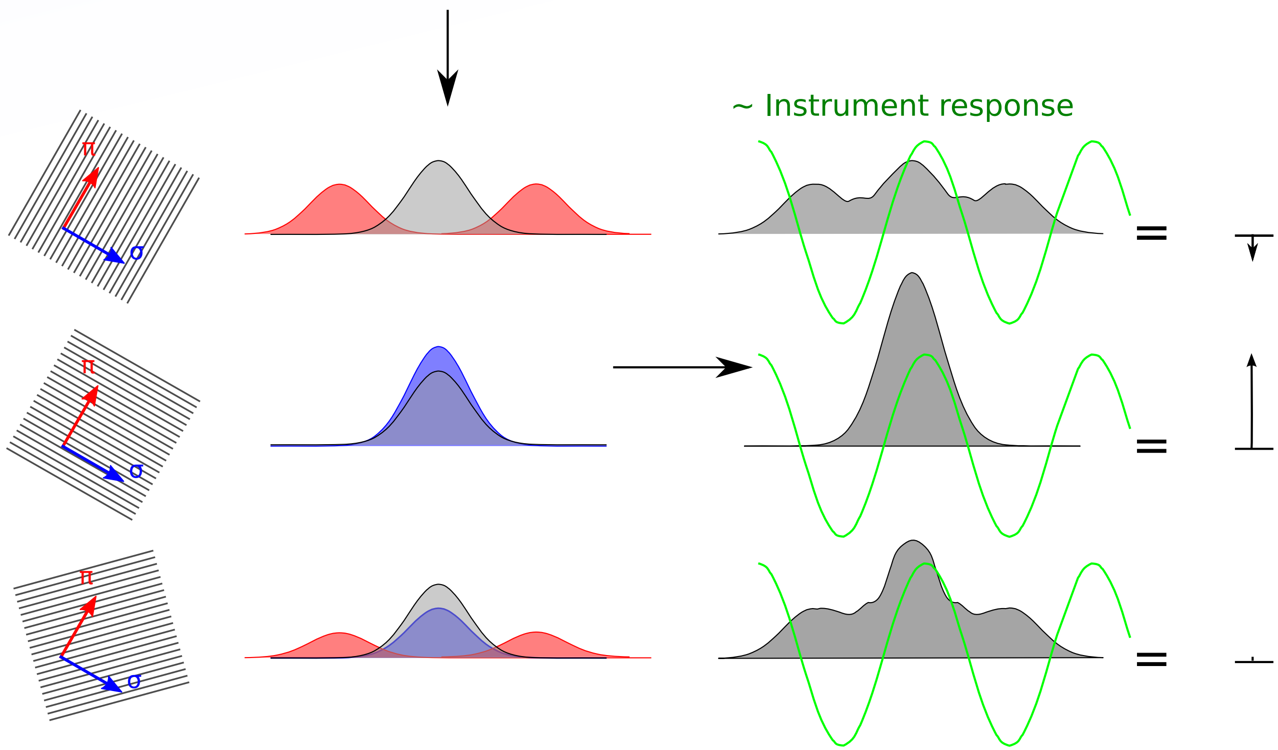
Intrinsic contrast calibration optimisation.

To get the best calibration of μ, calibration polariser needs to be near one of the θa ~ 22.5° regions.

As the polariser rotates, it selects different amounts of different parts of the spectrum (due to the polarisation of σ and π components), although is always emits (and polarises) 50% of the **un**polarised σ light.
Because all the transmitted light ends up with the same polarisation, if the selection is wrong (i.e. the integrated intensity in the σ and π parts of the spectrum are roughly equal), then the optimisation of the IMSE system for spectral dependance of the fringe phase will perfectly remove all the fringes.



For Stark splitting, the polarised part of the sigma matches the π in intensity (fully populated states) and the π is always entirely polarised .



The exact response will depend on the system absolute angle, on the viewing geometry and on the pitch angle.

Alignment with π will be diminished due to the unpolarised σ partly cancelling it.

Alignment with σ will always give the best signal, but the spectrum is then not representative of the measurement (although this shouldn't matter in principle)

At 45°, polariser π and σ cancel leaving only the (re-polarised) unpolarised σ.

The final choice of polariser angle(s) needs to be a compromise between this effect and the requirement of (one of the) 22.5° points.

*The figures on this page are made up - they're not real simulations.

Oliver Ford
IPP Greifswald

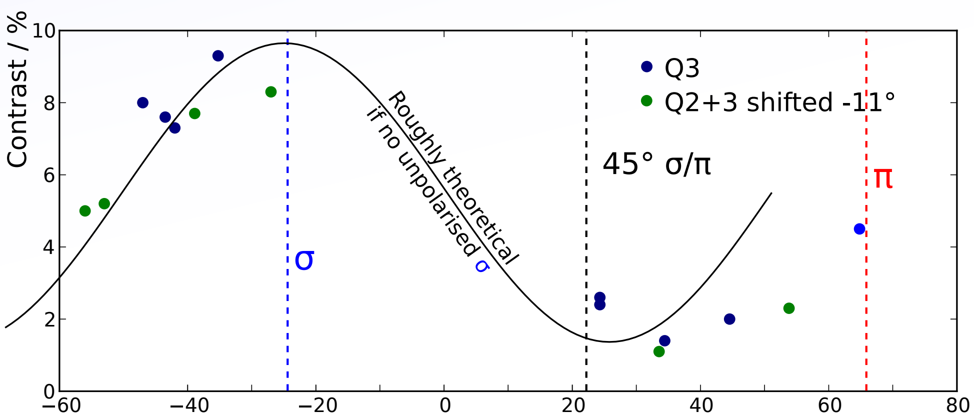
Intrinsic contrast calibration optimisation.

The oven is deliberately oriented so that a typical plasma has π/σ at ~22.5° (Q3). There are 4 possible 22.5° polarisations and depending on where σ and π are, they will give:

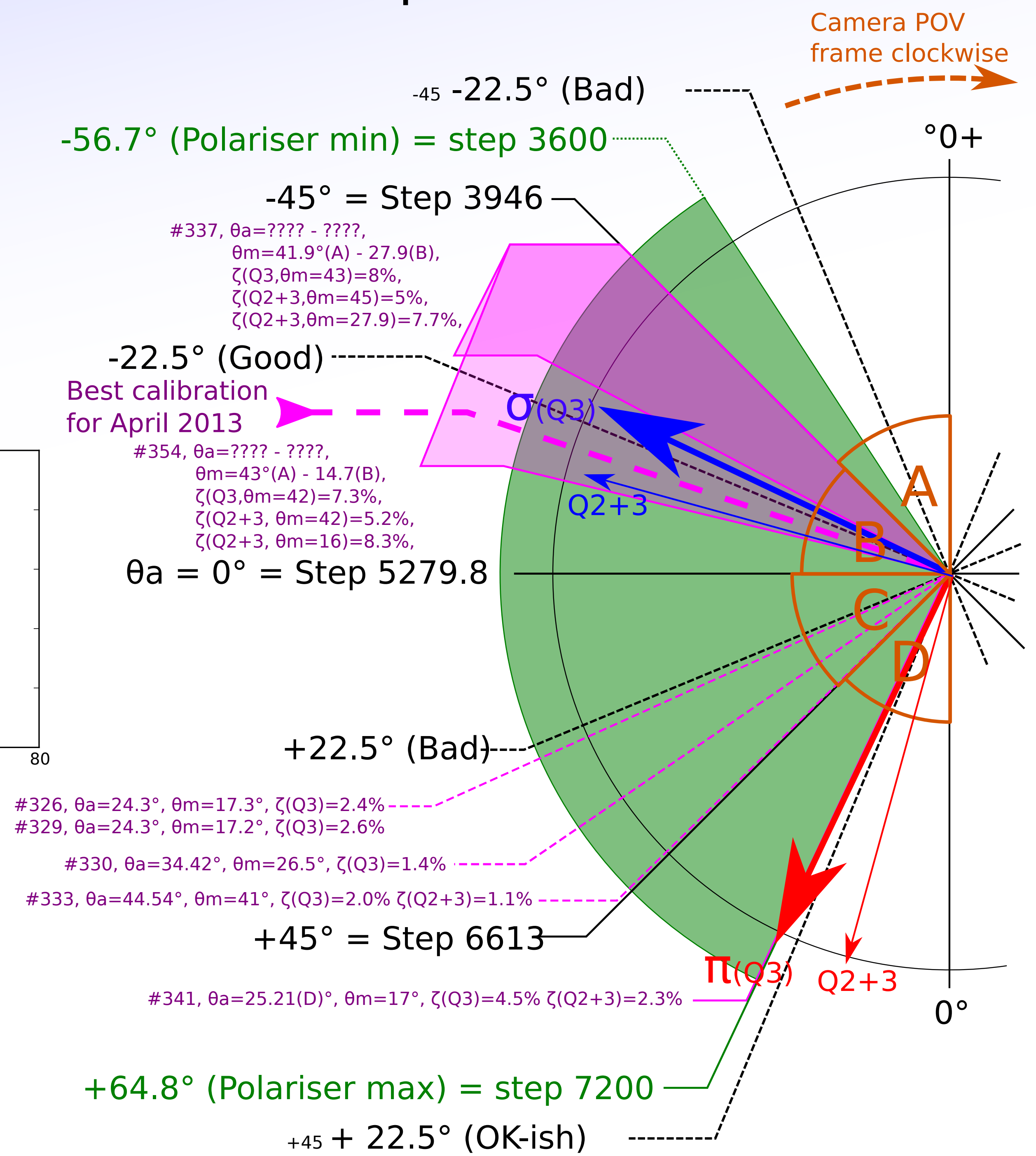
- σ aligned: Best contrast
- π aligned: Quite bad contrast (only unpol σ seen)
- 2x between σ and π: Very bad

The worst should be inbetween 45° and π aligned.

Measure contrasts (for Q3) vs θa gives:



So now we know where σ and π are relative to calibration wheel.



Angle names:
- θm = Raw angle as measured by Savart plate.
- θa = 'Actual' angle at Savart plate. Either global (approx -90 to 90) or in 45° sections (μ corrected θm).

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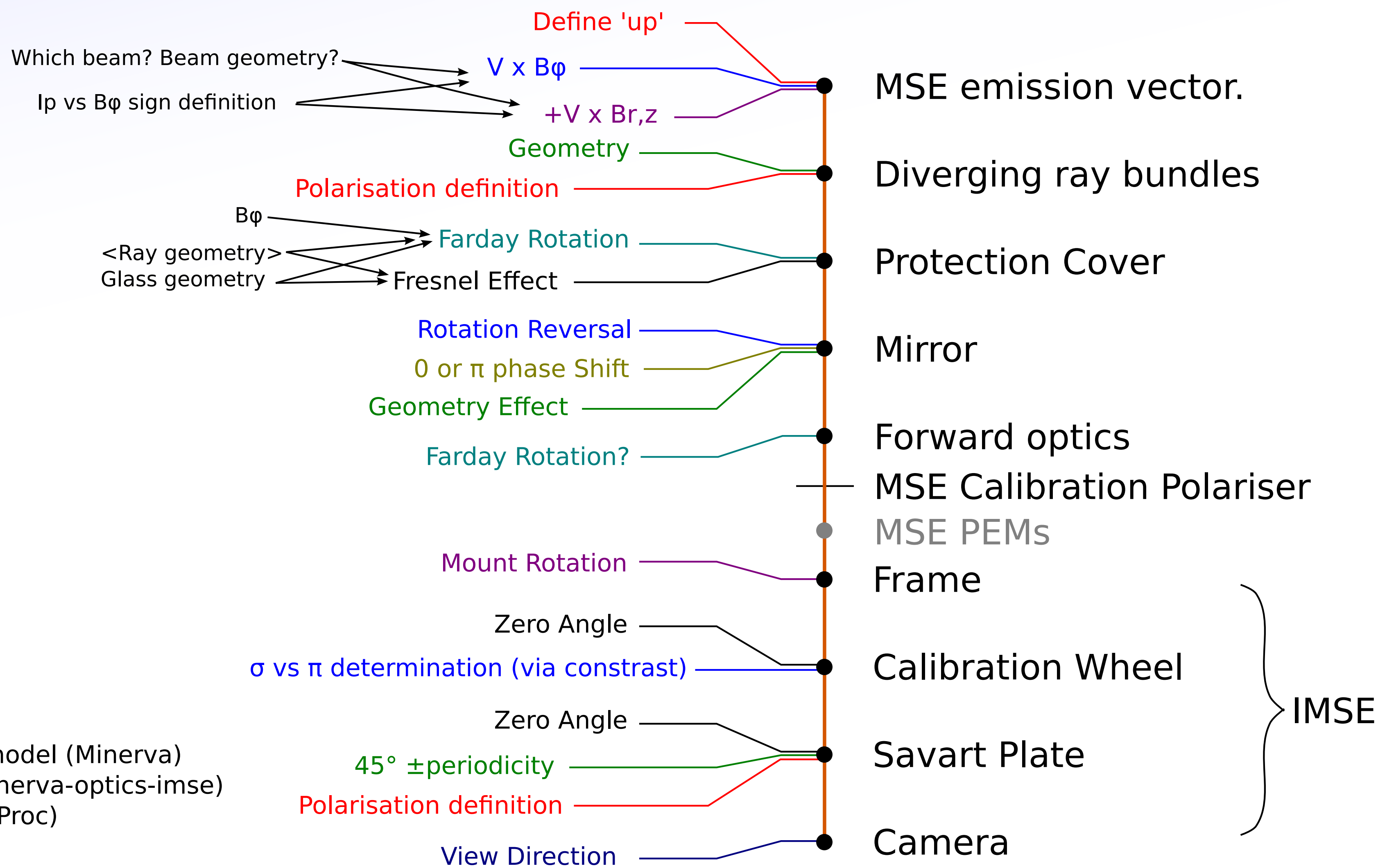
Which way is up? Overview

Although it won't be accurate enough without a separate calibration for analysis, it is useful to try to calculate the actual absolute polarsation direction and check it against the measurements.

The involves a lot of calculation, and pinning down a lot of conventions and definitions. It's a very long and complicated story, but is very useful to help document and declare exact definitions for signs, directions, phases etc and particularly solve some issues regarding exactly how one defines polarisations in 3D:



Codes:
- MSE forward model (Minerva)
- Ray tracer (minerva-optics-imse)
- Lab S/W (IMSEProc)

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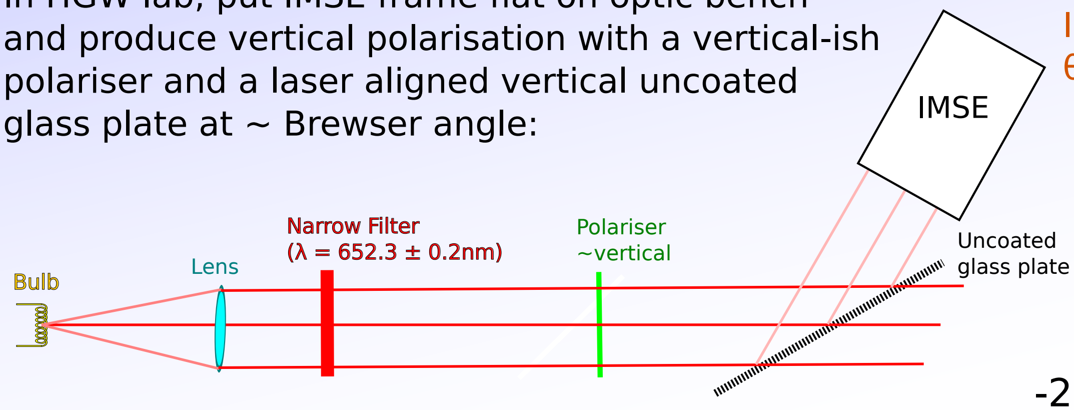
Which way is up? Part 1 - Savart + Calibration polariser vs the IMSE frame

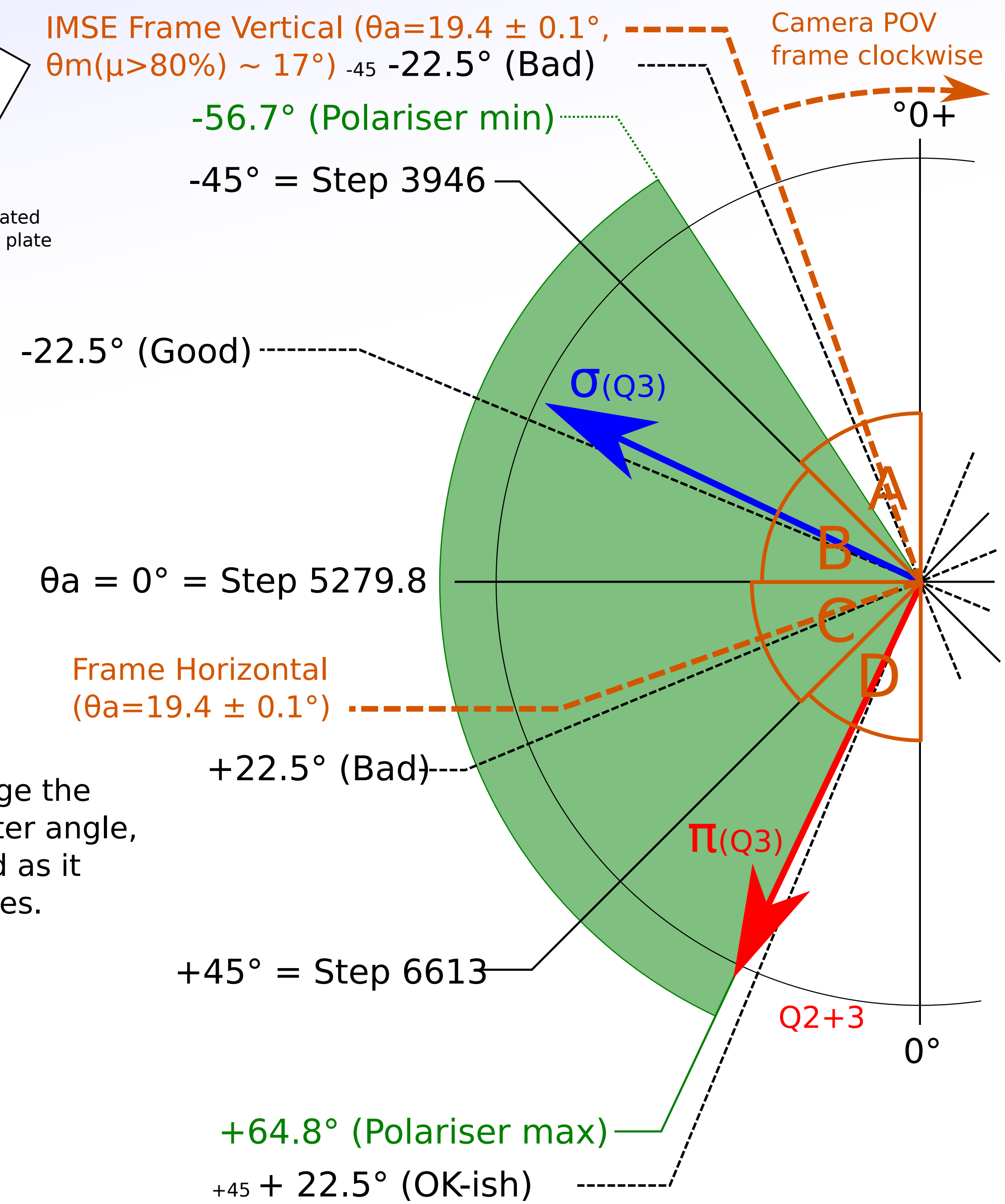
In HGW lab, put IMSE frame flat on optic bench and produce vertical polarisation with a vertical-ish polariser and a laser aligned vertical uncoated glass plate at ~ Brewser angle:



The minimum intensity on a polariser scan (#xxx) gives polariser position for horizontal w.r.t the IMSE frame:
θa = 19.4°.
Without calib wheel, IMSE measures this as θm~17° (unknown μ, but should be quite good due to optical setup used).

Rotating that polarisation to the right from vertical makes θm initially decrease - **Consistent with picture so far.**

As a check, removing the ~vertical polariser doesn't change the IMSE measurement, so either the plate is exactly at Brewster angle, or (more likely), the small horizontal contribution is ignored as it makes a small unpolarised componet which the IMSE ignores.



Angle names:
- θm = Raw angle as measured by Savart plate.
- θa = 'Actual' angle at Savart plate. Either global (approx -90 to 90) or in 45° sections (μ corrected θm).

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Which way is up? Part 2 - Global definitions.

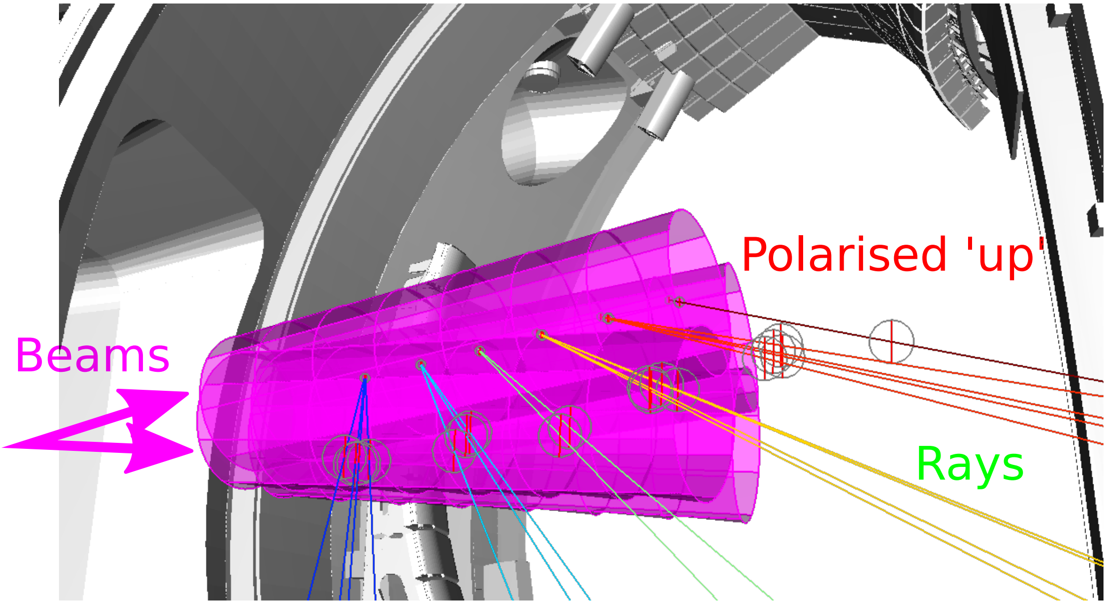
The measured polarisation of σ and π are now known in a real physical sense relative to the 'up' of the IMSE metal frame.
This is *roughly* the same as the torus physical 'up', so it can now be checked against the ray traced polarisation.
This will never be accurate enough for calibration, but provides a sanity check of all the known information and a check that there's no huge surprises in the forward optics.

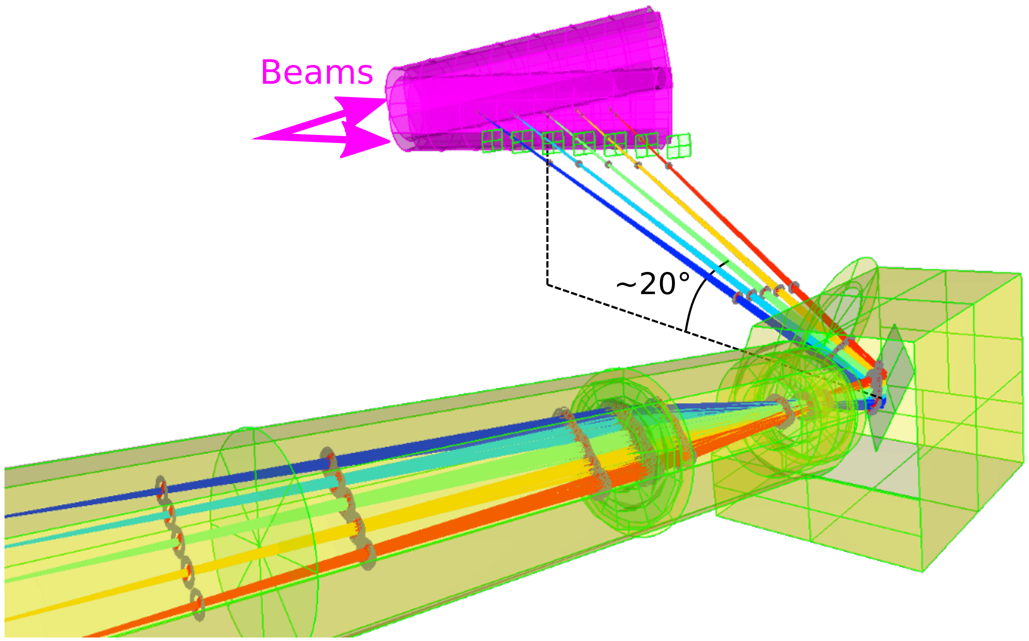
There's lots of ways of defining θ=0. A common way for MSE systems and especially equilibrium codes is to defined θ=0 when E is // to V x Bφ for the beam used for MSE, so that θ is roughly proportional to Bz. However, here V depends on the beam, is not exactly known, and the E = V x B things are done as part of the forward modelling rather than at the ray tracing end. We need a more general 3D common definition to link the two calculations.

The most unviersal and obvious is to choose, for each ray, is the closest direction to the global 'up' that is perpendicular to that ray. Specifically:

Linear polarisation with E // to ((r x z) x r).
r = ray direction, z = Z = Tokamak up.   (For the main MSE beam Q3, this is ~6° away from the usual E // to V x Bφ)

The MSE view is some arbitary 3D direction, in this case tilted up at ~20°, and the emission cone of the collected light (that makes it to the CCD) from each point is actually quite wide (~1°). These facts cause some subtle conceptual issues with exactly how polariastion can be defined consistently for different ray bundles and for each ray within a bundle.





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Which way is up? Part 2b - Polarisation definitions.

For a diveraging rays in a bundle with central axis x, we want to have 'the same' polarisation for all rays (// to y) . There are two ways to define this:

Polar consistent: Each ray has E // to (r **x** y) **x** r.

It's independent of x and describes systems with no plane involved. The is what the MSE emission will make (with y // to the Stark E field for π light).

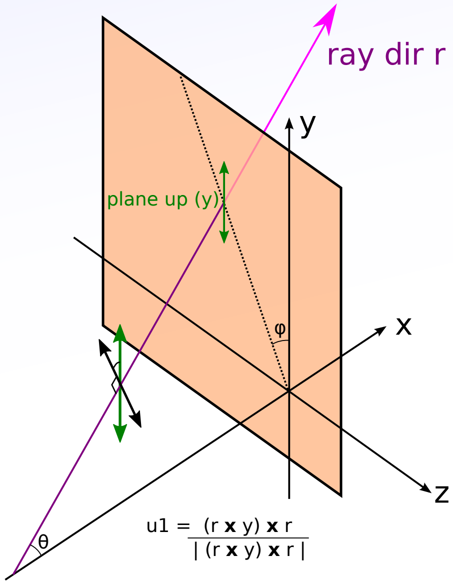
Planar consistent:

Each ray has the same p/s ratio as the p/s ratio in the plane perp to the bundle axis. This is what a polarising surface will make and most instruments measure. It is equivlent to focusing the light to make all the rays parallel first.

The difference is largest at φ=22.5° and large θ. For the MSE rays, the max effect within a bundle is only ±0.05° (with x on the bundle centre).

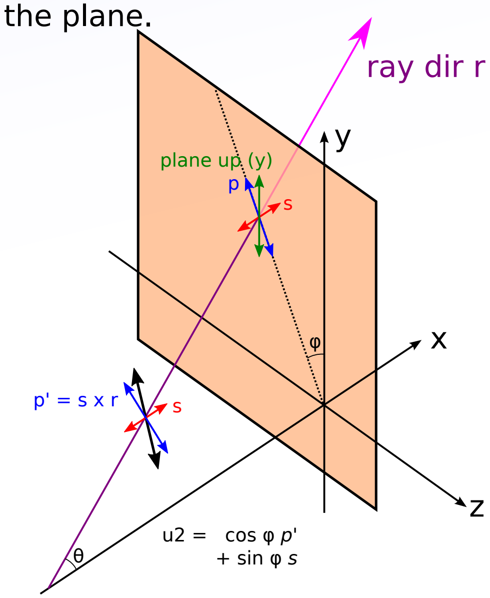
POLAR consistent

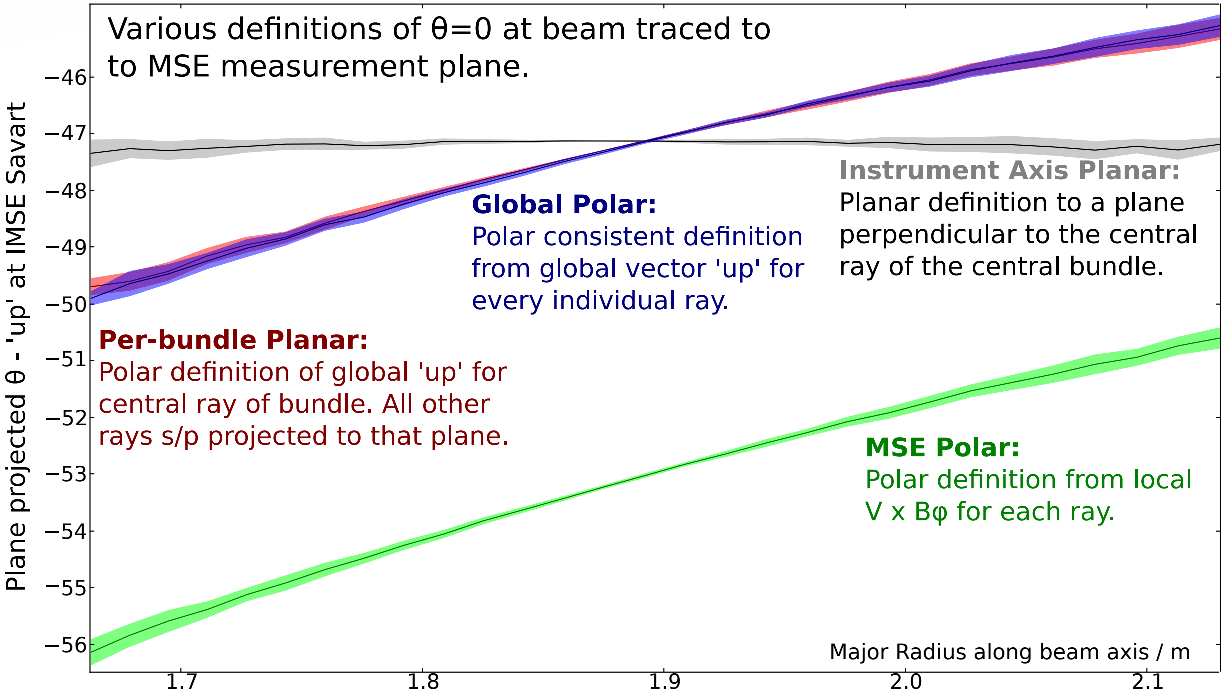
u1 = Nearest vector to 'up' ≠



PLANAR consistent

u2 = Same p/s ratio as 'up' has in the plane.





However, our global 'up' (and also the Stark E field) are at a ~20° to the (y,z) plane, so are seen to have a ~5° variation across the field of view. This is entirely due to the MSE emitting a spherically symmetric polarisation but being measured by a planar system with a 20° tilt to that direction.

The important thing is to use the same intermediate definition between the forward model (Minerva) and the ray tracer. Either one or the other will add the 5° variation which should really be seen in the measurement. It is a function of the viewing geometry.
To really get this correct, the ray tracer should be in the forward model.

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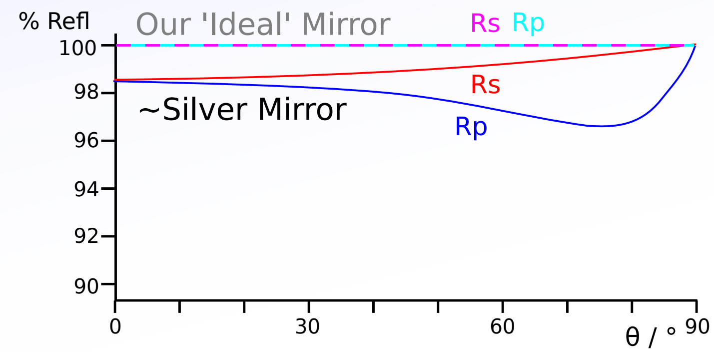
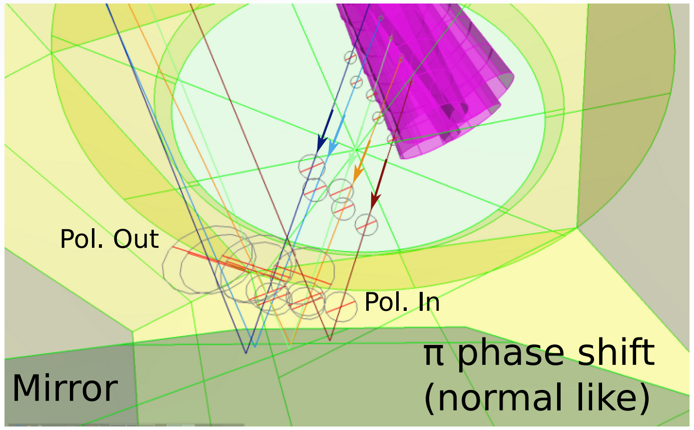
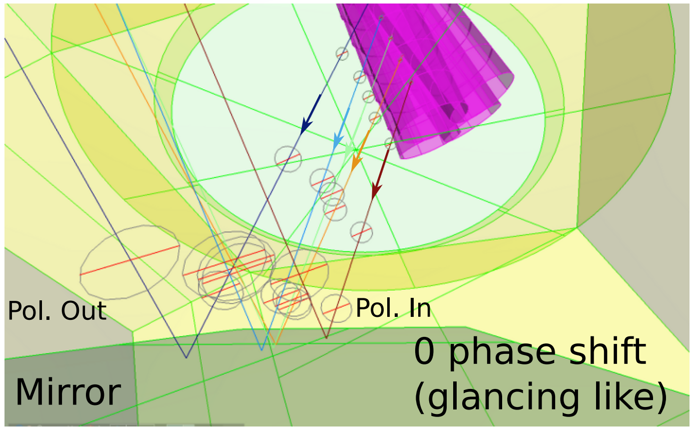
Which way is up? Part 3 - The mirror.

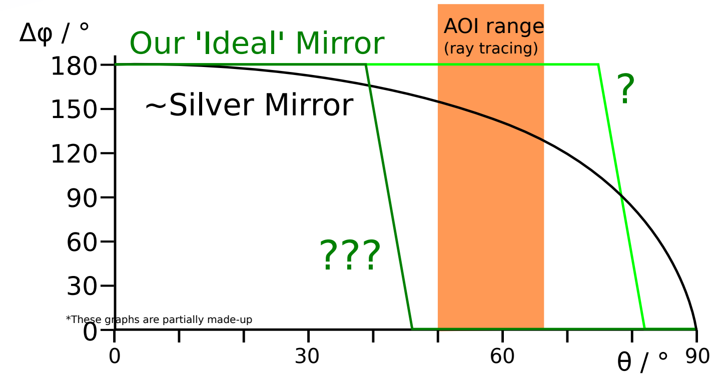
The polarisation properties of our mirror are not exactly known. What is known is that its 'effect on polarisation' is minimal i.e. rotation by 360° remains linear all the way around after reflection. We therefor assume that the mirror has 100% transmission for both p and s, and that the (effective*) phase shift is either 0 or π over our incidence angle range. This phase shift must be π at normal incidence and 0 at glancing incidence, and we cannot know if the actual angle (around 60° to the normal) behaves as glancing-like or normal-like reflection. However, the flip is *usually* at much steeper angles, so it is *more reasonable* that we **do** have a 180° phase shift:



At the mirror, the 'up at beam' polarisation looks like this for our two cases:
The left case is more reasonable to expect.







* On 'ideal' mirrors w.r.t polarisation:

It's often written that "ideal mirrors phase shift the p component by π", which is quite misleading. At normal incidence (or infinitly close to it) a mirror is isotropic. There is no p or s and the emitted E field must be parallel to the incoming E field. The change of ray direction requires flipping one other axis to maintain a left/right handed coordinate system. This in turns requires inverting the polarisation amplitude in that coordinate (the π phase shift) in order to keep the same E field direction. In proper 3D reality, nothing has happened to the polarisation.

Applying the same for a 45° polarised ray at a glancing incidence, the E field direction of the outgoing ray (which is near parallel to the incoming) does actually flip by 90°. Maintaining the E field in this situation contradicts the normal incidence case. Reality is more cunning, and all real reflectors (glass surface, metal, multi-layer dielectric) seem to have a p component transmission that varies in either phase or amplitude (sign) such that the global E direction is maintained at both extremes. So if you're considering all angles of incidence, the polarisation effect has to change and in this sense, there can be no ideal mirror.

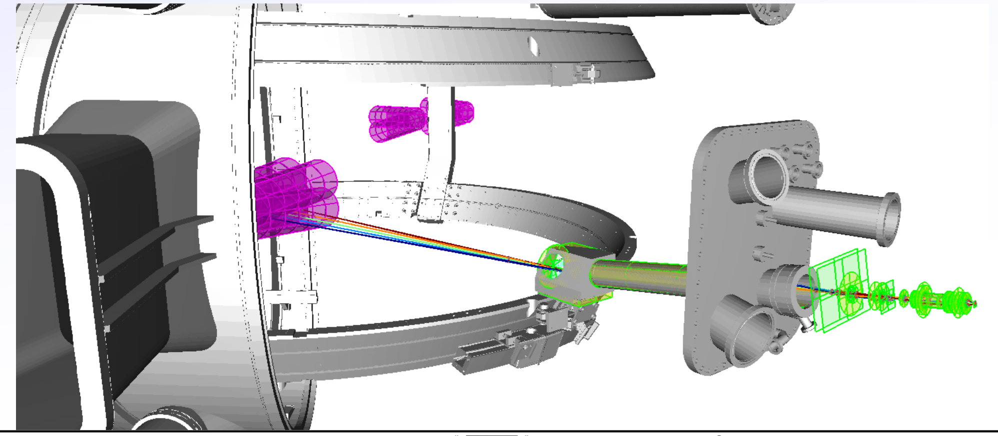
Oliver Ford
IPP Greifswald

Which way is up? Part 4 - Tube optics

The ray-tracer now traces the effects up through the PEMs, virtual image (fibre plane) and the IMSE system.

Farday rotation in the optics is currently ignored (dealt with elsewhere).
Depolarisation due to collected ray paths through lenses.

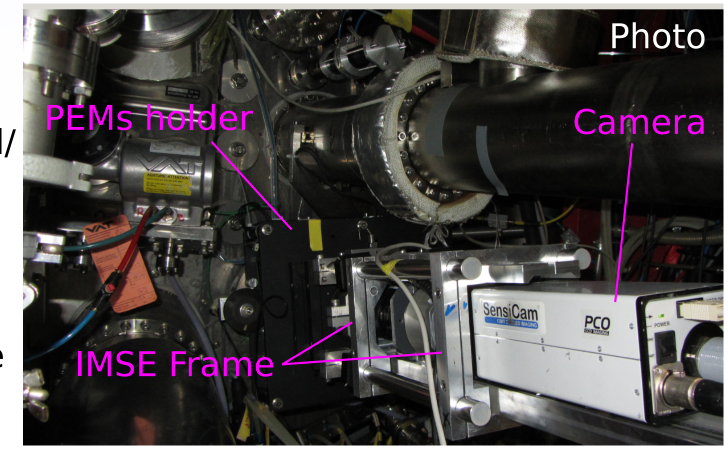
We should now have the correct orientation and sense relative to 'up' at the IMSE system.

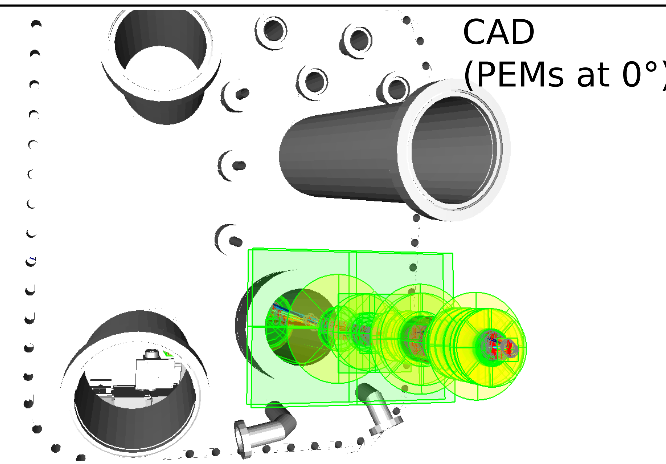


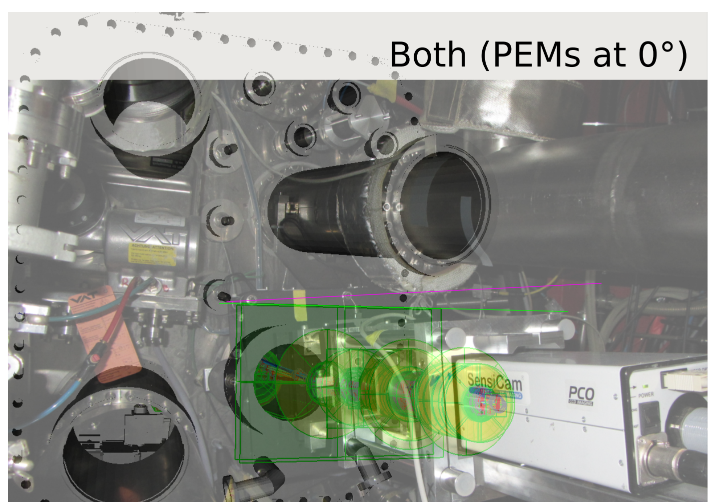
All forms of the CAD data are rotationally symmetric around the optics tube and there's no indication that the PEMS holder has a partcular setting relative to the global/ torus up.

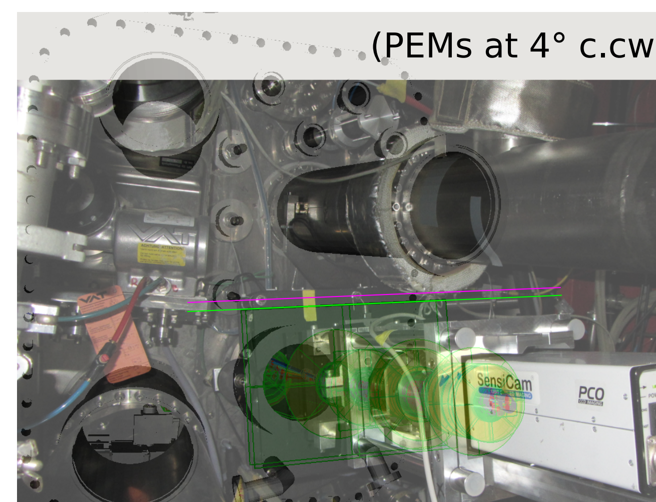
The IMSE frame is mounted to the rods which are reasonably safely assumed mounted aligned to the PEMS holder. So the PEMS holder angle (which in reality looks a bit crooked), is the angle of the IMSE frame relative to 'up'. It can be estimated by:

Align CAD+ray-tracing view to match photo of mounted system.
Rotate PEMs in ray tracing until it matches the holder in the photo:
= 4° anti-clockwise from camera POV.
±0.3° angle assesment.
±1.0° projection alignment assessment.
** Nov2013 measurement with digital spirit level says this is 3.1° anti-clockwise camera POV **









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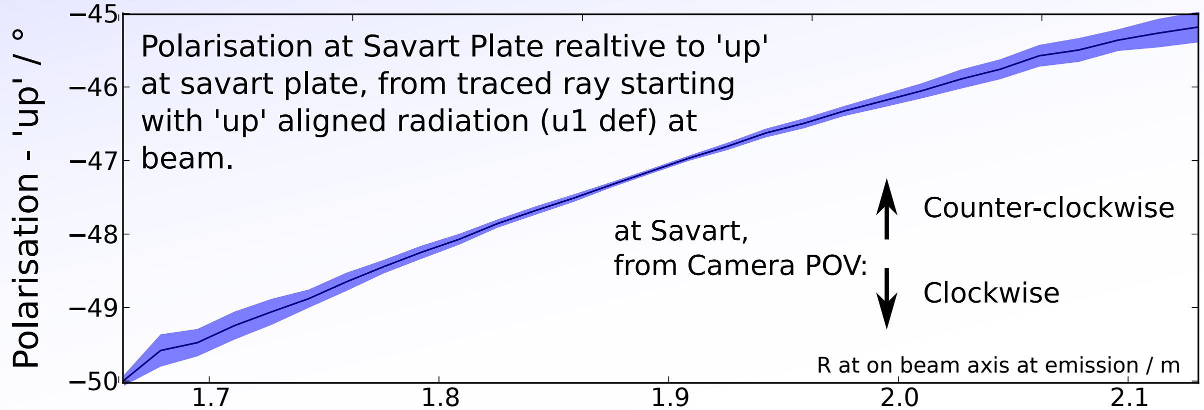
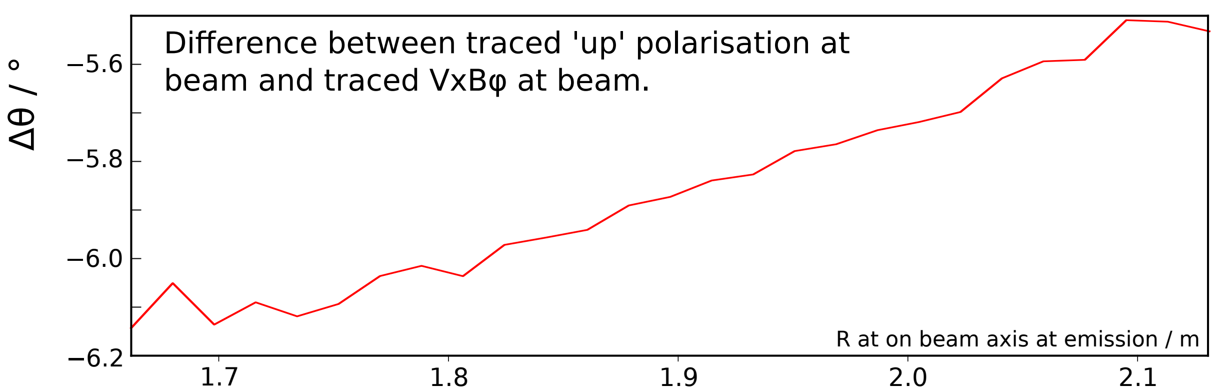
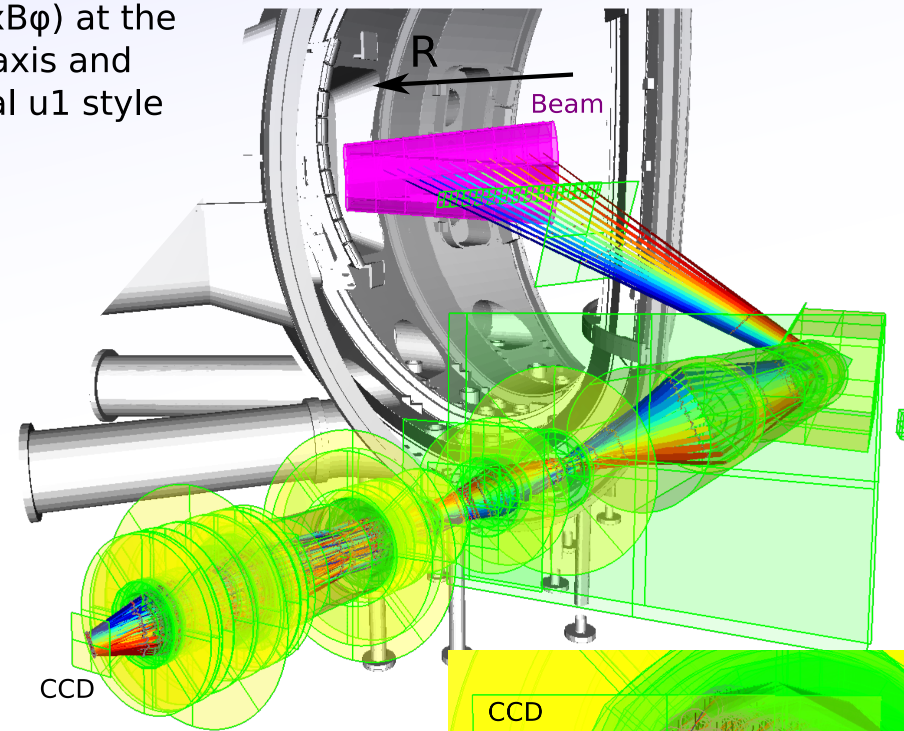
Which way is up? Part 5 - End to end.

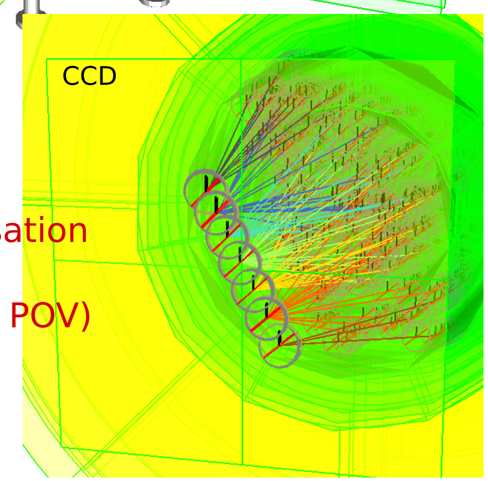
It's now possible to have the ray tracer tell us what 'up' (and equally VxBφ) at the beam should give us as an actual measurement w.r.t. the Savart plate axis and can break this down into what is causing what. Sticking with the general u1 style 'up' as the inital direction. The final situation looks likes this:

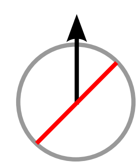


Tracing V x Bφ gives roughly the same thing. It would be intuitive to believe that this variation is just a result of the variation in Beam/Bφ vs view variation, but no, it's just from the polarisation definition.









There's a bulk ~45° change due to the direction change at the mirror.
There's a bulk 4° due to tilt of IMSE metal frame versus the global 'up'.
There's a ~5° variation due the 20° back tilt and polarisation definition.
There's a ~6° offset and ~0.6° variation due to V x Bφ geometry.

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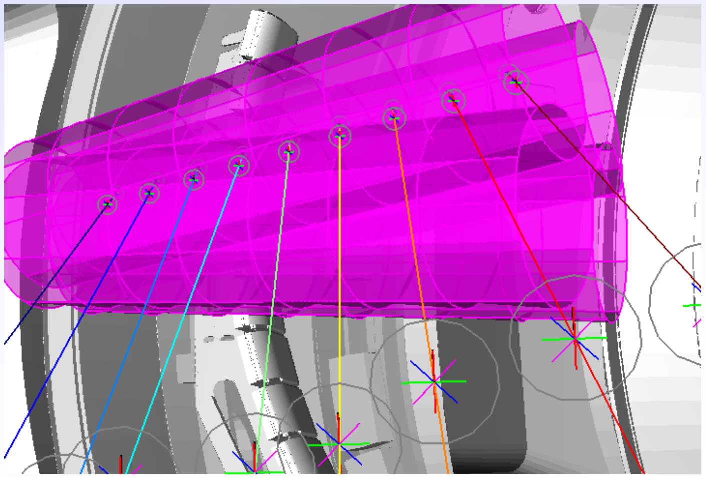
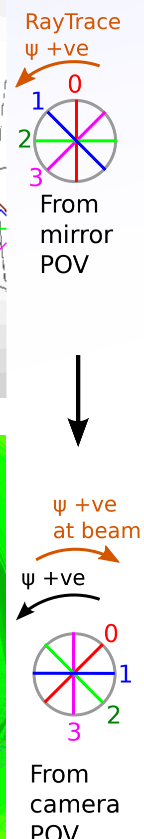
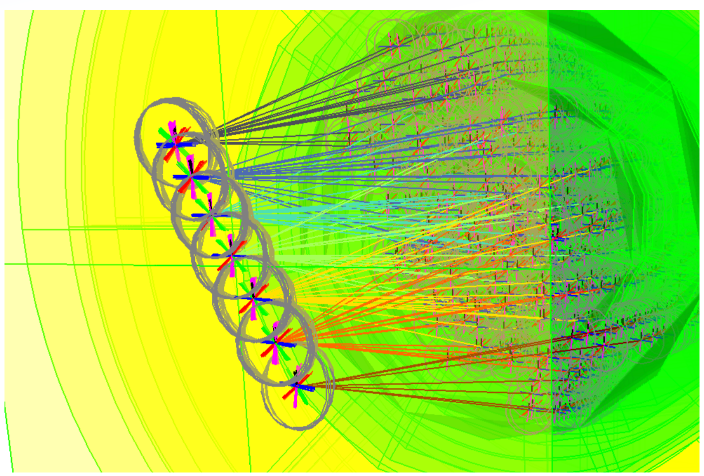
Which way is up? Part 6 - Rotation.

We also need to check the rotation direction from this, and can confirm that all the definition nonsense and the mirror shift don't make a polarisation scan nonlinear (important, since the IMSE picks up both σ and π, unlike the MSE).



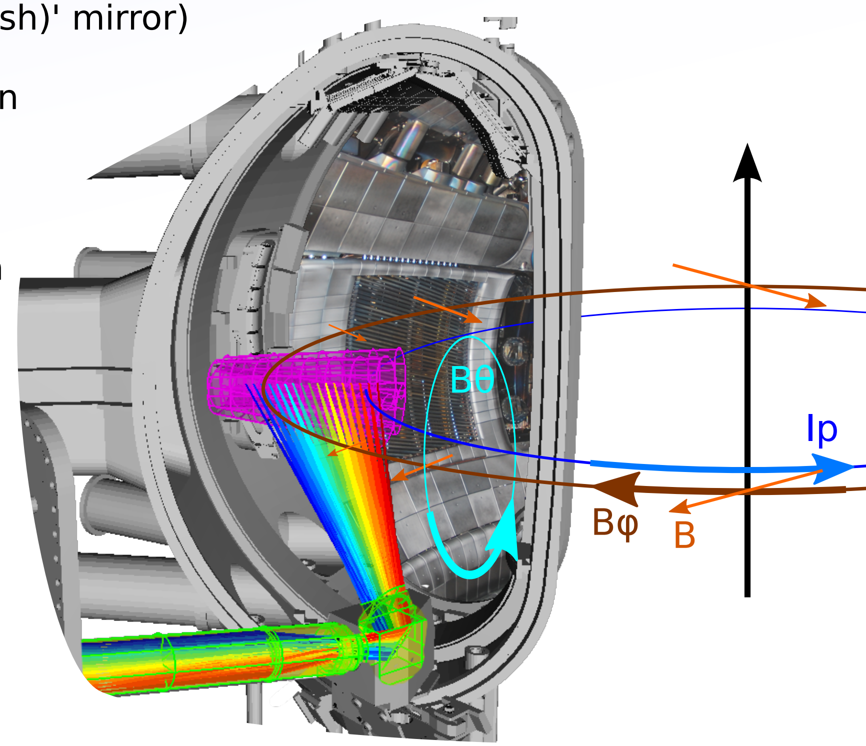




A high-res scan gives a perfect 1:-1 relationship between θ at beam and θ at Savart. i.e. we don't expect any non-linearity or jumps. (assuming the 'ideal(ish)' mirror)

The switch of direction is due to mirror.

The AUG current and field are always given as Bφ=-ve and Ip= +ve. This gives the real field direction at the MSE emission points, which is consistent with the photos of the ICRH grill.

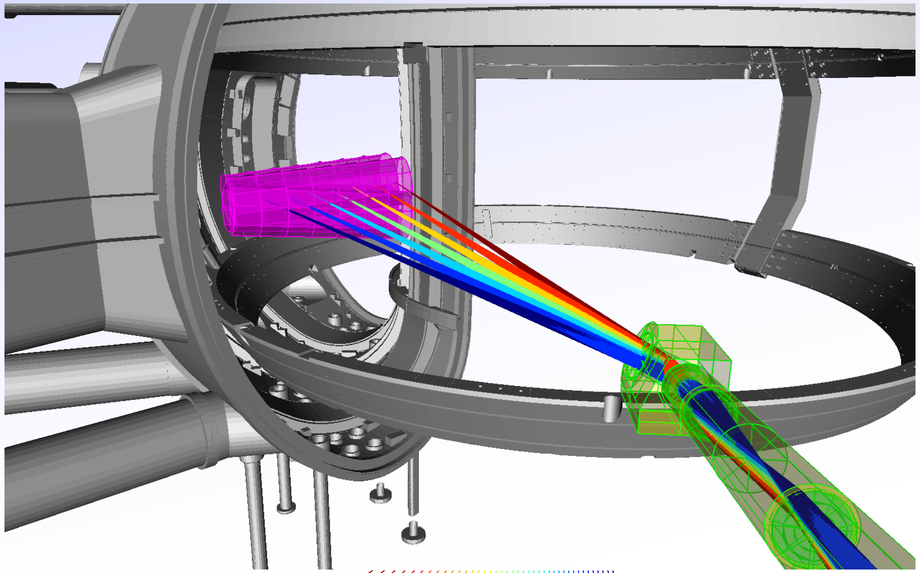


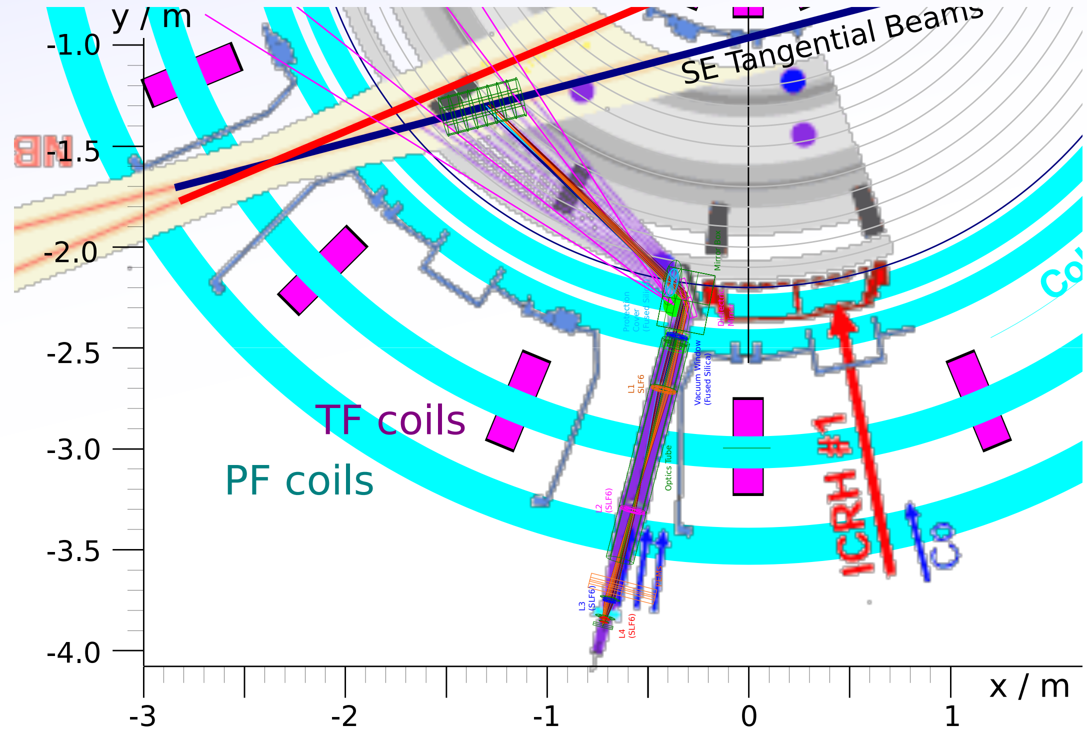
For higher Ip (more -ve Bz), the projected VxB rotates clockwise from mirror POV at beam (-ve). The polariastion at the IMSE Savart therefor rotates anti-clockwise from camera POV, (which is +ve for the raytrace output). Switching to beam 2 (lower) will also rotate in the same direction.

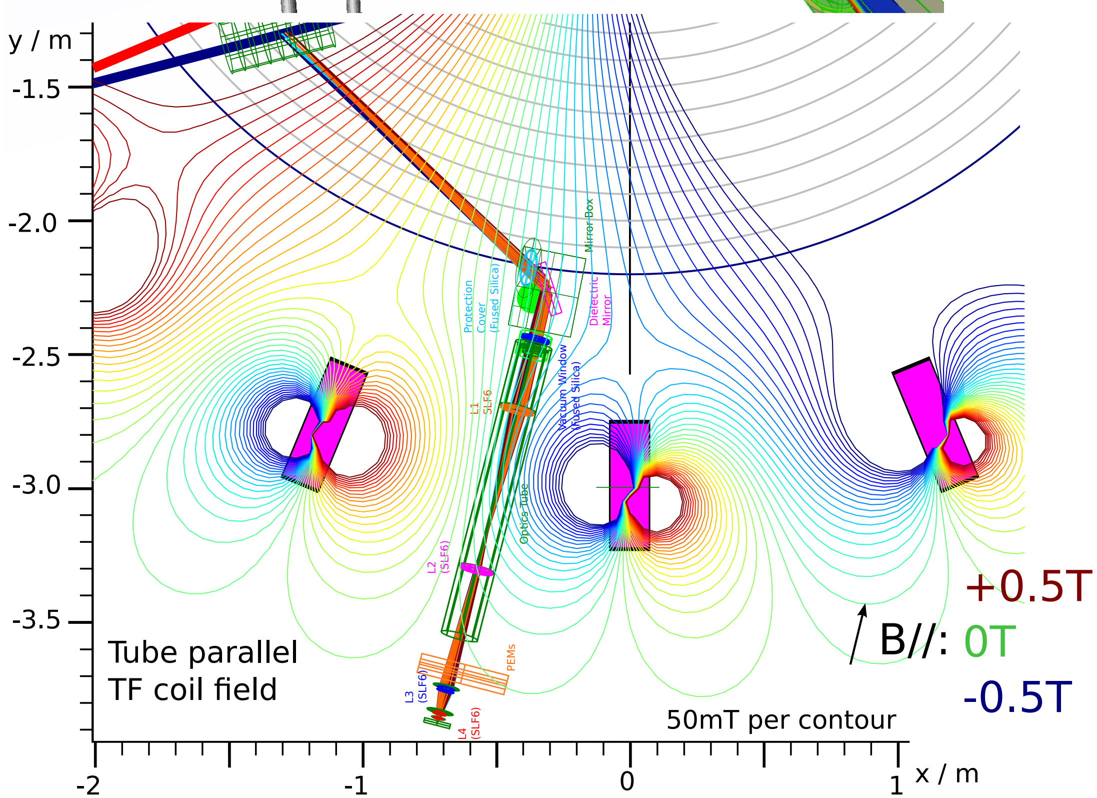
Faraday Rotation - SFL6 Lenses

Oliver Ford
IPP Greifswald

Faraday rotation in the forward optics significant, particularly in the 3.5mm Fused Silica protection cover.







Lenses are SL F6 glass: ~ 0.2°/T/cm (0.418rad/T/m @ λ=653nm)

Field from TF coils is < 300mT at Lens1(15mm) and vacuum window (10mm). Rotation is < 0.15° (... of course it is, everything is ~0.1°).
If vacuum window is really Fused Silica, it will be 0.6°.

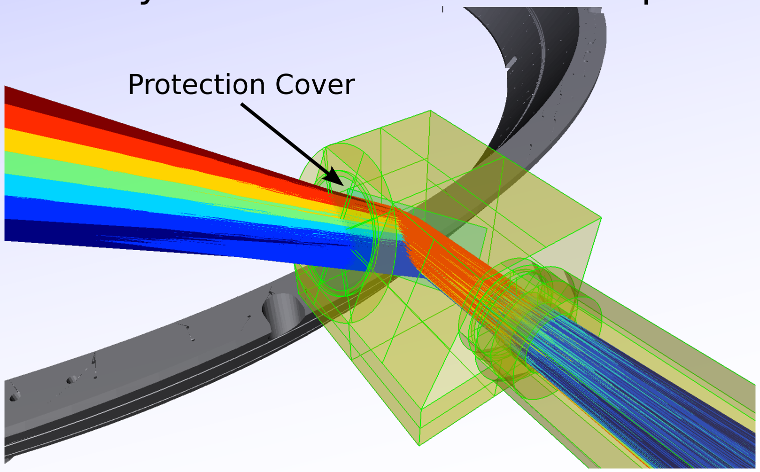
According to [doi:10.1117/12.48307], Faraday rotation is clockwise looking along B regardless of ray direction, for +ve V and most glasses (BK7, SF x etc) all have +ve V.

SF L6 has slightly -ve V at short λ but is just +ve at 653nm. For standard Bφ < 0 case, rotation due L1 will be

Faraday Rotation - Protection Cover

Oliver Ford
IPP Greifswald

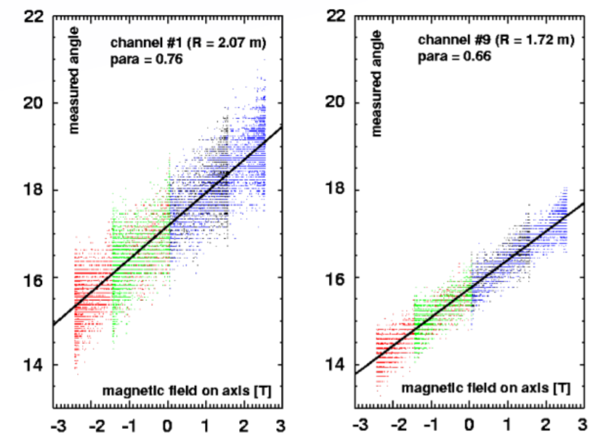
Faraday rotation in the forward optics significant, particularly in the 3.5mm Fused Silica protection cover.

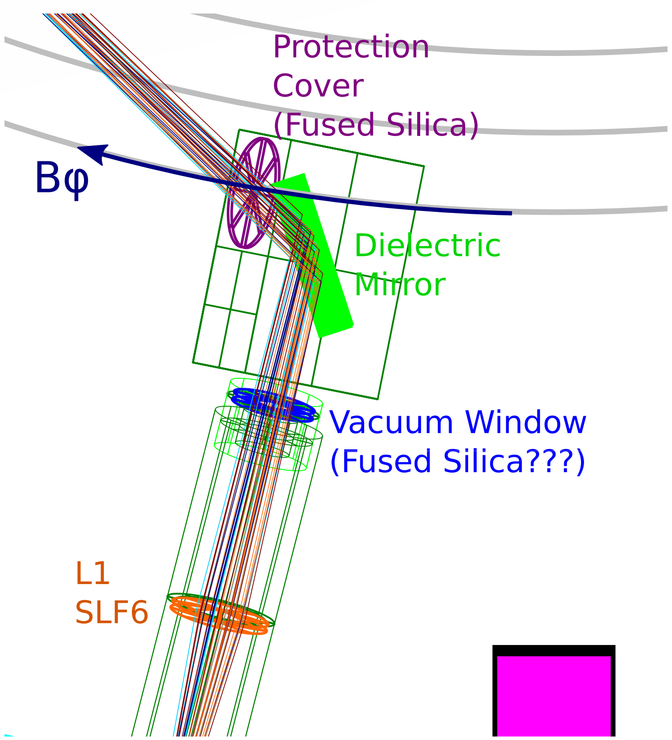


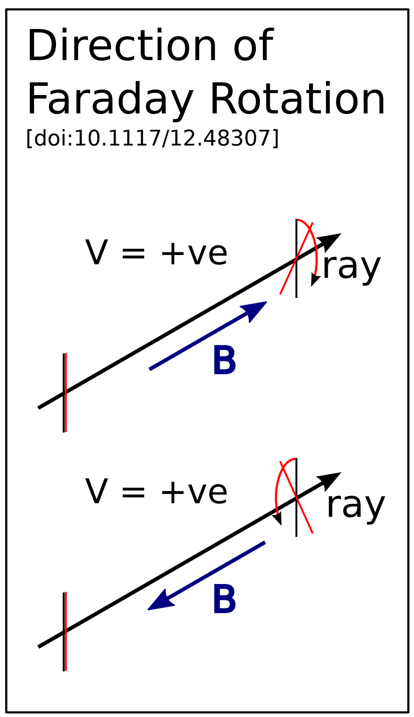
Cover is roughly perpendicular to toroidal field. Rays vary in angle through glass and to toroidal field dramatically with source/image position but also slightly with position across glass (i.e. the collection cone angle).

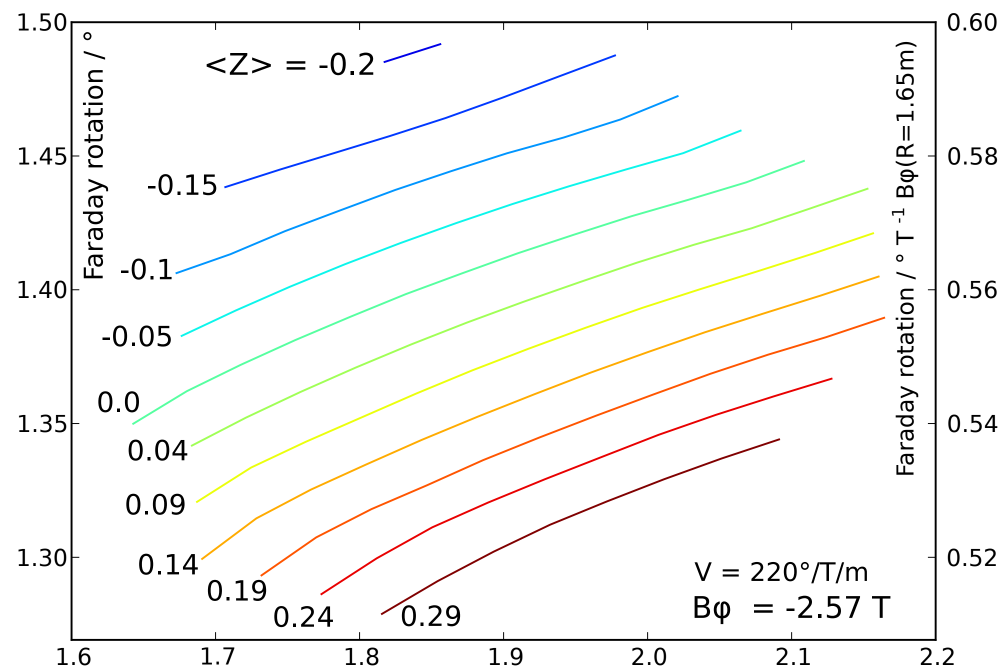
Verdet for fused silica ranges 220 - 300 °/T/m. For 3.5mm,
Bφ(R0)=-2.5T, Bφ(box) ~ -1.9TΔθ ~ 1.4°
For -ve Bφ, rotation is clockwise from mirror POV looking at beam and anti-clockwise at IMSE from camera POV (+ve).

	Ray tracer	2007 Measurements [MReich EPS 2007]
Core	0.55°/ T	0.66°/ T
Edge	0.56° / T	0.76° / T









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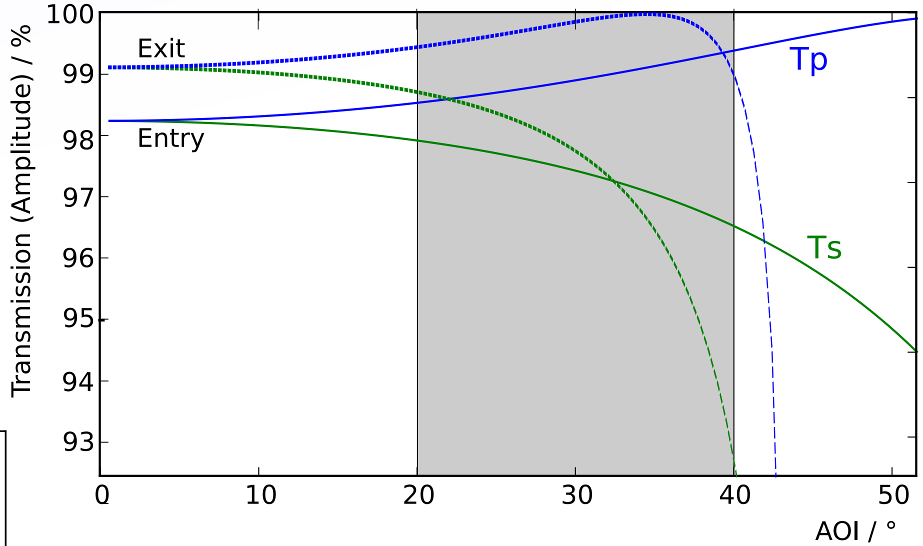
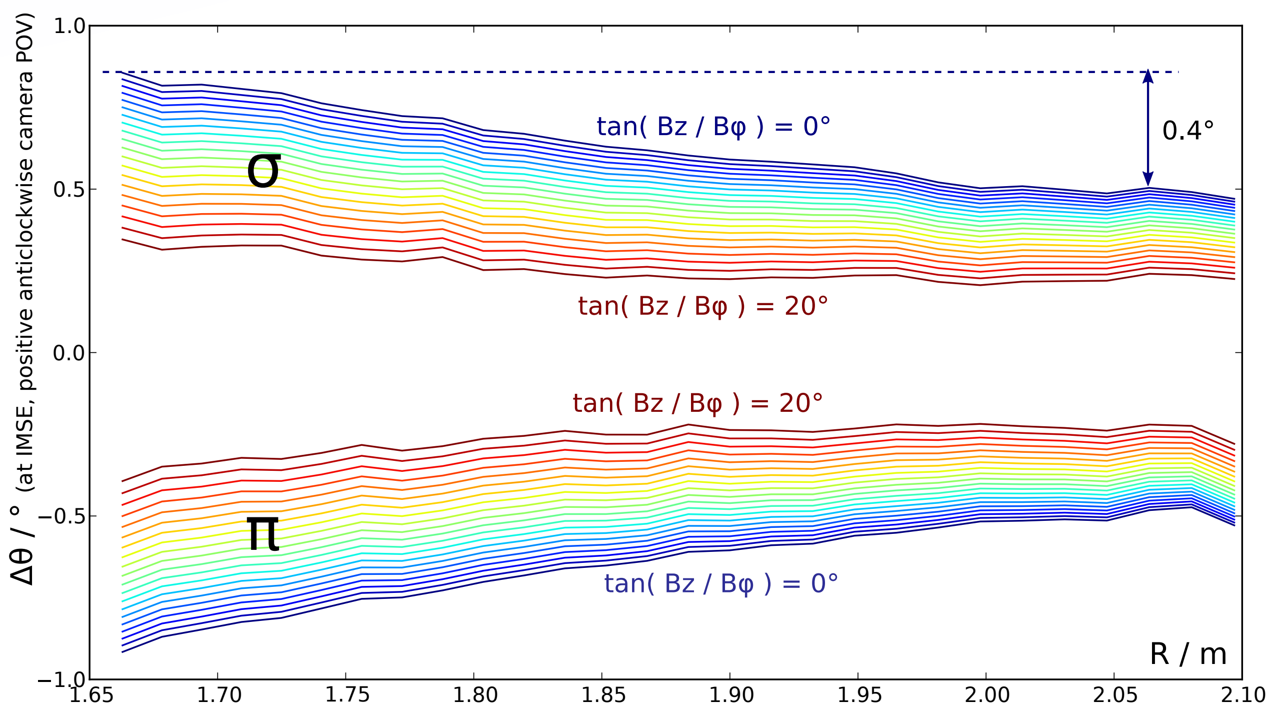
Which way is up? Fresnel Coefficients Effect

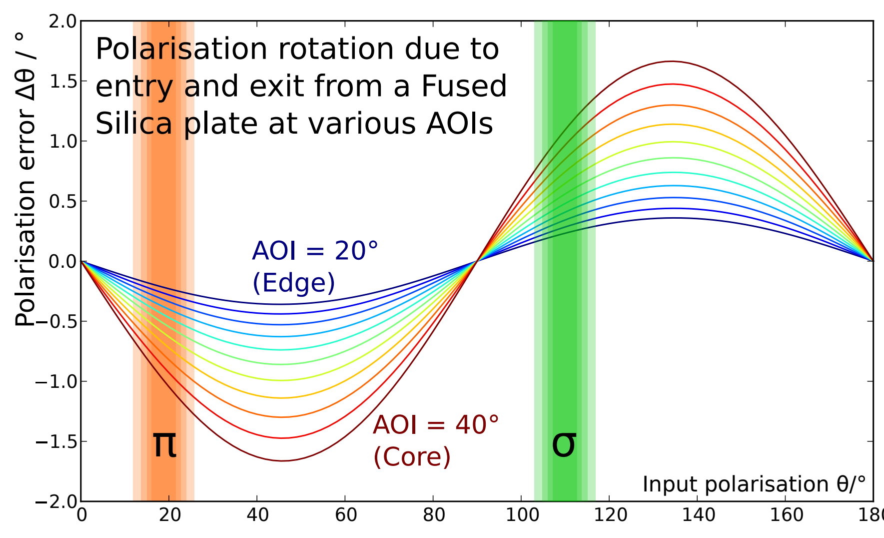
Fused silica protection cover is not anti-reflection coated, so difference in Fresnel (S and P transmission) coefficients can also rotate polarisation. It also refracts rays but the effect on image position is insignificant (< 5mm at beam).

Fused Silica refractive index at 653nm = 1.456.
Incidence angle through protection cover: 22° < θ < 40°
Transmission coeffs (n=1.456, θ=37°): Ts = 95.7% * 96.9%, Tp = 99.2% * 99.8%
At 45° incident polarisation, rotation is ~1.8°

Effect varies with AOI and with input polarisation, so response is now non-linear and changes with beam.
The π and σ components are at 90°, so always have the opposite response to the Fresnel coefficients. The IMSE measuremes some ratio of the two depending on the contrast functions (which also depends on almost everything). At best, the σ and π effects entirely cancel. At worst, the π isn't measured and the full σ effect is seen as a +0.1° < Δθ < +0.4° shift at the core, relative to the edge.







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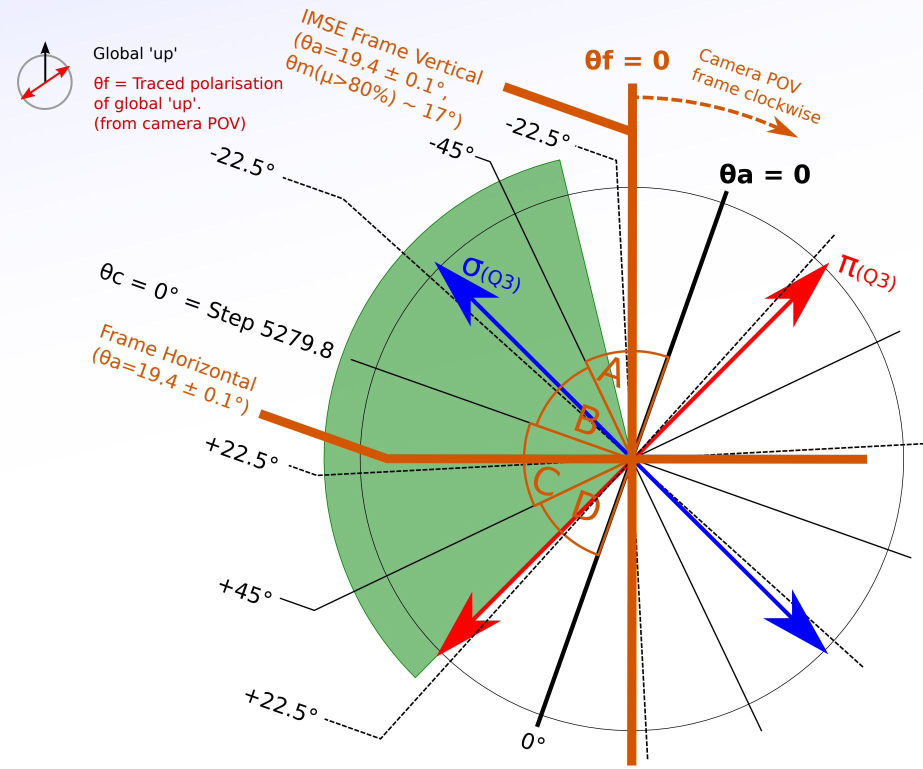
Which way is up? Part 7 - Final comparison

The measured angles are ambiguous in every 45° (90° periodic with each 45° reversed). To avoid confusion, compared angles are:

θf = Angle of π polarisation from IMSE metal framework 'up', +ve for anti-clockwise from camera's POV.



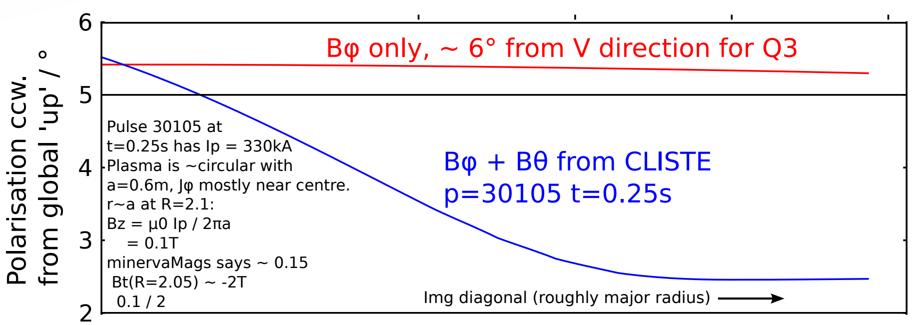
The contrast of the calibration wheel scans give the approximate σ/π direction (from the contrast) and also the IMSE metal frame 'up', so:

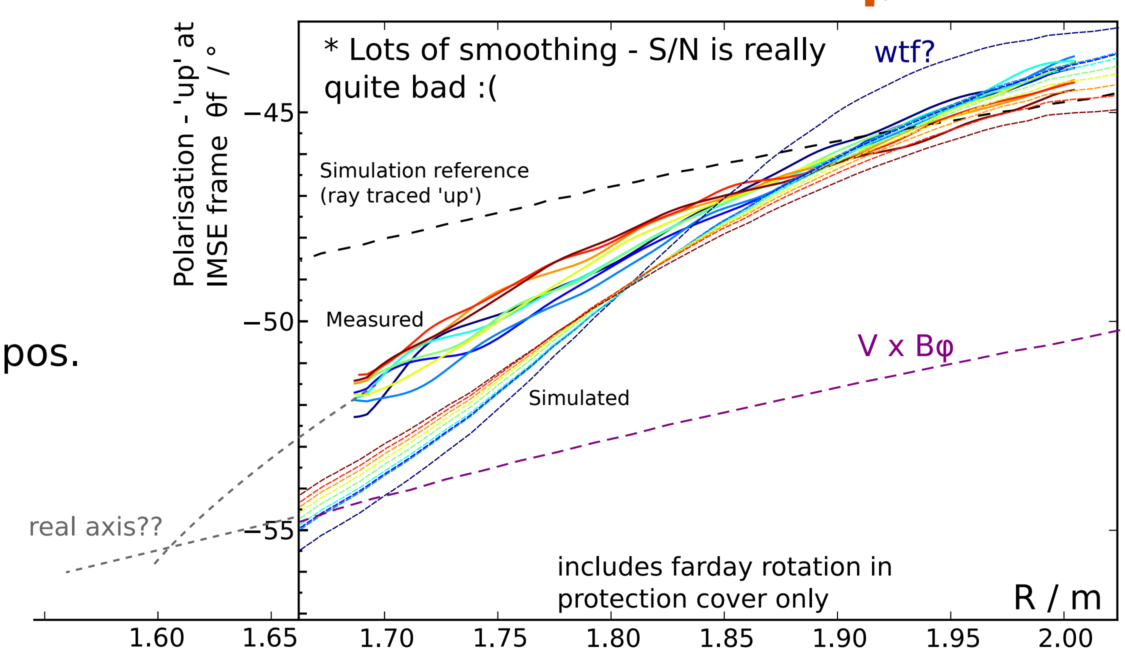
✔ 1 At this point, we can confirm we have the correct 45° segment and approximate direction .

The calibration wheel also links the 'actual' measured θa (μ corrected) to the IMSE frame. For the normal operational range, the π component sits in segment D, so we get:

θf = -θa - 19.4° (for segment D)

Take a shot with low Ip/Bφ and plasma edge almost in view. Forward modelling gives:





? Match at magnetic axis is off, but could be axis pos.

? About 1.5° out in variation.

✔ 2 Correct sweep direction.

✔ 3 Correct current development direction.

✔ 4 Spectacular match of absolute angle at edge!?!

Need to be careful of XY-RZ transform in sim and in measurement.

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Which way is up? Sensitivity to mirror position

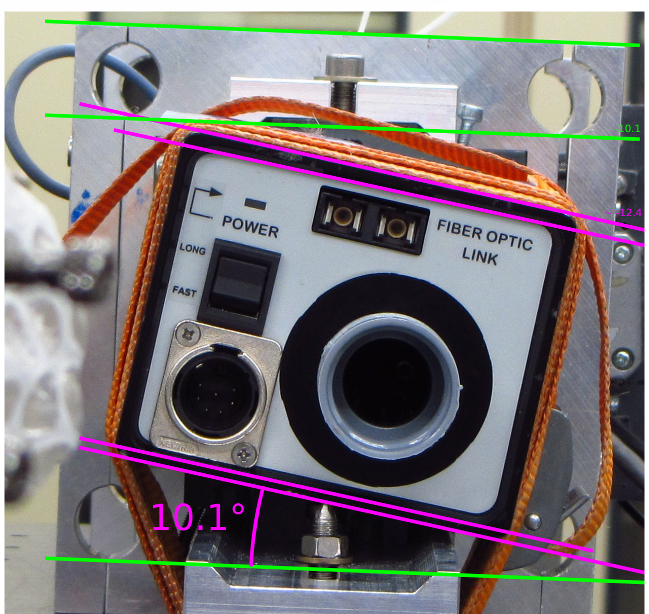
Movements of the mirror by ~few cm in the ray-tracer change image position at the CCD a little and change the fixed offset of the polarisation at the IMSE by a few 0.1°.

Tilting the mirror by 3°, which moves the beam image accross the CCD by about 1/4 the width of the CCD, can change the polarisation variation (due only to the 'up' definition) by up to 0.5°.

Misalignment of the IMSE plates (i.e. not-quite perp to optic axis) by 3° changes the offset by ~0.5° and the sweep by 0.3°.

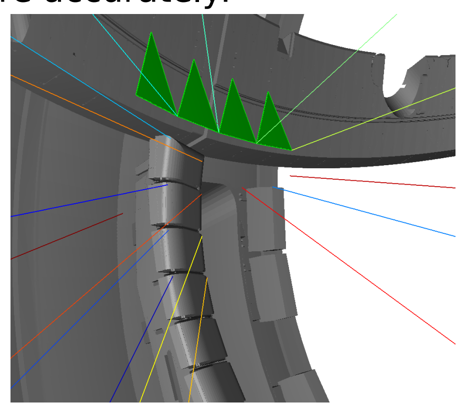
So, in order to correctly identify the polarisation sweep, weneed to know the mirror angle quite accurately. Need to fit the ray-tracer to the experimental transform.

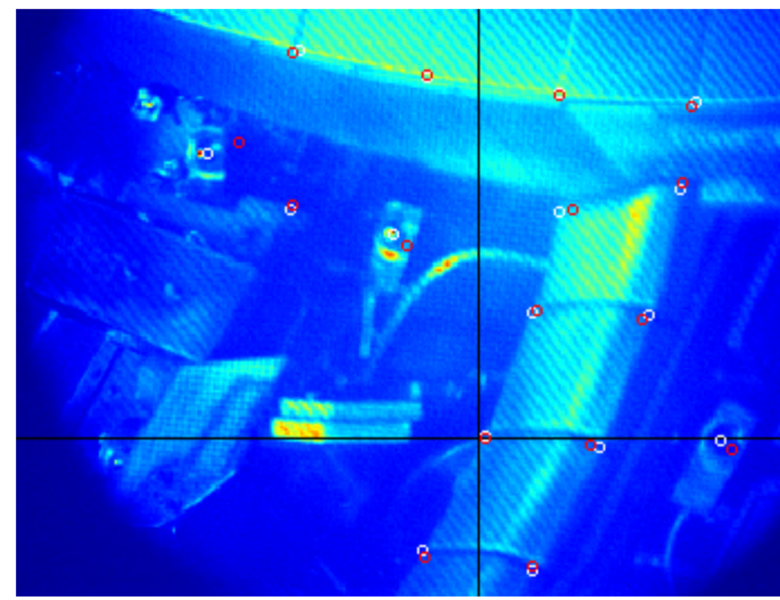
For April2013, the camera was tilted w.r.t the IMSE frame:

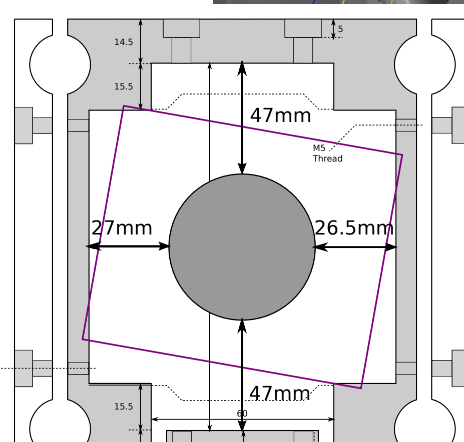


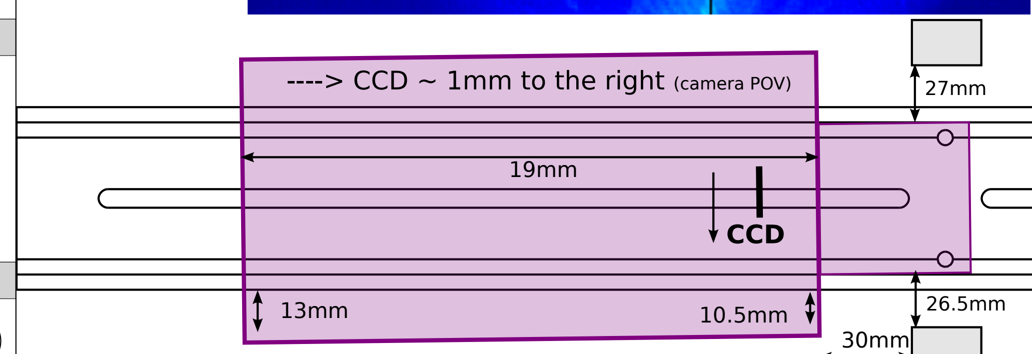
Camera tilt for April = 10.1°
For January, was ~0°.

Reaquire the transform a bit more accurately:









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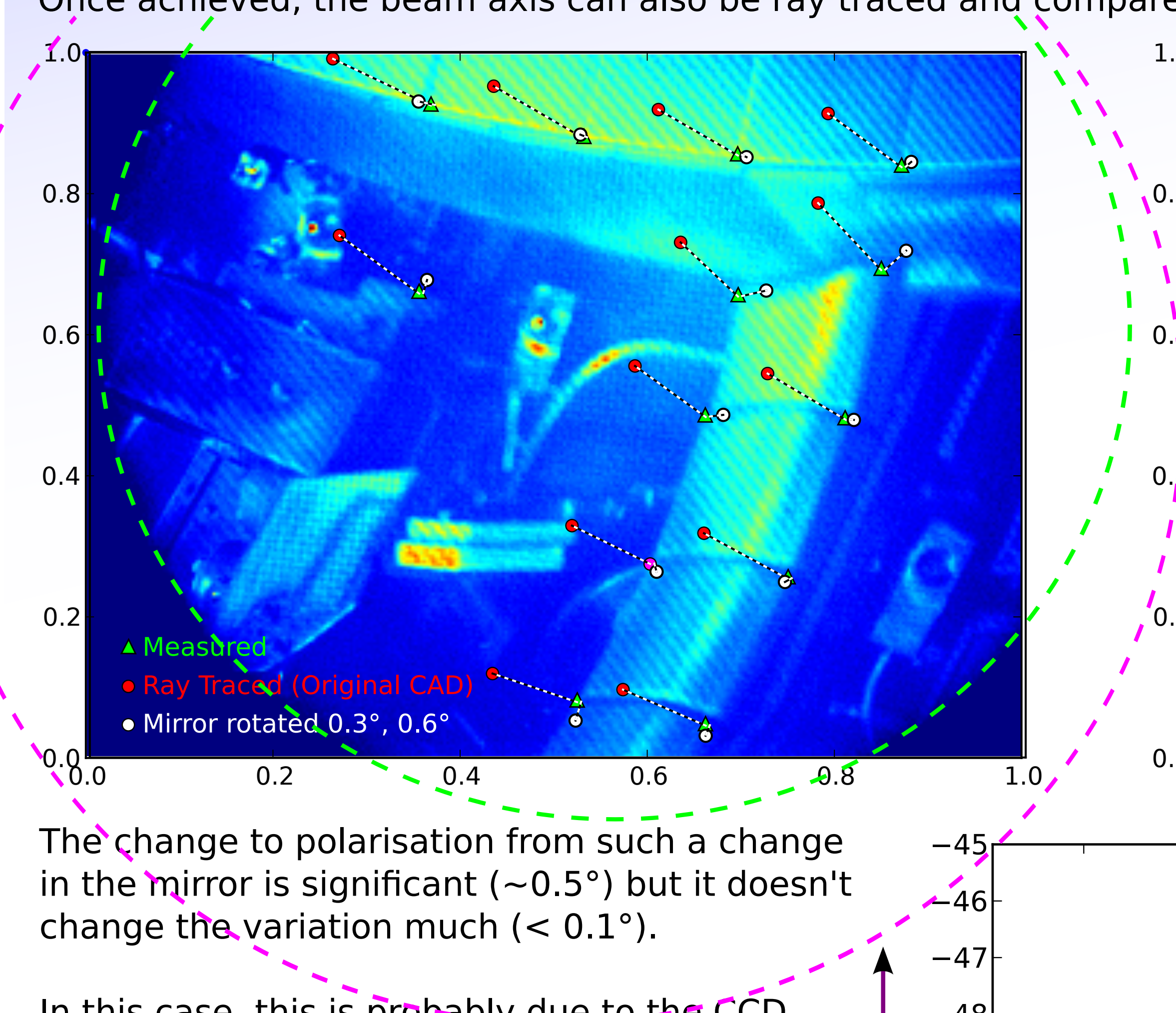
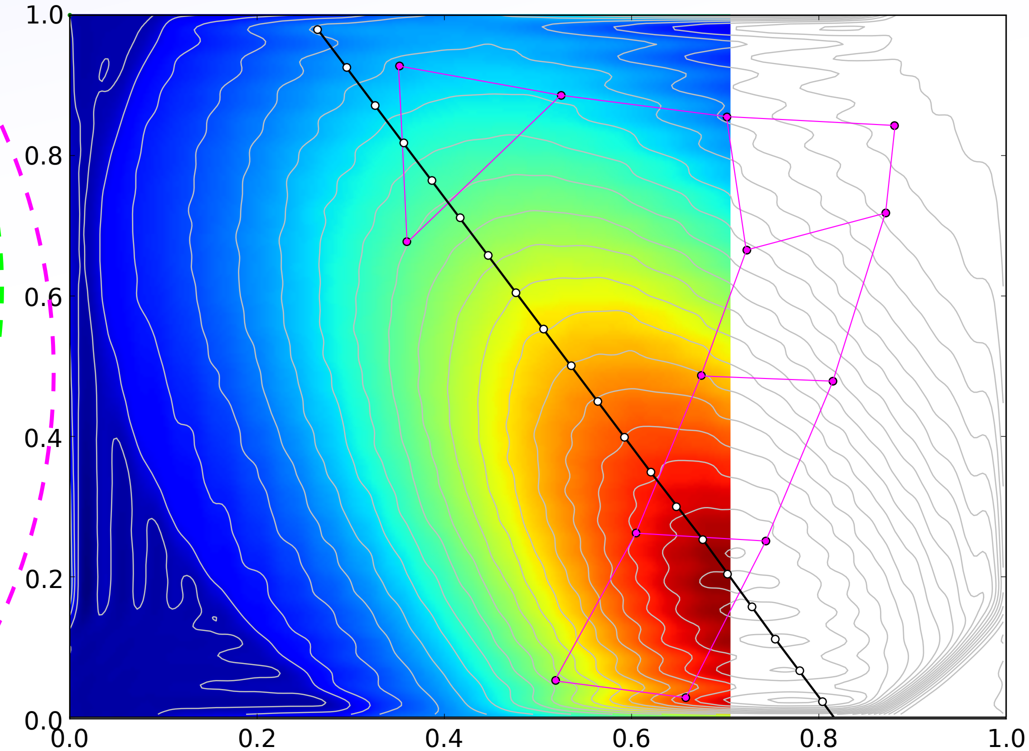
Which way is up? Raytrace vs Transform

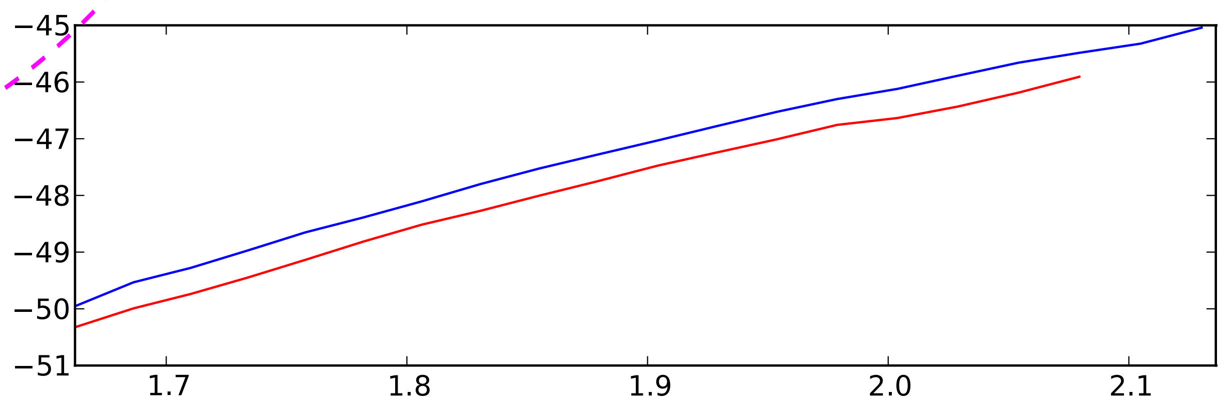
Ray trace 3D points to camera CCD through full optical chain. From spec (CAD, measured from diagrams, guessed etc) optics, points are a little out. These can be recovered by moving CCD from the axis (which I know is at least slightly wrong) and/or by tiling/shifting mirror (which is also likely to be wrong). Entirely by mirror requries < 1° rotation.
Once achieved, the beam axis can also be ray traced and compared to the beam emission pattern:





The change to polarisation from such a change in the mirror is significant (~0.5°) but it doesn't change the variation much (< 0.1°).

In this case, this is probably due to the CCD being off-centre by ~1mm, which is consistent.



Ray traced window hole.

Window aperture was a crude estimate from a CAD diagram and is probably wrong.

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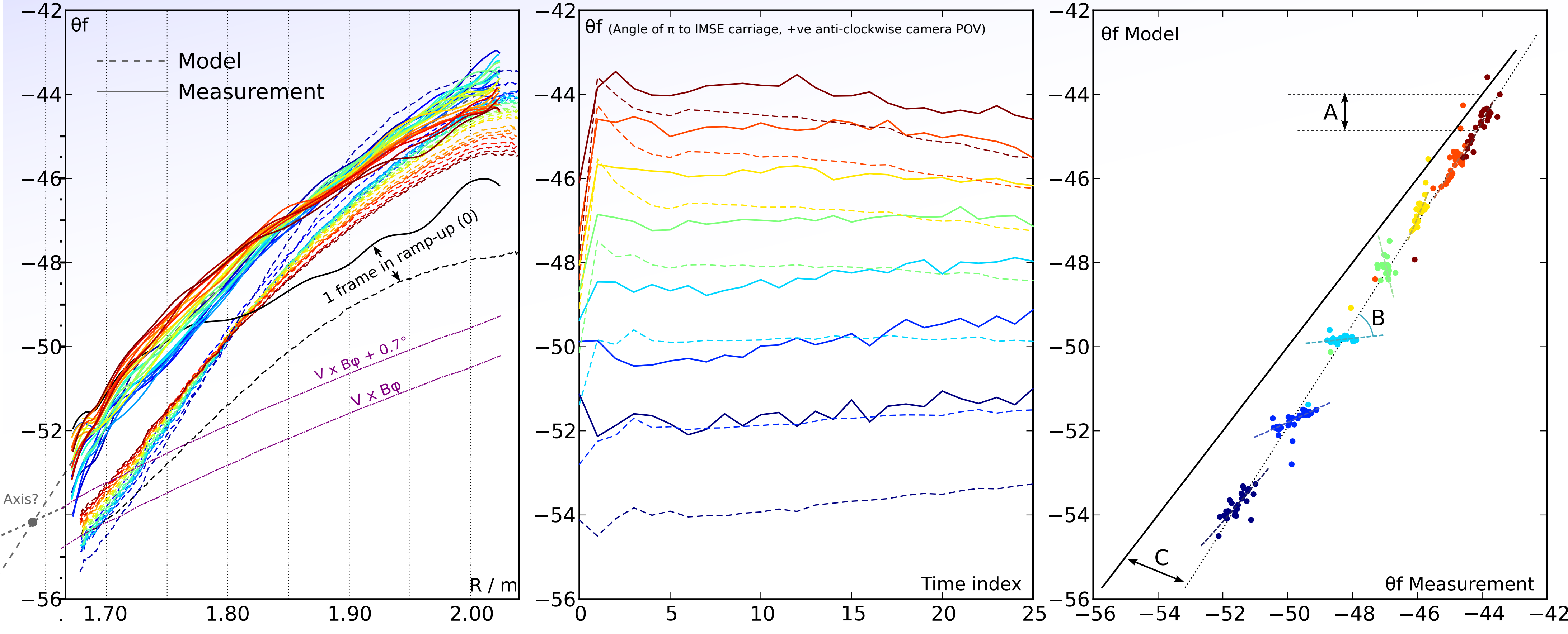
Which way is up? Part 13. Raytrace Match

Connected ray tracer into forward model (Minerva). This now produces the polarisation image including everything known.
(Fresnel effect is turned off due to the belief that π/σ effects roughly cancel).
The fully automated match for the current ramp down now look like this:



From this, we can begin to asses what cannot be due to the instrument response (i.e. must be equilibrium errors)

A) Offset at edge - Almost certainly instrument - known by total Ip, from 'which way is up' story, surprising it's within ±10°.

B) Point non-linearities in centre - Mid-radius, too steep to be μ, *measurement* changes, so must be equilibrium error.

C) Global sweep - Might be instrument linearity (μ value, and/or μ FOV variation) - possible, but shouldn't be this big.
Could be error in magnetic axis position in equilibrium - possible but would need R0=1.64m.
This can be tested with the current tomorography (±equi).
Could be errors in 'which way is up' - something missing, inaccurate mirror angle?? - can't think of anything else right now.

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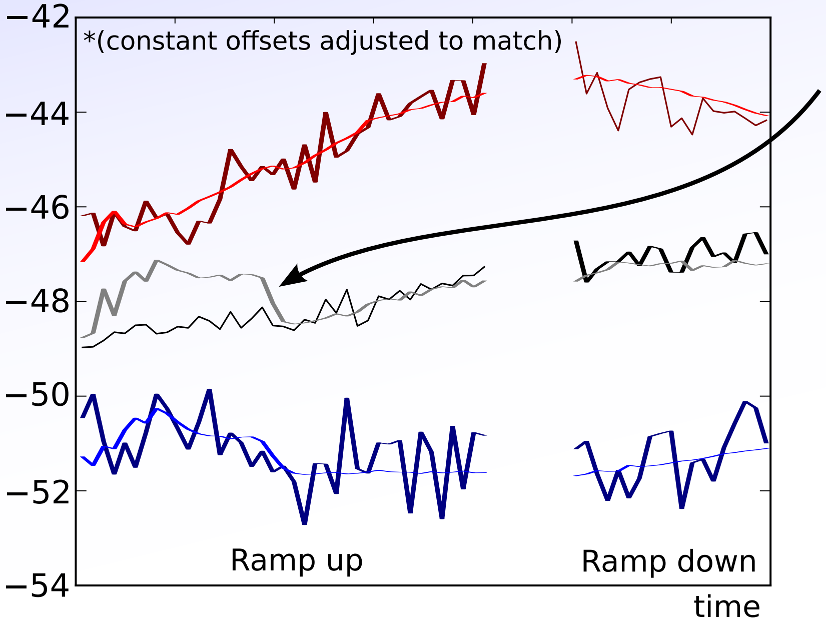
Which way is up? Part 14. Raytrace Match 2

Actually, it turned out to be due to too low resolution of the flux grid from which magnetic fields are calcualted.

A different shot, with long current ramp-up phase:



Equilibrium based prediction shows
a jump during current ramp, when none
is in measurement, so this is definitely not real