Max-Planck Institut für Plasmaphysik

Full 3D Ray-tracer for optical diagnostics.
- (I)MSE optical design, analysis and investigations.

IPP Greifswald, December 2013

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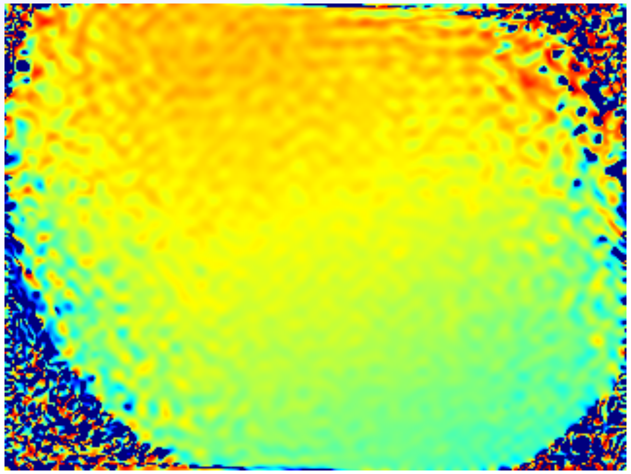
- IMSE:
  - Status and issues
  - Geometric effects on polarisation.

- Ray tracer:
  - Basics / Features
  - Structure and components
  - PSF Interpolation
  - Optimisation

- Use of ray tracer for (I)MSE:
  - Image fitting
  - Preliminary design of the new IMSE.

IMSE Status



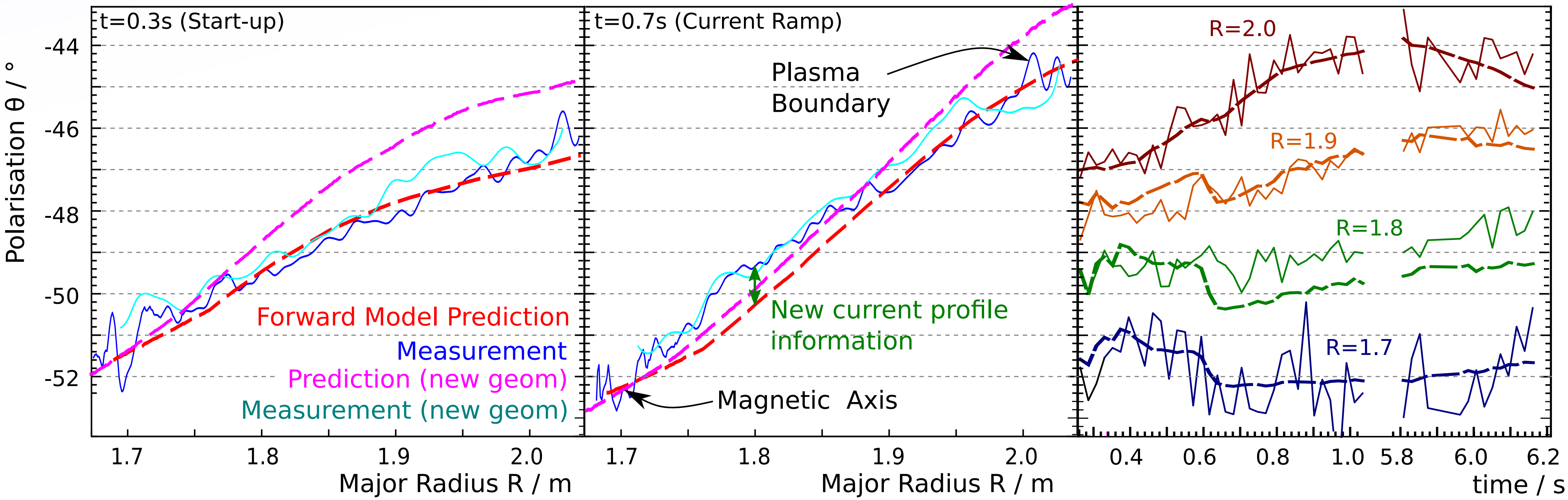
- IMSE thoroughly tested at HGW and operated twice at ASDEX Upgrade.
- Calibration issues resolved, polarisation measurement is working well.
- Diagnostic agrees with MSE measurements.
- Data was quite noisy but will be improved (S/N ~ x10) in next experiments (April 2014) with a better camera.

Now I have the usual MSE problem:

polarisation --> pitch angle --> Bz --> jφ

The first step is hard - no one has ever succeeded in showing the expected MSE angles from an in-vessel absolute calibration

For the EPS, I showed good agreement with the equilibrium based prediction in the core, and at the edge:



However, we have now improved the geometry and optics information ....
The model prediction has changed and it no longer agrees.

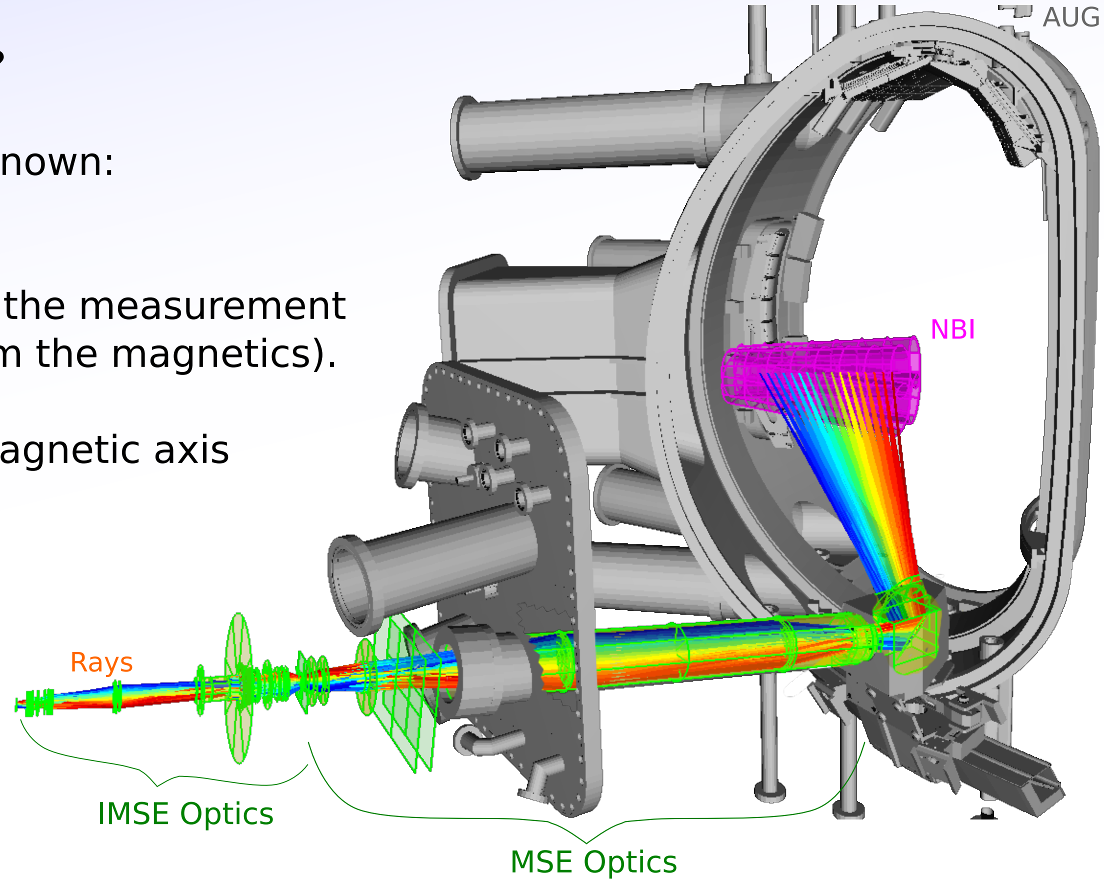
(I)MSE Geometry

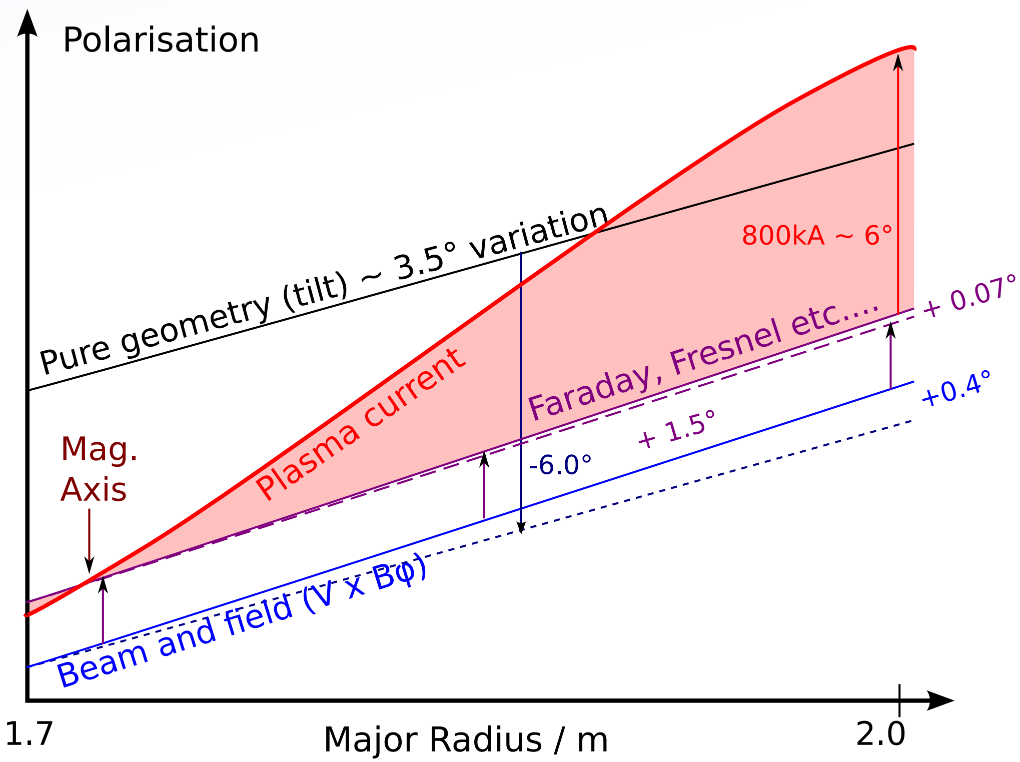
- Why does the prediction change with the geometry?

The first two orders of the polarisation profile are unknown:
0^{th}: Offset, 1^{st}: Linear variation

The offset is effectively unknown, but can be fixed to the measurement at the edge (as the edge field should be accurate from the magnetics).

The 1st order variation now related to knowing the magnetic axis position (which is accurate to ±5cm)

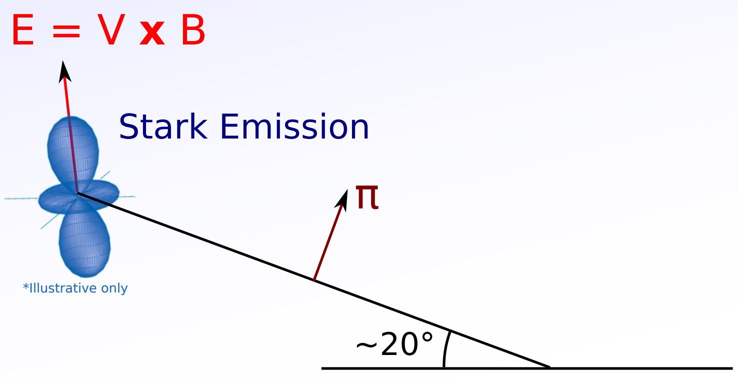




What is the 'pure geometry' variation? ...

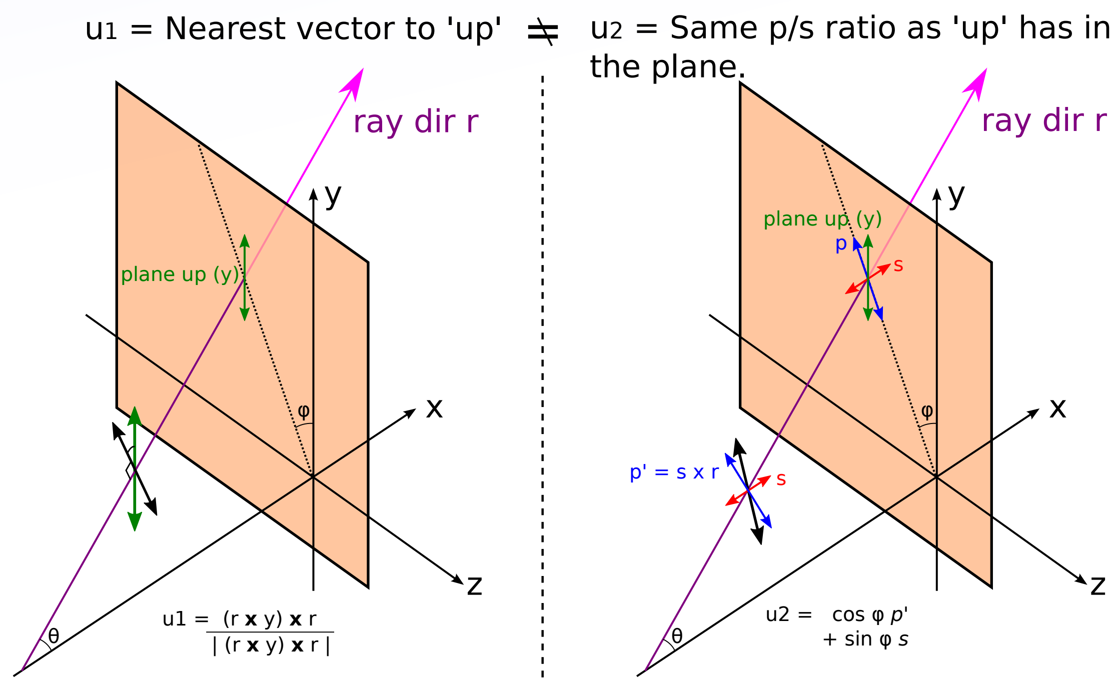
Polarisation Tilt

The MSE polarisation is generated by state transitions in a uniaxial system - only the Stark 'E' field gives a preferred direction, which is ~vertical.
The line of sight is at 20° to the horizontal but the polarisation state must be prependicular to it.
The projection is just the nearest vector to E, that is perp. to the line.



We could define 0° to be the closest vector to 'up' (Z) that is perpendicular to the line of sight.

However, diagnostics measure against a single plane for all lines of sight, and the 'up' projected into the plane changes. The variation depends on θ and φ of the ray with respect to the plane.

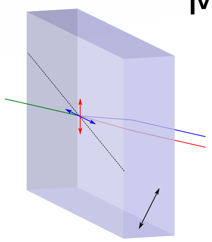


For the (I)MSE, this is after a mirror, several lenses and the V, B and E all change directions across the field of view.

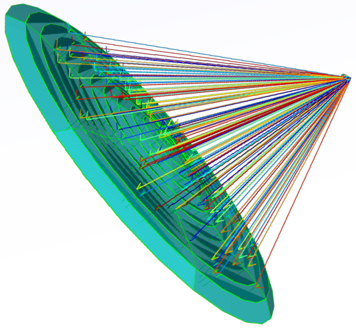
The easiest way to deal with it all is to ray-trace everything as part of the forward model.

The Ray Tracer

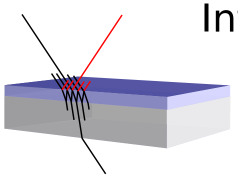
Full 3D geometric optics ray tracer.
- Polariastion aware (coherent / incoherent)
- Recursive mulitpath or fast sequential tracing.
- No GUI, but does output SVG and VRML files of optics and rays.
  VRML files can be viewed in Sergey's 'wendel' program, along with all the W7X and AUG CAD models.
- Written in Java with a simple architecture, all the work done is in modular components so very flexible.



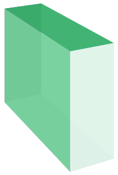
Media:
- Isotropic
- Uniaxial
- Isotropic in magnetic field (Faraday rotation).



Surfaces:
- Plane: (Circular, Rectangular, Triangular, Iris)
- Dish (Spherical cap)
- Cylinder
- Aspheric Dish (parametric f(r))
  + any for which you can solve the intersection point with a ray



Interfaces:
- Isotropic-Isotropic:
  - Ideal (non-reflective).
  - Standard Fresnel,
  - Anti-reflection coatings.
- Isotropic - Uniaxial:
  (Solutions for Birefingent Fresnel coefficients)
- Ideal Reflector ($\pm\Delta\varphi = \pi$)
- Ideal Polariser (s/p)
- Ideal Absorber



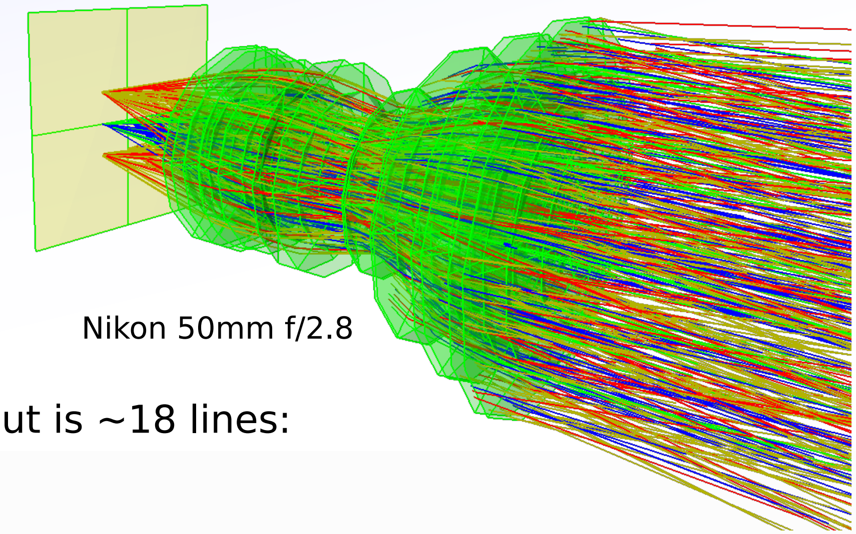
Materials (glasses):
- Fused Silica, Crystal Quartz, BK7, Calcite,
- Lithium Niobate, Barium Borate,
- Yttrium Orthovanadate
- Schott SLF6 (the magic low Faraday rotation glass).
  +Basic fixed index and dispersive glass.
  +Table/interpolation based.
  +Sellmeier formula based.

Ray-tracer: Compound optics

Various compound optics classes are also provided:

- Simple double convex lens.
- Double Gauss lens.
- Lens surface sequences (+ loading from Zeemax files)
- Some photography lenses from Patents (+fitting):
    - Schneider 25mm/0.95
    - Nikon 50mm/1.1
    - Nikon 105mm N2
    - Nikon 135mm/2.8
    - Canon 200mm/2.8
    - Nikon 28 200mm

VRML Output (via *wendel*):



Nikon 50mm f/2.8

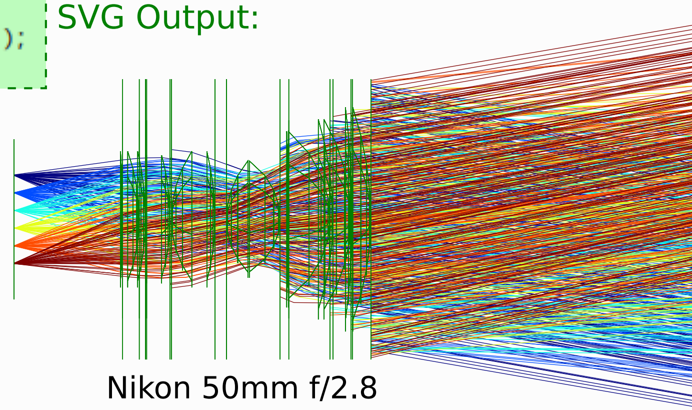
For basic ray tracing / imaging, to produce the VRML/SVG output is ~18 lines:

```
/** Shortest possible code to produce a nice imaging SVG
 * @author oliford  */
public class SuccinctImagingSVGExample {
    final static String outPath = MinervaOpticsSettings.getAppsOutputPath() + "/rayTracing/succinctImaging";
    final static int nRays = 500;
    final static double z[] = OneLiners.linSpace(-0.2, 0.2, 6);

    public static void main(String[] args) {
        Nikon50mmF11 lens = new Nikon50mmF11(new double[]{ 1, 0, 0 });
        Square imgPlane = new Square("imgPlane", new double[]{ 1.0526, 0, 0 }, new double[]{ -1, 0, 0 }, new double[]{ 0, 1, 0 }, 0.040, 0.040, Absorber.ideal());
        Optic all = new Optic("all", new Element[]{ lens, imgPlane });

        double col[][] = ColorMaps.jet(z.length);
        SVGRayDrawing svgOut = new SVGRayDrawing(outPath + "/imgTest", new double[]{ 0, -1, -1, 2, 1, 1 }, true );
        svgOut.generateLineStyles(col, 0.0002);

        for(int iZ=0; iZ < z.length; iZ++) {
            for(int i=0; i < nRays; i++) {
                RaySegment ray = new RaySegment(new double[]{ 0, 0, z[iZ] }, lens);
                Tracer.trace(all, ray, 30, 0.01, true);
                svgOut.drawRay(ray, iZ);
                Pol.recoverAll();
            }
        }

        svgOut.drawElement(all);
        svgOut.destroy();
    }
}
```

Optics definition

SVG Output:

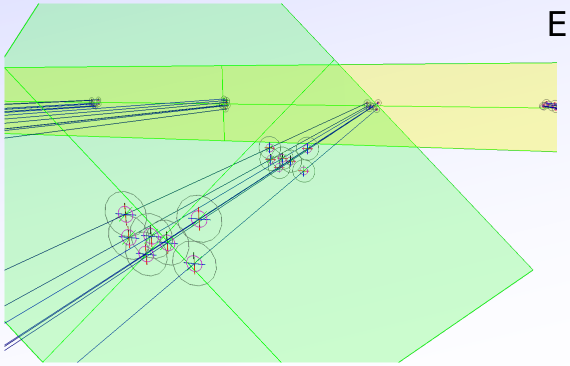
Ray tracing



Nikon 50mm f/2.8

Ray-tracer: Polarisation

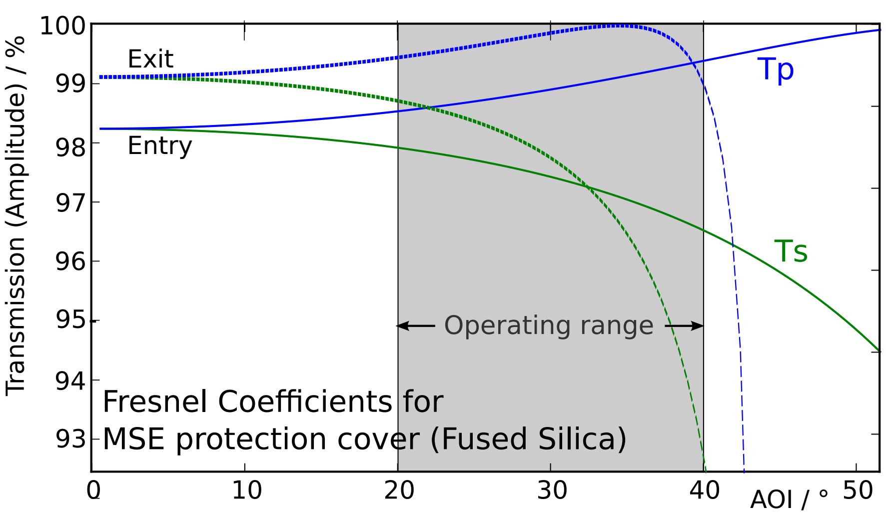
Polarisation states are held as multiple complex states, remaining fully coherent along each ray.
For ease of calculation, each ray segment has a unit vector for it's sense of 'up'

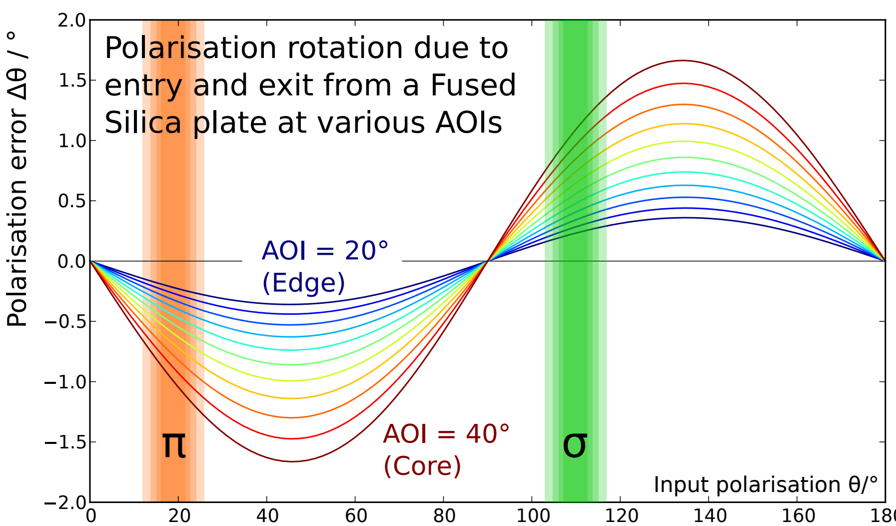


E = double[] { $\begin{bmatrix} \Re(E_u) \\ \Im(E_u) \\ \Re(E_r) \\ \Im(E_r) \end{bmatrix}$, ... }

For linear behaviour, 4 states are used to calculate the effective Müller matrix of the system.
Otherwise, any desired set of polarisations can be used.

Normal glass partial reflections (i.e. Fresnel coefficients) give a non-linear rotation... (video).
For the MSE, we have a Fused Silica protection cover (possibly with Boron/plasma coating).
The MSE collects only σ, so this is significant. For the IMSE, the ray tracer says we could have have a partial immunity since we collect roughly equal σ and π.

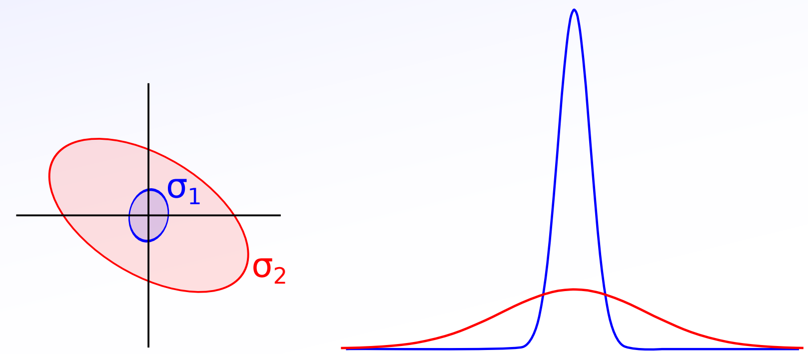




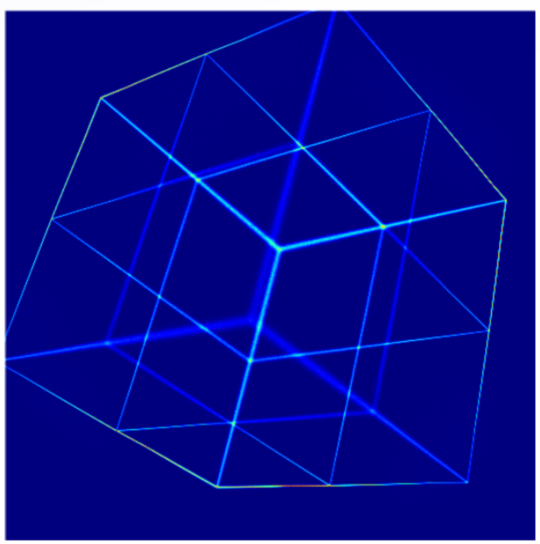
Ray-tracer: PSF Interpolation

To use as part of a forward modelling for an imaging system, the ray tracing is usually too slow.

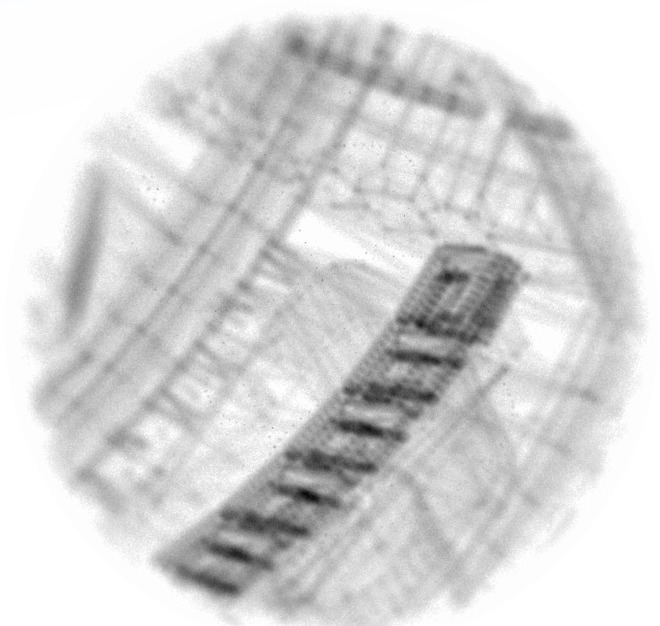
Instead, it can collect statistics of Point Spread Functions (PSFs) for a given 3D object grid and the respective Müller matricies and interpolate these for fast imaging later:



DoubleGaussianPSF



PSFImagingExample



Raytraced CAD for IMSE background
(calculated before first experiment)

IMSE background Image

Ray-tracer: Optimisation

The Minerva optimisation library [J. Svensson, A. Meakins] is also integrated, so it is relatively easy to optimise any set of parameters to any desired cost function. Some basic optimisationsare already included:
- Autofocus (moving elements).
- Determining unknown lens propeties (e.g. refractive indices) by fitting target image properties.
- Aspheric surface optimisation for focusing and abberation reduction.

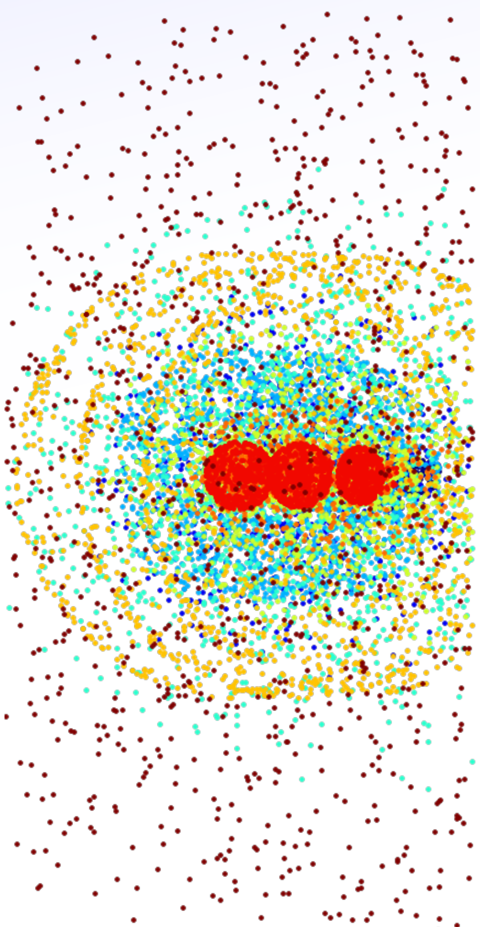
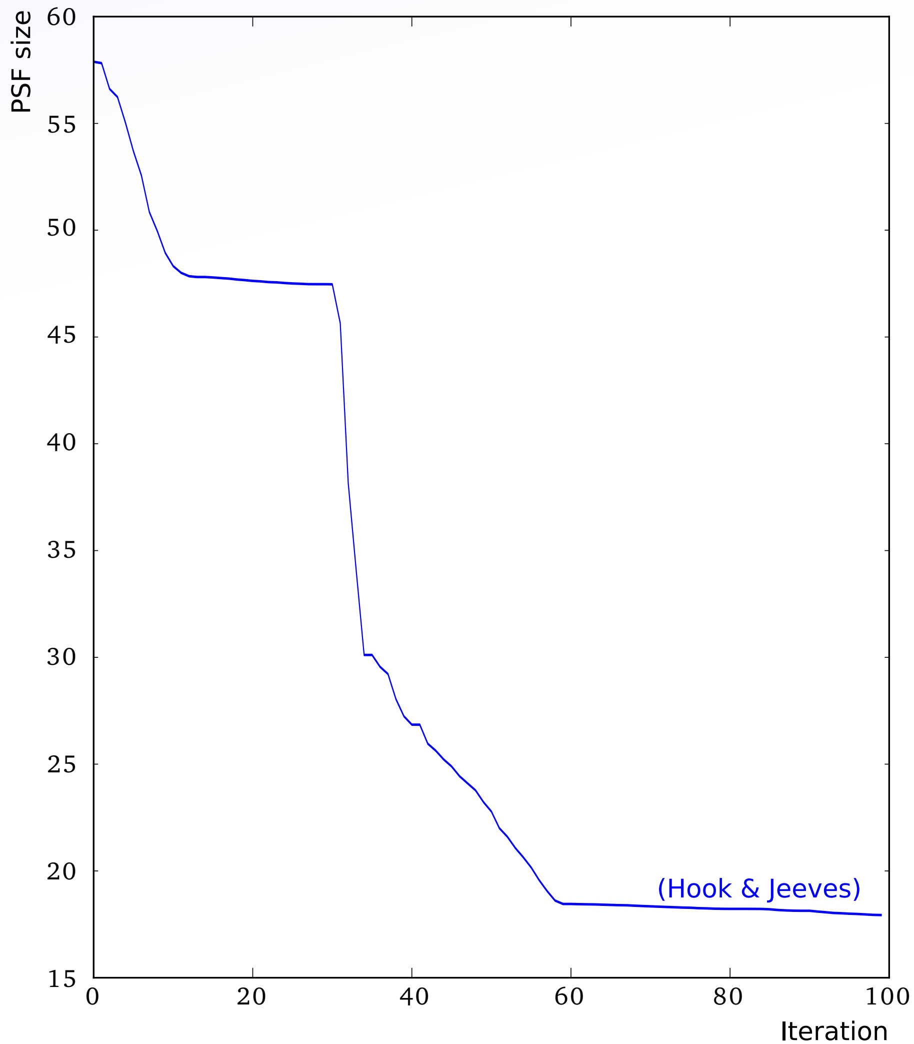
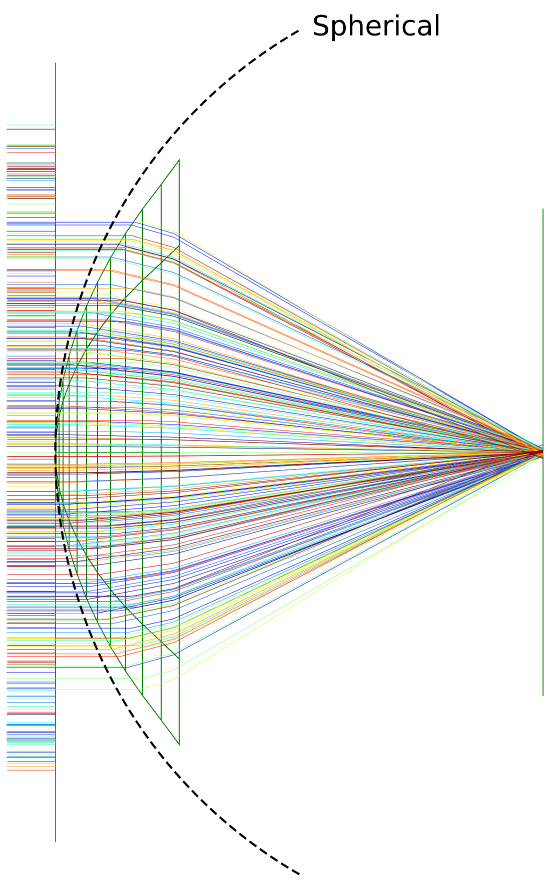


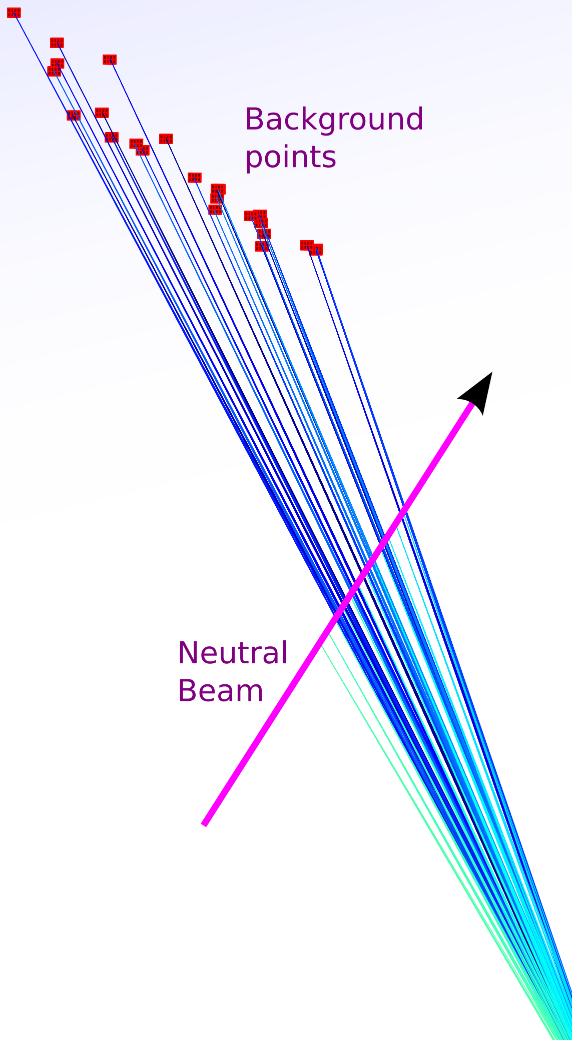
Image plane hit points.
(Color = iteration)



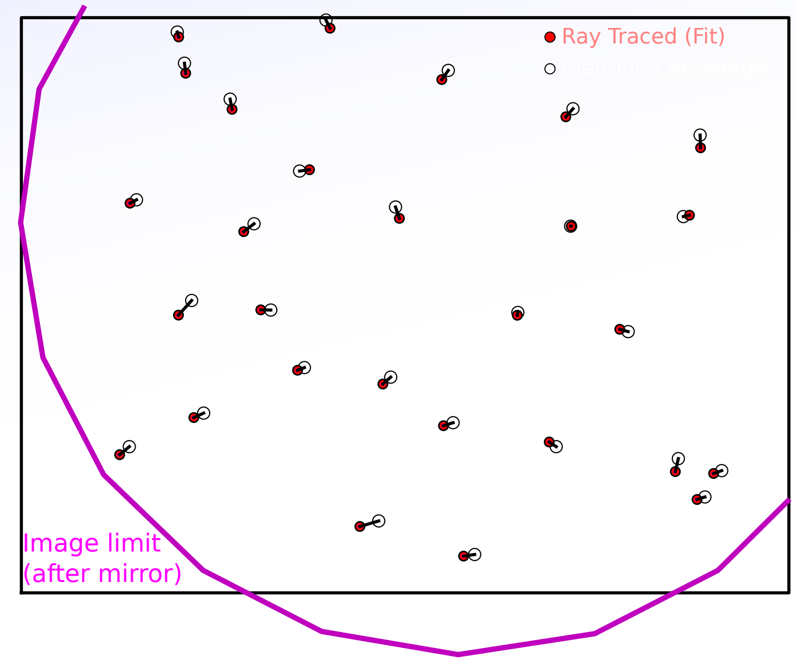


IMSE Transform ray-trace matching

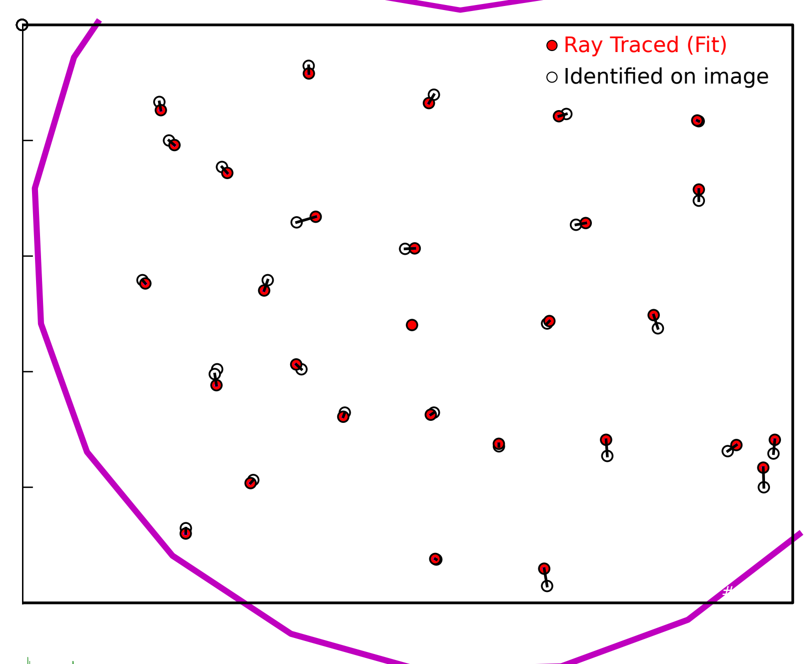
The (I)MSE mirror position and angle were not exactly known. To produce a working model, the optimiser can fit the CCD position to the image limit (which is after the mirror), and then fit the mirror angle to reproduce the observed background positions.

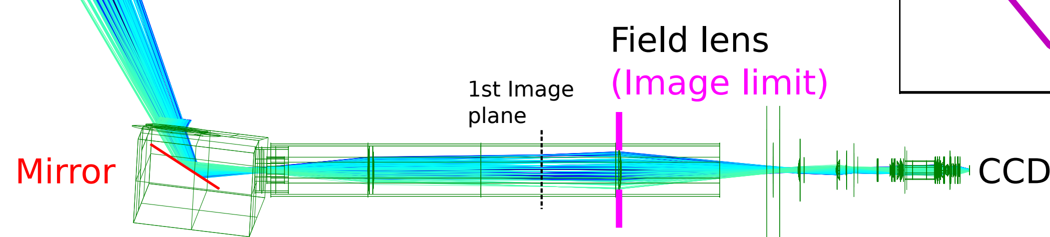


It's reassuring that only the unknowns need to be fit and everything else is already correctly reproduced from the CAD data:
- Deformation / aberration.
- Perspective
- Scaling / Limit sizes



For the later (April) experiments, the IMSE carriage was completely reassembled and refitted. Only the CCD position needed to be refit to recover a good match - confirms the mirror hasn't moved, and verifies the procedure to some extent.



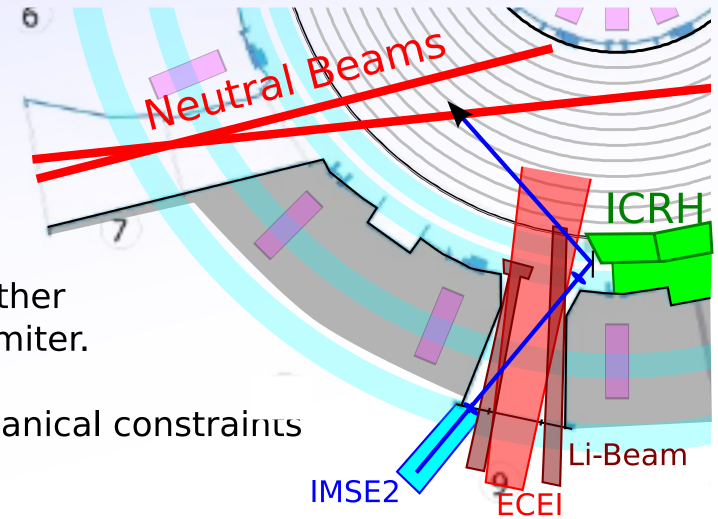


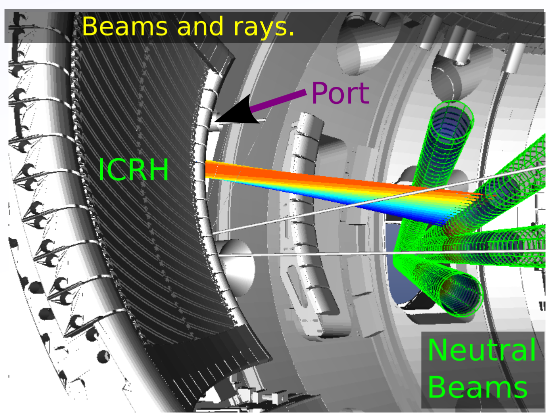
O. P. Ford, A. Burckhart, M. Reich

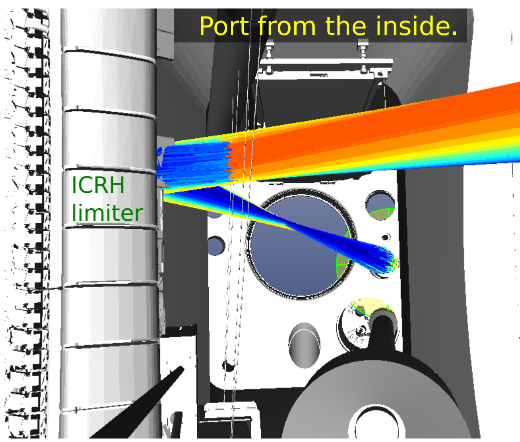
Permenant IMSE Preliminary Design

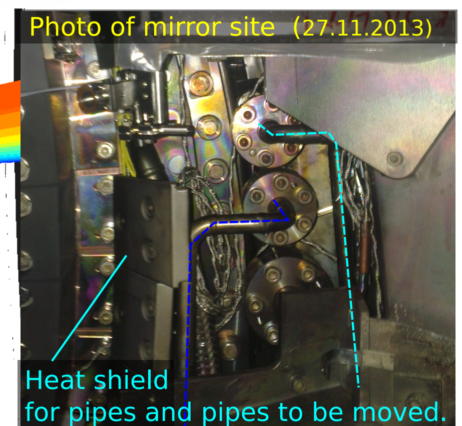
Due to the success of the prototype, ASDEX Upgrade will install a permenant IMSE system in 2015. Port space at AUG is very limited and we will be restricted to the entry port, shared with the Lithium beam, ECE imaging thermography and other diagnostics. Avoiding the ECE lines of sight is not possible with a normal design (full optics tube etc) but by investigating with the CAD data and ray tracer all in 3D together reveals a possible option of crossing the port via a mirror tucked behind the ICRH limiter.

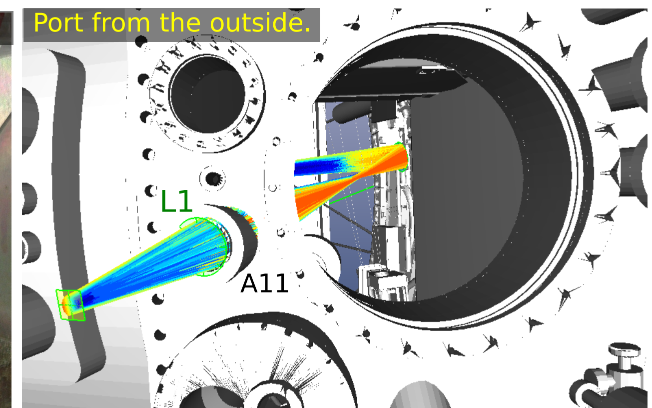
Optimising the optical system within the IMSE forward model, bounded by the mechanical constraints leads to a more compact system than the standard MSE.



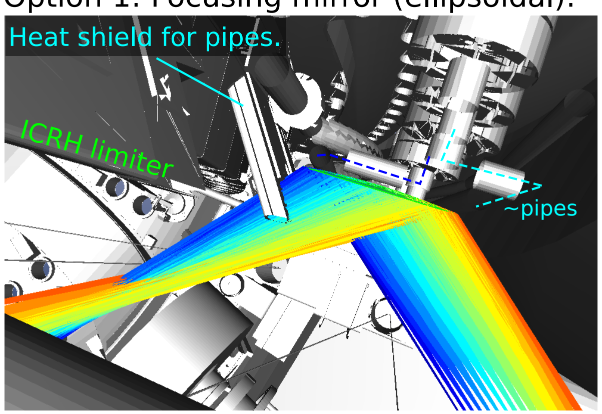




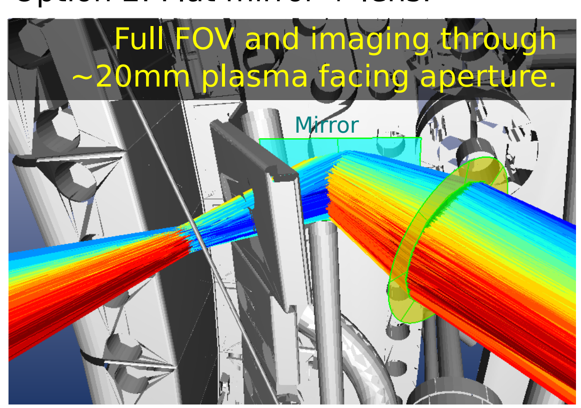




Option 1: Focusing mirror (ellipsoidal):



Option 2: Flat mirror + lens:



Avoid the ECEI lines of sight: