3rd IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis

Forward modelling for the design and analysis of polarisation imaging diagnostics.

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ASDEX Upgrade has an existing 10-channel MSE system.

- Hα/Dα beam emission is Doppler shifted and split by the Motional Stark Effect into $\pi$ and $\sigma$ components.

- Components are polarised perpendicular and parallel to projected $v \times B$ direction:

Image of the beam emission using a CCD camera, > 60x60 $\theta$ measurements.

Replaced the MSE for two short periods of plasma operation to test the basic principle.
Prototype IMSE Design

Prototype IMSE designed to match end of existing optics.
- Ray tracing of existing optics performed in 3D.
- New optical system matched to light delivered by existing optics.

Determination of:
- Optimal collimation/imaging lenses
- Optimal interference filter
- Expected polarisation angle
Ray-traced forward model

To fully understand effects of optics, everything put into ray-tracing model:

1) Field of view effects:
   - Subtlety of how polarisation is created, defined and measured.

\[ \mathbf{E} = \mathbf{V} \times \mathbf{B} \]

Stark Emission

\[ \theta \approx 20^\circ \]

\[ \mathbf{u}_1 = \text{Nearest vector to 'up'} \]

\[ \mathbf{u}_2 = \text{Same p/s ratio as 'up' has in the plane.} \]

**POLAR consistent**

**PLANAR consistent**

Various definitions of \( \theta = 0 \) at beam traced to to MSE measurement plane.

Vertical E field:

Polar definition from global vector 'up' for every individual ray.

Vertical polariser:

Planar definition to a plane perpendicular to the central ray of the central bundle.
Polarisation effects

To fully understand effects of optics, everything put into ray-tracing model:

2) Faraday rotation
   - Fields due to both:
     - TF coils: Strong, but static
     - PF coils. Weak, but time-varying.
Polarisation effects

3) Fresnel coefficient effects (e.g. uncoated protection cover)
   - Variation of transmission/reflectance with AOI --> Non-linear rotation of polarisation

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**Graphs:**

- **Transmission (Amplitude) % vs AOI:**
  - Entry and Exit curves show variation with AOI.
  - Ts and Tp curves indicate non-linear rotation.

- **Polarisation error Δθ °:**
  - Mostly cancels for σ+π (IMSE), but important for MSE.

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**Equations:**

- \( \tan(\frac{B_z}{B_\varphi}) = 0° \)
- \( \tan(\frac{B_z}{B_\varphi}) = 20° \)

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**Notes:**

- Fresnel coefficient effects for polarisation imaging diagnostics.
- Non-linear rotation of polarisation due to AOI variation.
- Important considerations for uncoated protection covers.
4) Mirrors
- Simple ‘ideal \( \pi \) phase shift’ for dielectric mirror.
- Lated with measured spectro-polarisation transfer properties of mirror.
5) Mechanical angles/positions
- Angle/position of camera - Measured with uncertainties
- Small inaccuracies in lens/mirror positions - fitted...
Ray-tracing match

- Fit mechanical model parameters to match ray-traced CAD 3D points.
- Match vignetting curves from different stages in system
  --> Determines most mechanical parameters.

Correctly predicts beam emission intensity axis:
Model agreement

- Final prediction entirely without calibration within ~0.7° of measurement.
- Remaining uncertainties only affect offset.
- $d\theta/dr$ most important - well modelled.

Forward Model

Measurement

Plot showing polarisation angle $\theta$ as a function of radius $R$.

Graph showing measured and predicted polarisation angles with a predicted offset of +0.7°.
Model agreement

- Remaining disagreement is largely what is unknown in equilibrium code.
- Different beam geometries also approximately predicted
  --> Confirmation of geometric effects, variation over image etc.

![Graphs showing polarisation θ° over time and radial distance R/m for different beams and times.](image)
FusionOptics Ray Tracer

- Ray tracing core is a relatively simple to use Java library.

```java
/** 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) {
        Nikon50mmF1 lens = new Nikon50mmF1(new double[][]{{1, 0, 0}});
        Square imgPlane = new Square("imgPlane", new double[]{-1, 0, 0}, new double[]{-1, 0, 0}, new double[]{-1, 0, 0}, 0.04, 0.04, 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

SVG Output:

VRML Output - Can be loaded into FreeCAD or CATIA
Many optimisation algorithms available (Hooke & Jeeves, Genetic Algorithms, ...), so easy to optimise any parameters to any cost function. e.g:
- Auto-focus (moving elements).
- Determining unknown lens properties (e.g. refractive indices) by fitting measured image.
- Aspheric surface optimisation for aberration control.
Imaging approximation

- High speed re-imaging:
  - Ray trace 3D grid in object space \((x,y,z)\)
  - Characterisation of point spread function in 2D image space \((x', y')\)
  - Average Müller matrix derived from propagation of 4 polarisation states (i.e. linear approx)

\[
\begin{bmatrix}
<x' > \\
<y' > \\
\sigma_{x'} \\
\sigma_{y'} \\
\sigma_{x'y'} \\
M_{ij}
\end{bmatrix} = f(x, y, z)
\]

\[E = \text{double}[] \left\{ \Re(E_u), \ldots \right\} \]

Polarisation states displayed in 3D output
FusionOptics Ray Tracer - In place design

Has now been used for optical design/analysis of various systems at IPP:
- Permanent IMSE at ASDEX Upgrade:
  - Complex multi-component system, fully maintaining polarisation and image quality.
  - 3 Spheric lenses, 2 Aspheric, 2 compound objectives.
  - 3 dielectric mirrors
FusionOptics Ray Tracer - In place design

Has now been used for optical design/analysis of various systems at IPP:
- CXRS at W7-X: Full optical system design.
- Thomson Scattering at W7-X [A. Dal Molin]: Bremsstrahlung calculation and filter optimisation.

Minimal window exposure:

Fibre head design for optimal focus:

Fit model alignment from backlighting:
ITER Flow Monitor

ITER ‘Flow Monitor’
- Coherence imaging system for SOL impurity/bulk flow.
- Use polarisation to discriminate reflections.
- Several other measurements simultaneously.

Optical relay

Predicted view of divertor
Summary

FusionOptics:
- 3D general ray-tracer developed for design/analysis of optical diagnostics.
- Intended for coupling into diagnostics forward models.
- Simple modular object-oriented structure.
- Detailed treatment of many realistic components (mirror, lenses, glasses, filters etc)
- Good coupling to CAD programs.
- Full 3D treatment of polarisation states, easy to understand and visualise.
- Now used for several diagnostics at AUG and W7-X.

General:
- Fitting of known image points and vignetting/limit circles constrains many unknowns such that polarisation state is well predicted.
- Coupling of 3D ray-tracing and CAD allows easy simultaneous convergence of optic and mechanical design.
- Very complex optical chains can be handled without too much difficulty - (e.g. most optical ITER diagnostics)
- Small polarisation effects (~0.1°) are numerous, but can be modelled.
- Particular relevance for ITER Flow Monitor (coherence imaging / divertor viewing).
Image Transform

- Points with known 3D positions (CAD)
- Define affine/cubic transform directly \((x,y) \to (\phi, \theta) \to (R, Z)\)
- Fit unknown optics model parameters so ray-tracing matches:
  a) Camera position ±6µm
  b) Mirror angles ±0.1°
Sawteeth - Magnetic Reconnection

What do we see in the IMSE data?
- Sawtooth changes are very small - need good statistics.
- Average over Z near axis
- Synchronous average over many sawteeth in time.

Approx Current Density \( j_\phi \) / MA m\(^{-2}\)

Before crash

After crash

Invalid calibration

Current redistribution: \( \Delta j \approx 0.050 \text{ MA m}^2 \)

Measurements every ~3cm (resolution): \( \Delta(d\theta/dR) \approx 0.7^\circ \text{m}^{-1} \) --> \( \Delta \theta \pm 0.02^\circ \text{ required for } \Delta R=3\text{cm} \)
Shafranov shift:

Movement of plasma axis with pressure.
(including redistribution of fast-ions from neutral beam)

\[ E = v \times B + E_r \]

At some locations, \( \Delta E_r \) during sawtooth dominates measurement:
Integrated Equilibrium vs IMSE - Sawteeth

Required precision is so high, many other factors become important:

but...

we now have good agreement between full integrated model and IMSE measurements for sawtooth evolution in $\theta$.

- This is where we are - 'the state of the art ... science'

What next?

IMSE:
- Improve calibration systematics,

IDE:
- Modeling of effects.
- Tolerance to calibration systematics.

Converge
The crystal parallelism isn't enough to explain all of the magic number. E.g. United Crystals plate A has < 60° and is very flat in the middle (< 5° variation). That should give a constrast of > 98%, but the measured constrast is always below 90%.

So, there is more to the story....

Using a big sphere to light all of the CCD/lens and looking at the full 16mm CCD shows a consistent pattern:

United Crystals A

United Crystals B

CLaser Displacer