Magnetic field imaging at ASDEX Upgrade: The Imaging Motional Stark Effect diagnostic

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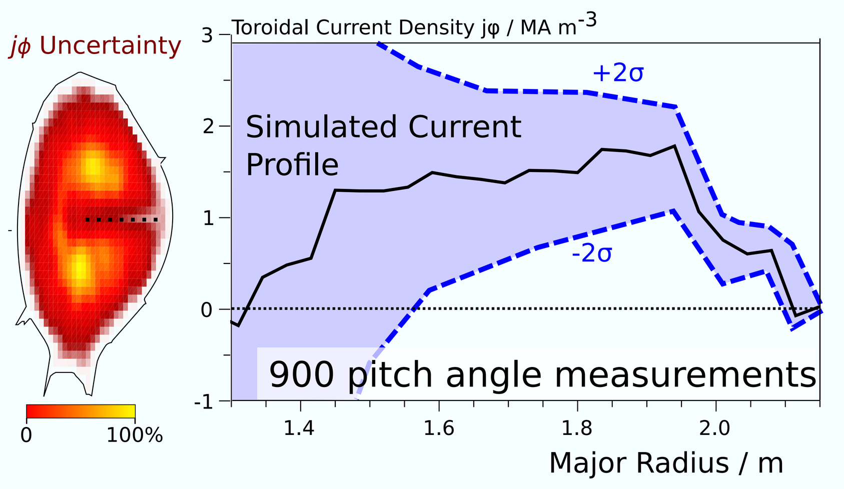
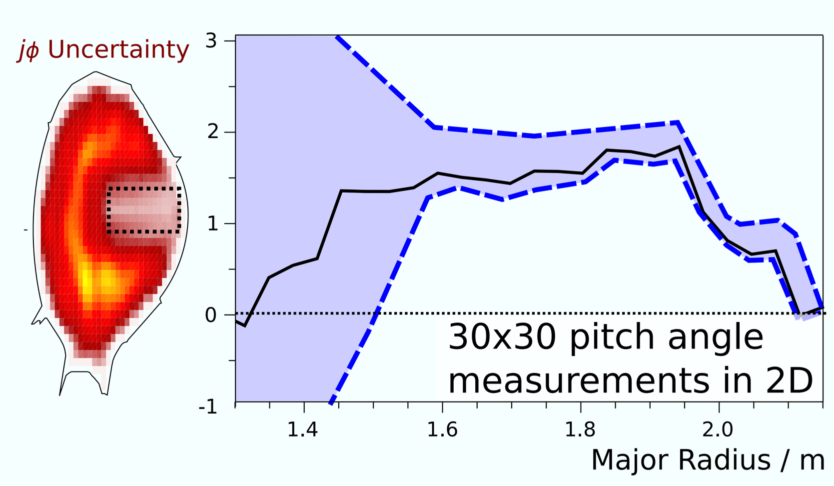
Imaging Motional Stark Effect (IMSE) is a new method of measuring magnetic field pitch angle for fusion plasma devices[1]. An image of a neutral beam is modulated with an interference pattern from which a 2D image of the pitch angle is inferred. The increase in data quantity, 2D nature, spectral insensitivity and hardware simplicity are among many benefits of IMSE over conventional MSE systems. An IMSE system was built and successfully operated at ASDEX Upgrade showing quantitative agreement with modelling and with the conventional MSE diagnostic.

Why 2D Measurements?

Diagnosis of the plasma current is of particular importance in Tokamak plasmas for analysis of stability, transport etc. Tomographic reconstructions of the plasma current[2] from simulated measurements tell us how useful these measurements are. Here, inference from an equal number of pitch angles on a line and in a 2D grid are compared:



Possible reconstructions of plasma current given external magnetics and a 1D line of 900 magnetic field pitch angle measurements.



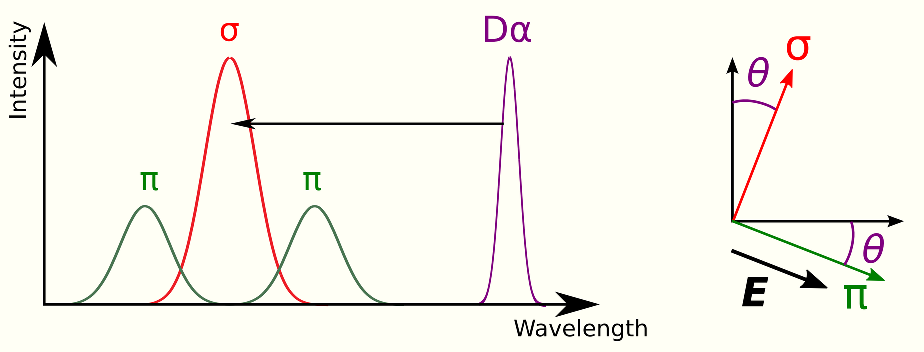
Reconstructions from an equal number of points spread out in 2D over a 30x30 grid. The inference improves dramatically.

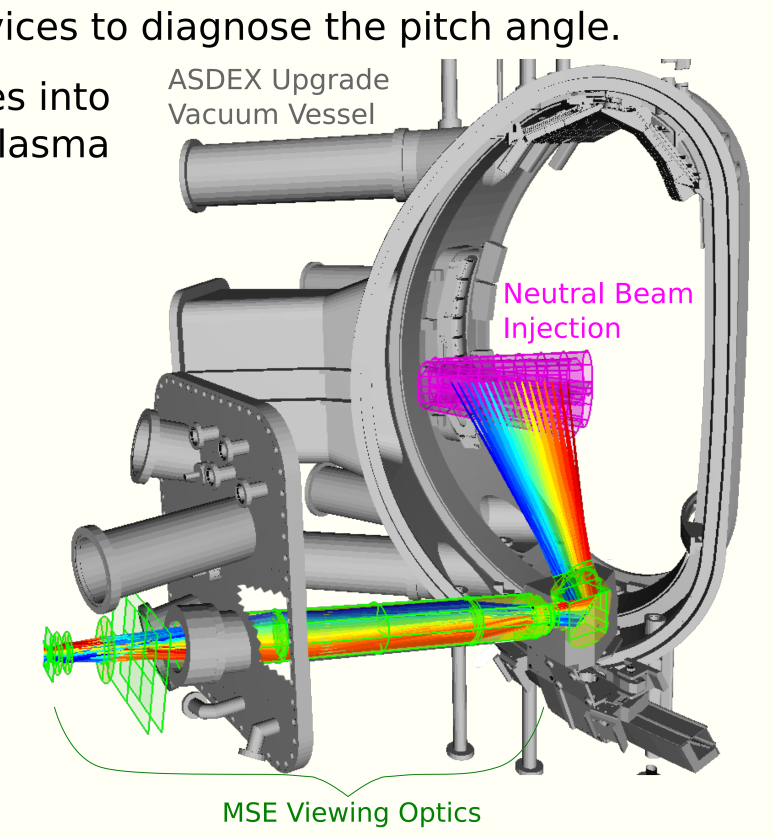
MSE: Motional Stark Effect.

The MSE diagnostic[3] is used on many plasma devices to diagnose the pitch angle.

A Neutral Beam Injector (NBI) fires neutral particles into the plasma. The particles are excited by the plasma ions and emit Dα radiation (Deuterium Balmer-α).

The line emission is Doppler shifted by the particle's motion and Stark split by the electric field in the rest frame of the atom ($\boldsymbol{E} = \boldsymbol{v} \times \boldsymbol{B}$), into two components:



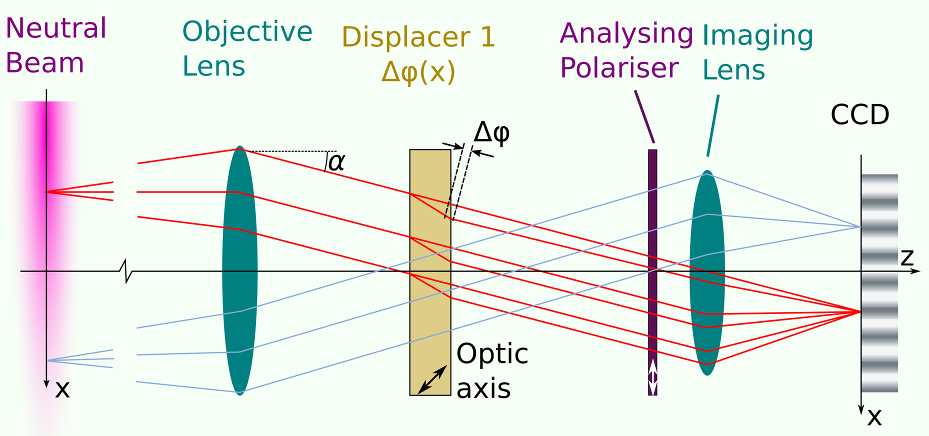


The π and σ components are polarised parallel and perpendicular to $\boldsymbol{E}$.
The direction of **v** is known, so by measuring θ, we can infer the direction of $\boldsymbol{B}$.

Conventional MSE polarimeters measure θ by spectrally selecting one component with a narrow filter and using e.g. a photo-elastic modulator (PEM) to analyse the polarisation. Because of the varying Doppler shift, each spatial point requires a very finely tuned filter, optics, sensor and digitiser. Typically only ~10-20 points are observed in a single line.

IMSE Diagnostic Principle

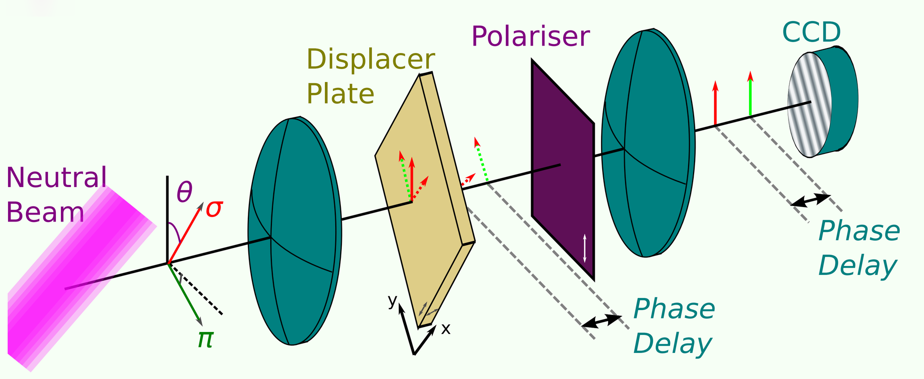
With Imaging MSE (IMSE), the neutral beam image is focused onto a CCD after passing through a birefringent *displacer* plate:



The displacer introduces a phase shift between polarisations that depends on the incidence angle α, and hence varies with image position x.

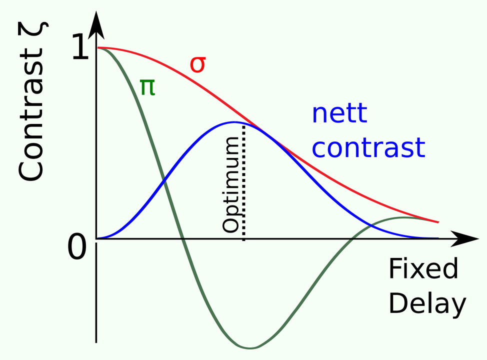
A polariser at 45° interferes the two components, producing fringes on the image. The fringe amplitude depends on the initial polarisation angle θ:

$$I \propto 1 + \cos 2\theta \, \cos(x)$$



For MSE, fringes from σ and π would cancel due to the 90° difference in θ. A thick delay plate is added so that the different wavelengths have different phases. The thickness is chosen so that the σ and π have the same phase again.

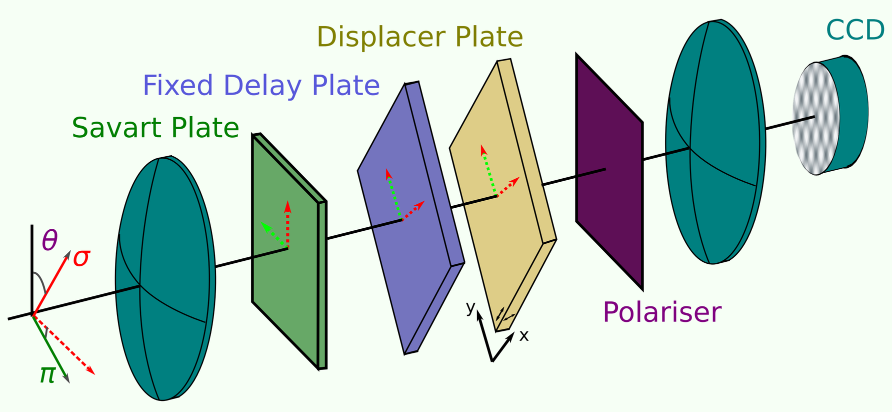
The fixed delay plate also causes wavelengths within the finite width of each component to interfere, reducing the amplitude. The combined effect is the spectral contrast ζ:



A second displacer plate (a Savart plate) produces orthogonal fringes and is placed with optic axis at 45° to the first so that it is sensitive to $\sin 2\theta$. The combined image is:

$$I \propto 1 + \zeta \cos 2\theta \cos(x) + \zeta \sin 2\theta \cos(x - y) - \zeta \sin 2\theta \cos(x + y)$$

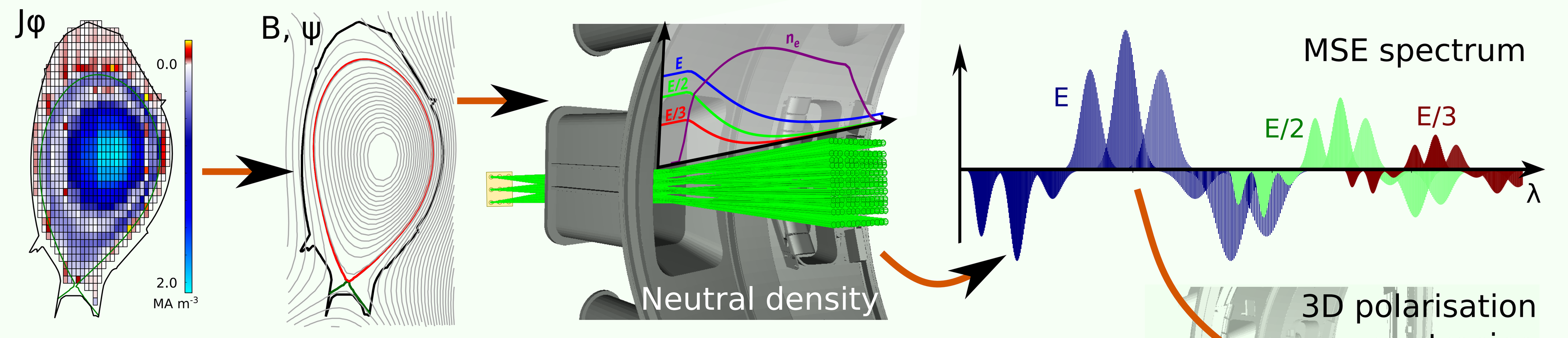
By dividing the amplitudes, the unknown ζ can be eliminated and an image of $\tan 2\theta$ extracted.

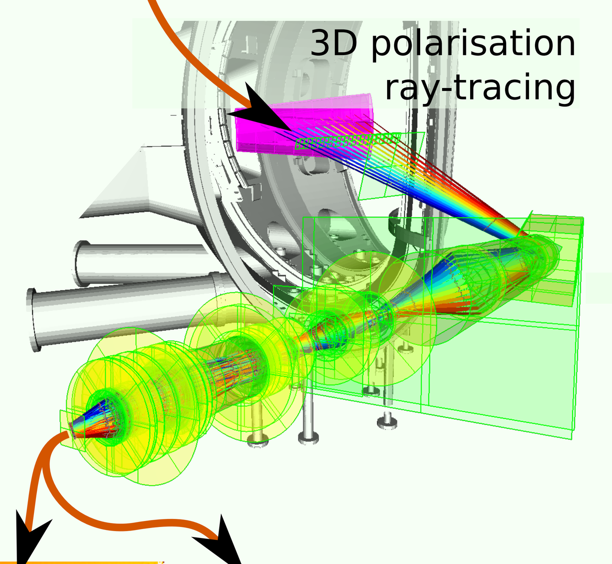


IMSE Advantages:

+ Better current inference: 2D Data.
+ Lots of data: > 60x60 θ measurements.
+ Simpler/cheaper hardware: One set of optics
+ More light: No narrow filters.
+ Only θ offset calibration required.
+ Insensitive to spectrum changes.

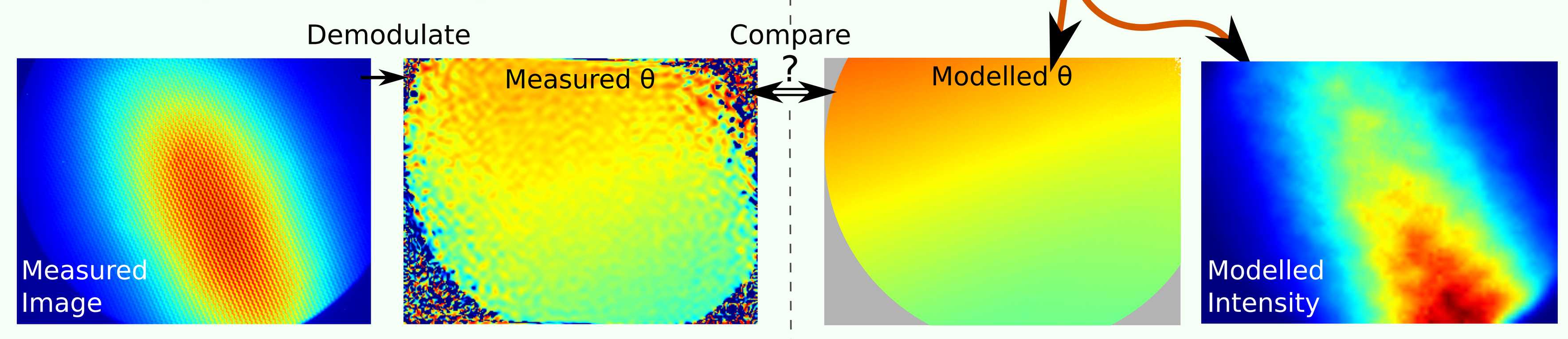
Detailed Forward Modelling





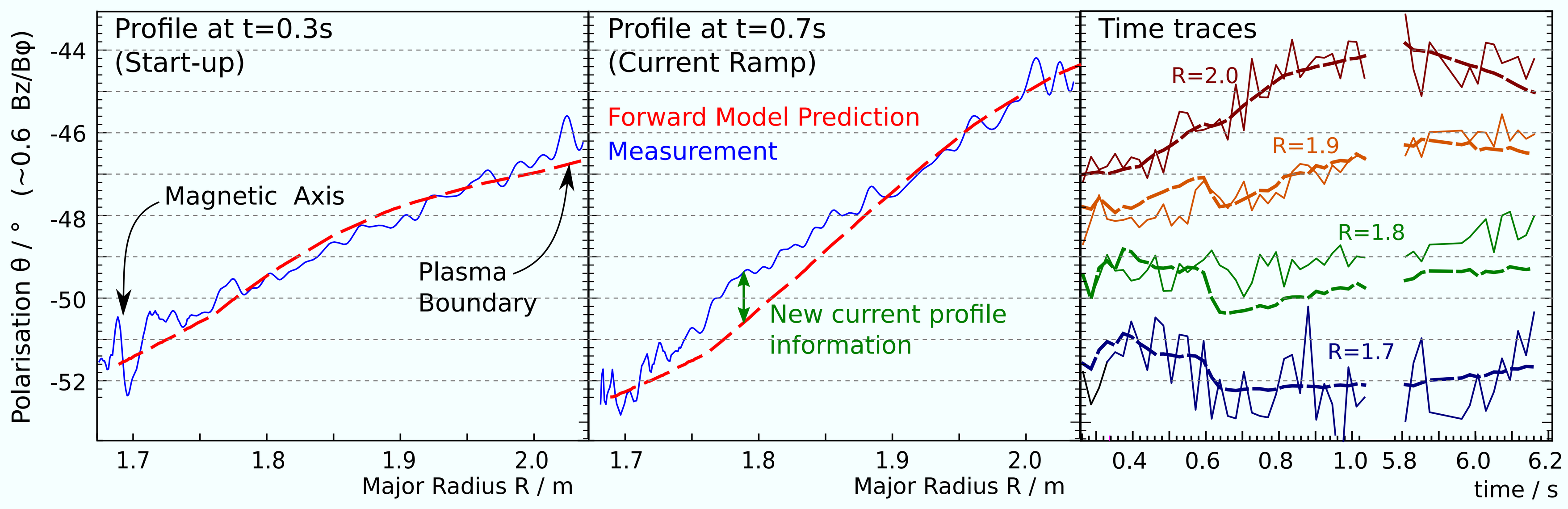
A detailed modular forward model is used both for the design and analysis of the diagnostic. It includes a general model of the plasma, neutral beams, MSE emission and a full 3D polarisation aware ray-tracing of the viewing optics.

A Bayesian inversion of the complete model can be used to infer information about the plasma current from the measured polarisation image.

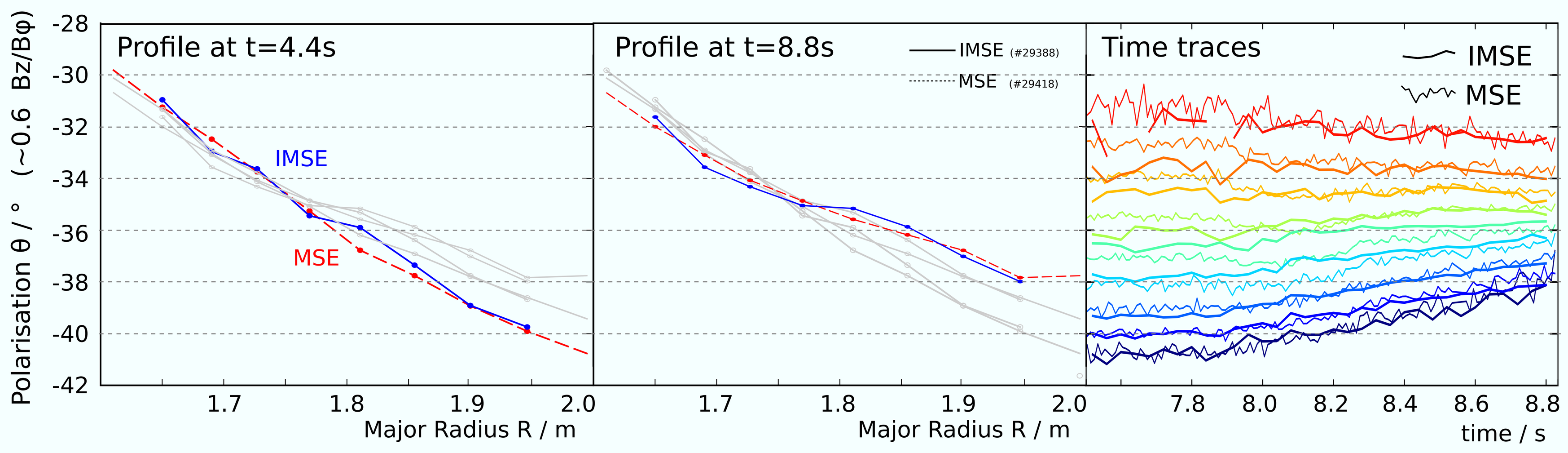


Initial Results (1D)

Based on an equilibrium solution for Jφ, the forward model accurately predicts the measured polarisation angle where expected (at the edge and in the core during low-beam power). The disagreement at mid-radius is useful information that will be used to constrain the current profile. A 0.7° offset has been removed. This is because the forward model is based only on the CAD and optics models - there is **no angle calibration** (yet).



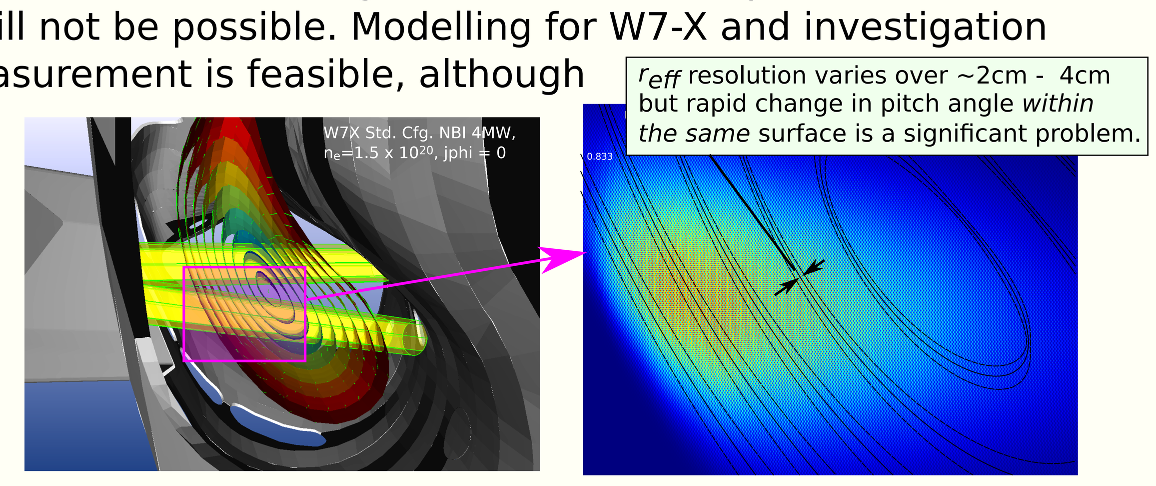
Further confirmation is seen in the comparison with the existing MSE polarimeter:



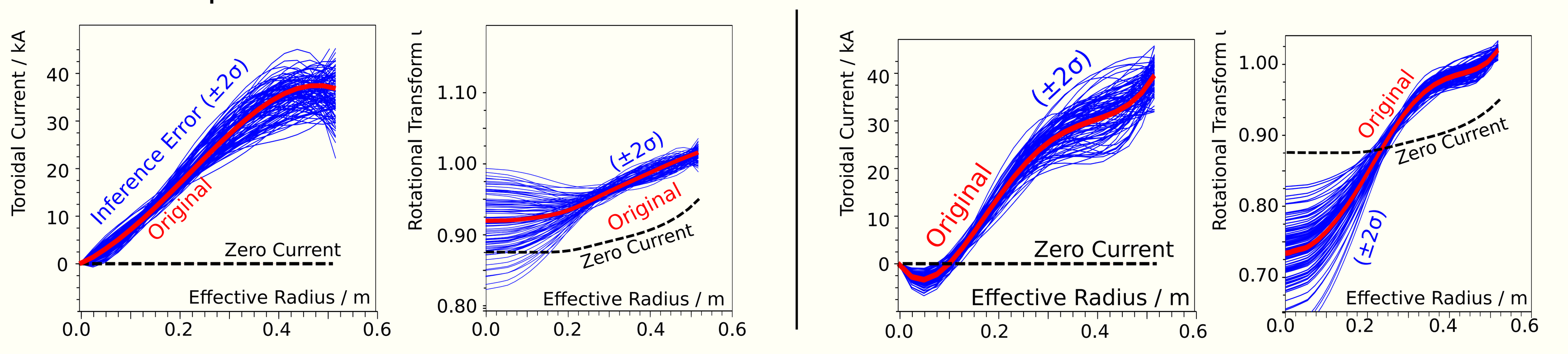
Modelling for Wendelstein 7-X

IMSE is also a prospective approach for measuring the small 'bootstrap' current in W7X, where a classic MSE system will not be possible. Modelling for W7-X and investigation of performance shows the measurement is feasible, although highlights a few particular problems for Stellarators:

r_{eff} resolution varies over ~2cm - 4cm but rapid change in pitch angle *within the same* surface is a significant problem.



Resolving changes of Δθ ~0.15° appears possible and would allow the inference of the magnitude and broad scale features of the current profile:



Status

- ✔ IMSE prototype was designed, built and installed at ASDEX Upgrade.
- ✔ Initial experiments show agreement with model and existing MSE when expected.
- ✔ Initial modelling shows applicability to W7X, based on AUG experience.
- ✔ A high detail forward model has been developed for modelling and analysis.
- ... Preparation underway for two more experiments with the prototype in 2014:
  - Faster camera for imaging within sawtooth / ELM variation.
  - Filter switching for investigation of calibration with Zeeman split cold Hα.
  - Application to investigation of off-axis NBI current drive experiments.
- ... Design work started for permanent IMSE installation at ASDEX Upgrade.

[1] J. Howard et. al. PPCF **50** 125003 (2008)
[2] J. Svensson, A. Werner. PPCF **50** 8:085002 (2008)
[3] F. M. Levinton et. al. Phys. Rev. Lett. 63, 2060–2063 (1989)
[4] J.Howard, J.Chung, et. al. Rev. Sci. Instrum. **83**, 10D510 (2012)

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