Viewing the Magnetic Field with Coherence Imaging Spectroscopy

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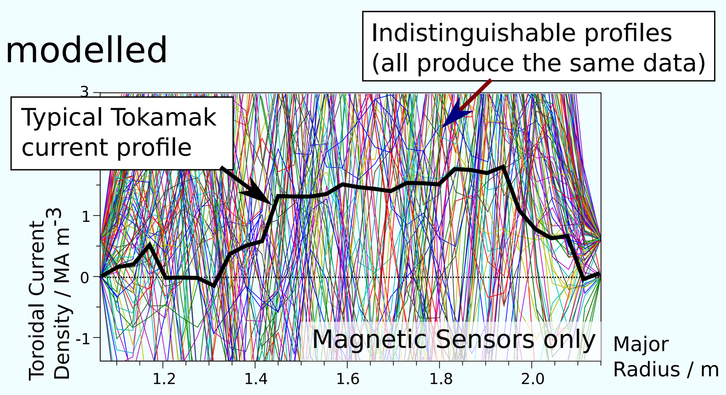
Imaging Motional Stark Effect (IMSE) is a new method of measuring magnetic field pitch angle for fusion plasma devices. Developed by the Australian National University (ANU)[1], it observes an image of the neutral beam from which a 2D image of the pitch angle can be inferred. IPP Greifswald is collaborating with ANU to further develop the diagnostic, the analysis methods and is constructing an IMSE system for ASDEX Upgrade (AUG) at IPP Garching. This poster outlines the motivation, principles and design progress, as well as some initial modeling and design for an IMSE system to measure the small bootstrap current in the Wendelstein-7X Stellarator.

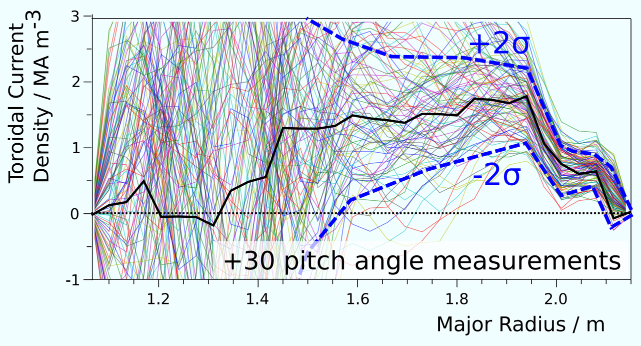
Plasma Current Diagnostics

Diagnosis of the plasma current is of particular importance in fusion plasma devices:
- Optimised Stellarators: The bootstrap current must be minimised to maintain the desired magnetic configuration, which requires measurement of it.
- Tokamaks: The large plasma current determines the magnetic geometry and hence strongly effects a wide range of physics.

Tomographic reconstruction of the plasma current[2] from modelled measurements tells us how useful they are...

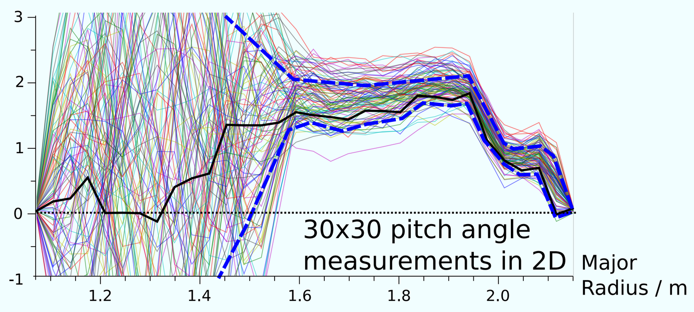


(Right): We can measure the magnetic field outside the plasma accurately, but this doesn't tell us much about the local plasma currents.



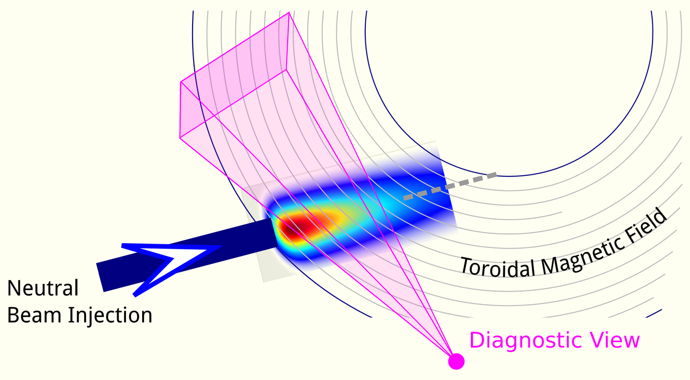
(Left): Conventional MSE diagnostics measure magnetic field pitch angle inside the plasma along a 1D line of individual points. This improves the inference, but it doesn't help much.

(Right): If we measure points spread out in 2D (but with the same overall S/N), the inference improves dramatically.



MSE: Motional Stark Effect.

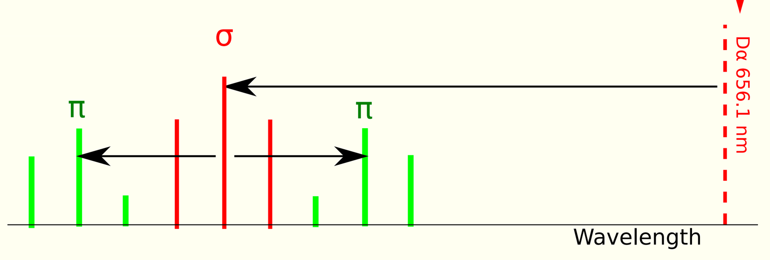
The MSE diagnostic[3] is used on many plasma devices to diagnose the magnetic pitch angle.

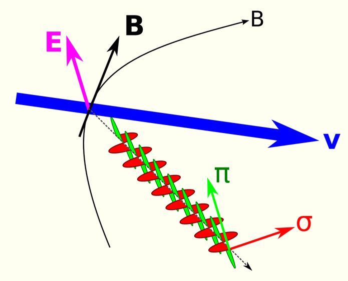


A Neutral Beam Injector (NBI) fires neutral particles (e.g. Deuterium) into the plasma.

These particles are excited by interactions with the bulk plasma and transitions between atomic states give rise to emission lines.
e.g. 'D_α' (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:





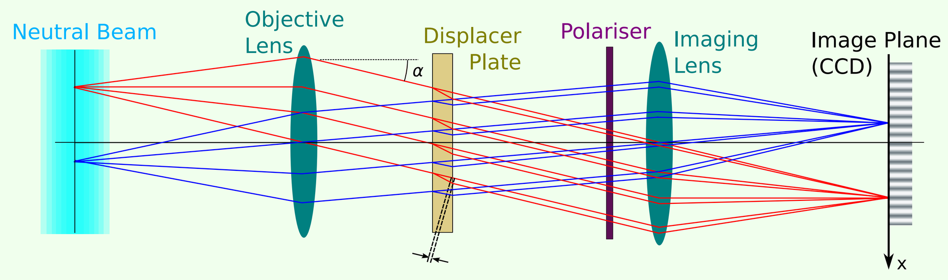
π components are polarised parallel to **E**.
σ components are partially polarised perpendicular to **E**.

Direction of **v** is known (beam), so by measuring the polarisation, we can infer the direction of **B**.

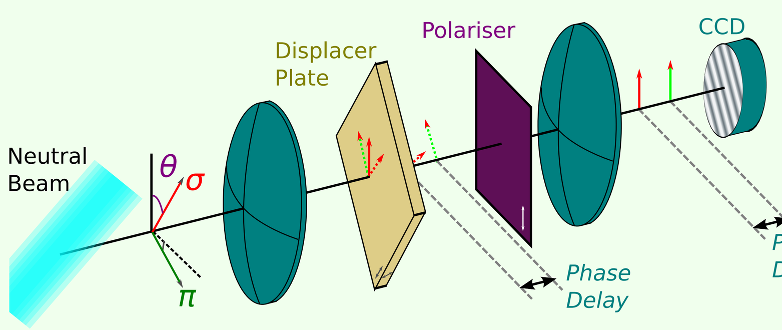
Conventional MSE polarimeters measure the polarisation by spectrally selecting one component with a narrow filter and using a photo-elastic modulator (PEM) to analyse the polarisation. Because of the varying Doppler shift, each spatial point requires a very finely tuned filter, optics, sensor and digitiser.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

CIS: Coherence Imaging Spectroscopy (and Polarimetry)

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



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

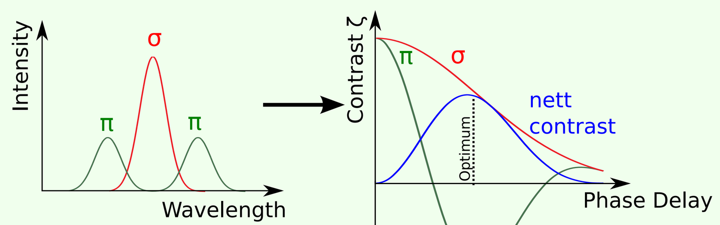


Adding a polariser at 45° interferes the two components, producing fringes on the image. The fringe amplitude depends on the initial polarisation angle θ and 'spectral contrast' ζ:

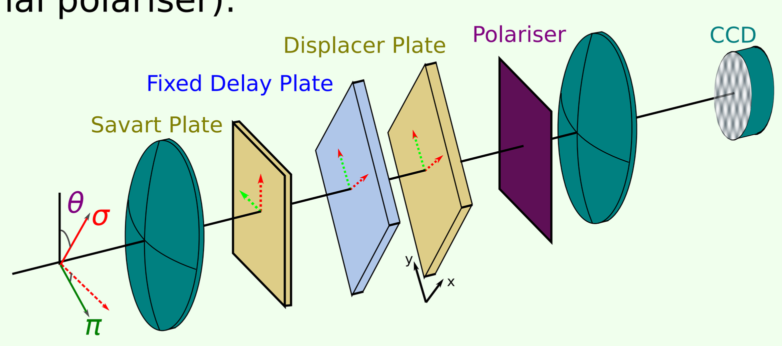
$$I \propto 1 + \zeta \cos 2\theta \cos(x)$$

For MSE, fringes from σ and π would cancel, due to 90° difference in θ.

The contrast ζ depends on the spectral shape and the phase delay. At a particular optimum delay, ζ becomes -ve for the π components and the interferrograms add. The unknown parameter ζ can be eliminated by adding a displacer plate which produces orthogonal fringes and introduces a phase shift at 45° to the first (aligned with the final polariser):
(because cos 2(θ+45°) = sin 2θ)



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



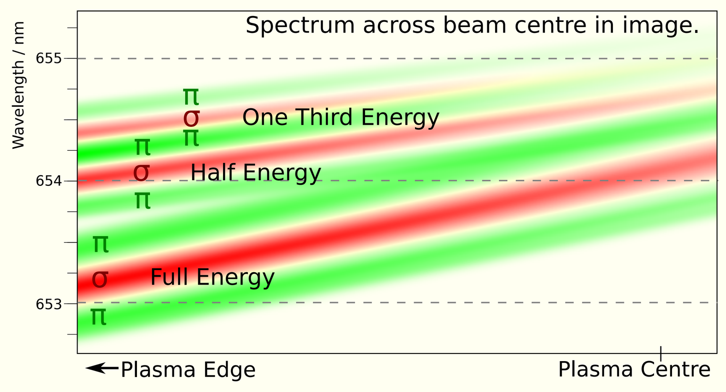
By demodulating and dividing, we can extract an image of $\tan 2\theta$.

Alternatively, adding an input polariser aligned with the final one eliminates the $\cos 2\theta$ term, and ζ can be measured. This has been used successfully to measure flow and temperature[4][5].

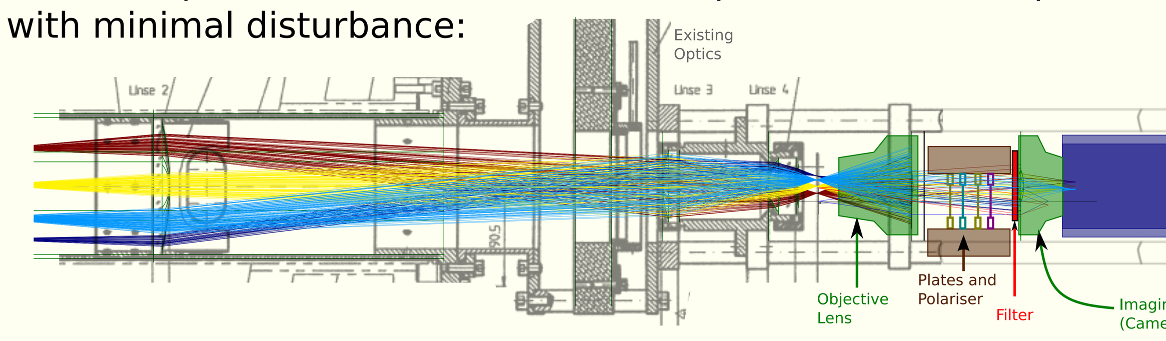
IMSE Advantages:
+ Better current inference: 2D Data.
+ Lots of data: ~100x100 θ measurements.
+ Simpler/cheaper hardware: One set of optics
+ More light: Only one broad filter.
+ Only θ offset calibration required.

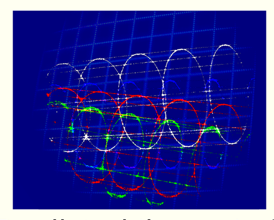
Design and Modelling for ASDEX Upgrade

Full 3D forward model modules has been developed for the Neutral Beams, Dα emission and CIS system. The spectrum (right) is complicated by changing Doppler shift, line integration, multiple beam energy components, etc but the model shows the system should still work as expected for ASDEX upgrade.



Using the modeling, together with a full ray-tracing of the existing optics, the design for ASDEX CIS system has been completed. It allows the IMSE components to be coupled in with minimal disturbance:

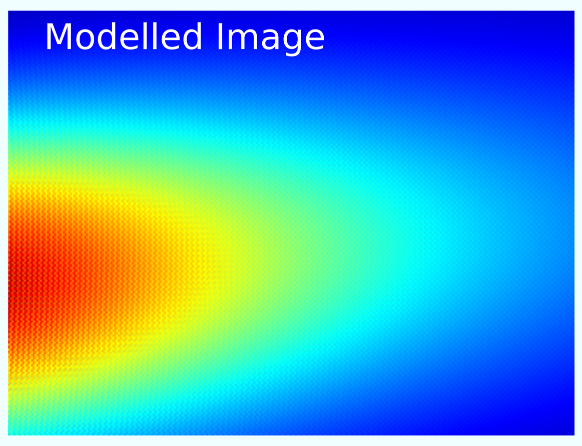




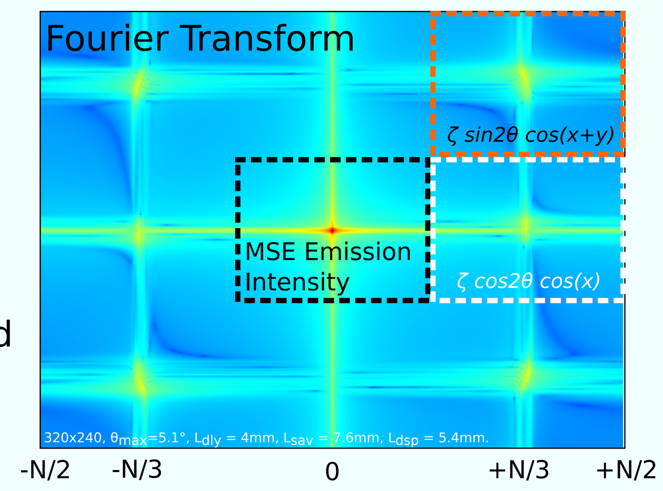
Predicted 'image' of beams at CCD

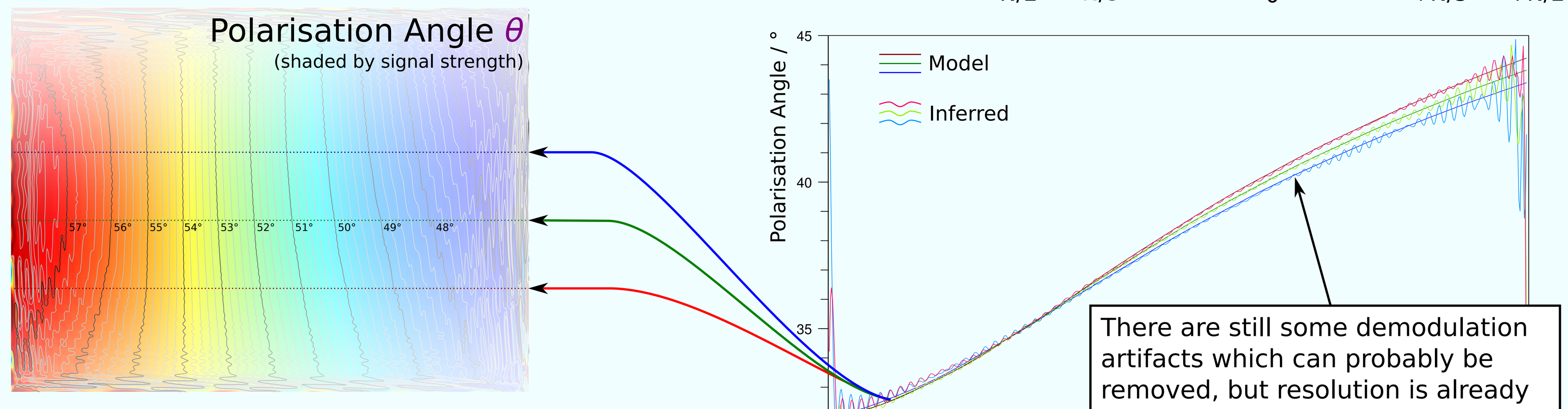
Image Analysis

The ASDEX Upgrade model predicts an image like this:



The Fourier transform shows the orthogonal components, which are then isolated, demodulated (shifted to 0 frequency) and divided to give the image of θ:





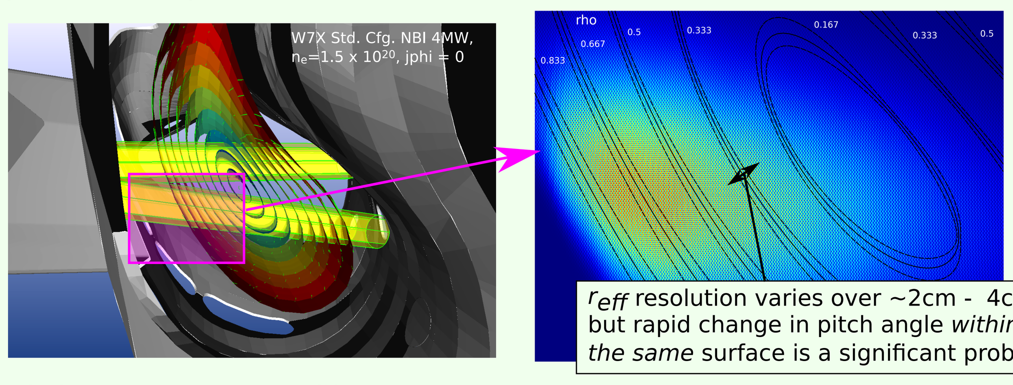
Spatial resolution of instrument design is ~1.1cm.
Line integration varies between 1cm - 6cm.

There are still some demodulation artifacts which can probably be removed, but resolution is already down to ~0.1°. This is sufficient to produce the accuracy of the current profiles in the top left pane.

Modeling for Wendelstein 7-X

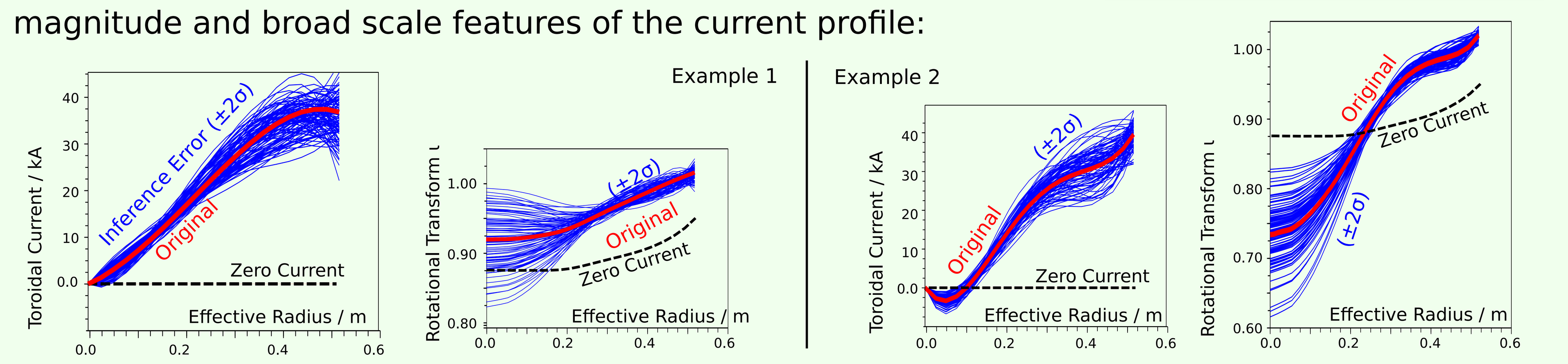
The CIS-MSE system is also a prospective approach for measuring the very small 'bootstrap' current in W7X. Modelling for W7-X and investigation of performance shows the measurement is feasible, although highlights a few particular problems for Stellarators.

The system would be installed on a port viewing the neutral beams from the side, The sight lines are almost parallel to the flux surfaces:



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

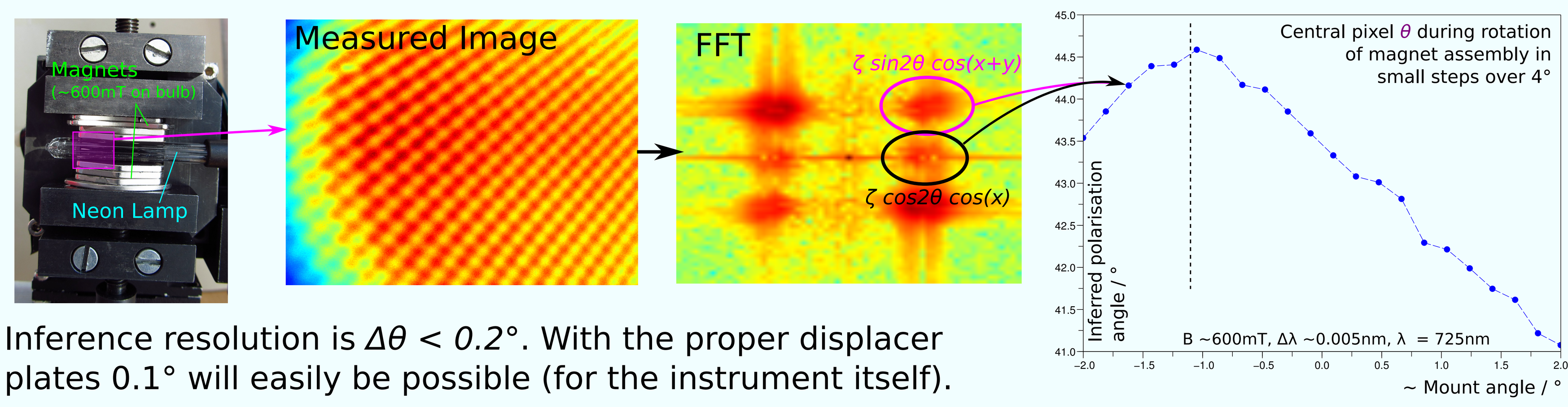
Resolving *changes* of $\Delta\theta$ ~0.1° appears possible and would allow the inference of the magnitude and broad scale features of the current profile:



Preliminary Concept Test

(See [1] for the first proof of principle)

A preliminary test of the CIS polarimetry concept was performed at IPP on Zeeman splitting of a spectral lamp using equipment available from a previous CIS Doppler Flow system[4]:



Inference resolution is $\Delta\theta < 0.2°$. With the proper displacer plates 0.1° will easily be possible (for the instrument itself).

Status and Outlook

- ✔ Inference of Tokamak current density is greatly improved by 2D pitch angle measurements.
- ✔ Detailed machine non-specific forward models have been developed for (I)MSE systems.
- ... (The MSE model needs improvement (Stark-Zeeman, non-statistical distributions, etc)
- ✔ An IMSE system has been designed and is being constructed for ASDEX Upgrade. Modelling indicates sufficient spatial resolution and accuracy to tomographically reconstruct current profiles (without requiring an equilibrium code).
- ✔ The diagnostic principal has been tested using weak Zeeman splitting with good results.
- ✔ Initial modeling work shows promise that an IMSE system could measure the bootstrap current in the W7X optimised Stellarator.
- ... (Some issues with pitch angle averaging need to be resolved here)

References

[1] J. Howard "*Snapshot-imaging motional Stark effect polarimetry*" PPCF **50** 125003 (2008)
[2] J. Svensson, A. Werner. "*Current tomography for axisymmetric plasmas*". PPCF **50** 8:085002 (2008)
[3] F. M. Levinton "*Magnetic field pitch-angle measurements in the PBX-M Tokamak using MSE*" Phys. Rev. Lett. 63, 2060–2063 (1989)
[4] J. Chung "*Time resolved coherence-imaging spectrometer on WEGA Stellarator*" PPCF **47** 919 (2005)
[5] J. Howard "*Doppler coherence imaging and tomography of flows in Tokamak plasmas*" Rev. Sci. Instrum. **81** 10E528 (2010)[4]