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Calibration methods for the MSE diagnostic at ASDEX Upgrade

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The direct measurement of the magnetic field pitch angle by using the motional stark effect (MSE) observed at several radially spaced locations presents an invaluable piece of information for a magnetic equilibrium code like CLISTE [1]. The numerical solution of the Grad-Shafranov equation determines the current density profile, which is the basis for the radial profile of the magnetic safety factor q. The derived magnetic shear $s = 2\,(V/q)\,dq\,/\,dV$ is a central ingredient for determining plasma behaviour in a multitude of topics (e.g. [2]) and thus a measurement in high demand. The strong dependence of the plasma internal magnetic configuration on MSE measurements dictates the need to maximize this diagnostic's accuracy. While the influence of statistical errors can always be improved upon with better hardware or improved software data evaluation routines, it is of interest to also reduce the systematic errors by proper characterization and validation of the diagnostic.

The MSE diagnostic at ASDEX Upgrade uses the PEM modulation technique to determine the plasma internal local magnetic field pitch angle with a 10 channel set-up. The lines of sight observe a 60 keV Deuterium heating beam at positions spread over the low-field side of the minor plasma radius. A validation of the installed line-of-sight geometry (figure 1) by use of a calibrated 3D positioning system (www.faro.com) was carried out inside the vessel to determine the boundary conditions (angles between LOS and direction of beam) as accurately as possible. The results proved consistency between Doppler shift measurements (beam into gas) and the calculated theoretical Doppler shifts of the Balmer line of Deuterium. Also measured were inclination and declination angles between beam direction and line-of-sight direction, which agree with the calculated geometry within the measurement accuracy. With known and validated geometry, projection coefficients for the polarized light onto the viewing plane can be calculated and used to calibrate the whole system.

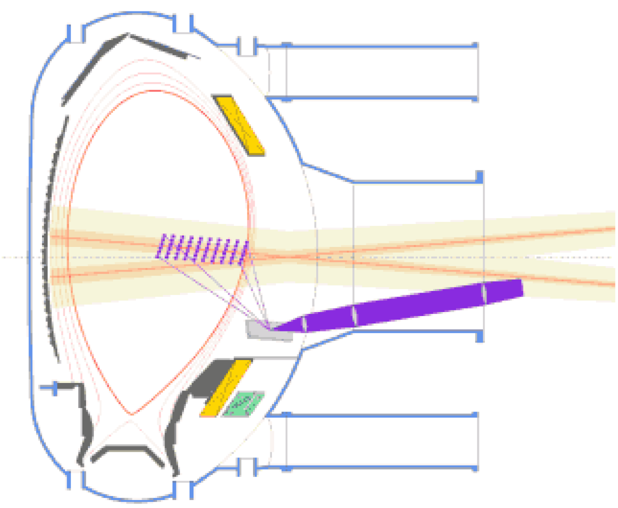


Figure 1: Schematic view of the observation geometry of the MSE system

Different methods for the calibration of separate aspects of the MSE diagnostic are carried out in order to test the set-up and gain confidence in the achievable accuracy. The data quality can be improved further by running dedicated „model“ discharges and cross-checking the results against model-based assumptions. The complexity of the diagnostic, which essentially measures a polarization direction of the linearly polarized σ-component of Doppler-shifted D_α light, makes this process non-trivial. Three main effects affecting the measured angles are considered. 1) Electronics introduce errors due to different amplification of lock-in signals, which themselves depend on the response of the photo-elastic modulators to their respective oscillation actuators (at 20 kHz and 23 kHz), leading to systematic offsets. 2) The optical elements between the measurement location and the analyser set-up introduce a rotation to the linear polarization vector, known as the Faraday effect, which depends on the applied magnetic field. 3) The 3D geometry of lines-of-sight onto the beam subject the instrument response to an offset (polarimeter orientation with respect to a reference at the measurement position) that varies from channel to channel which must be determined with an accuracy better than the desired instrument resolution.

The ansatz for the calibration is $\frac{1}{2p_2} arctan(\frac{S_1}{p_0 S_2} + p_1) = \Gamma_m + b_1 + b_2\, B_{0,tor}$, where Γ_m refers to the actually measured angle, S_1 and S_2 are the amplitudes measured by the 2 PEM systems, B_{tor} is the magnetic field on axis in the experiment and p_0, p_1, p_2, b_1 and b_2 are calibration factors. The parameter p_1 is only used as a phase offset during the calibration and set to 0 afterwards.

The lock-in technique which is used for the 2 PEM frequencies relies on electronics with small differences between the resulting amplitudes. The chosen method to correct this is to put a rotating polariser between a white light source and the observation optics inside the torus. When the polariser normal is aligned (by means of a 2-axis tilt-table) in an identical fashion parallel to each line of sight, the response from the system (the measured angle) is expected to be the same for each channel. Misalignments can be detected by measuring two fixed (non-rotating) settings of the polariser which differ by 45°. The correctly aligned polariser is then rotated about its normal and back-lighted. The measured angle is expected to evolve linearly in time due to the polariser's fixed angular velocity. The two parameters (p_0, p_2) are determined so that the response from the system in the experiment reflects this.

Once the system correctly measures polarization angles in its own reference frame, one can start to add corrections for systematic offsets during the actual measurement process, which are mainly due to the presence of a strong magnetic field. In optical components, the magnetic field induces a rotation of the electric field vector of the polarized light about an angle that is to lowest order proportional to the magnetic field strength itself and the path length through affected components. The proportionality constant (b_2) thus varies slightly with channel and is determined by placing a fixed polarized light source into the torus and measuring the angle while ramping the toroidal field. This was done with positive and negative field ramps and results are consistent in both directions.

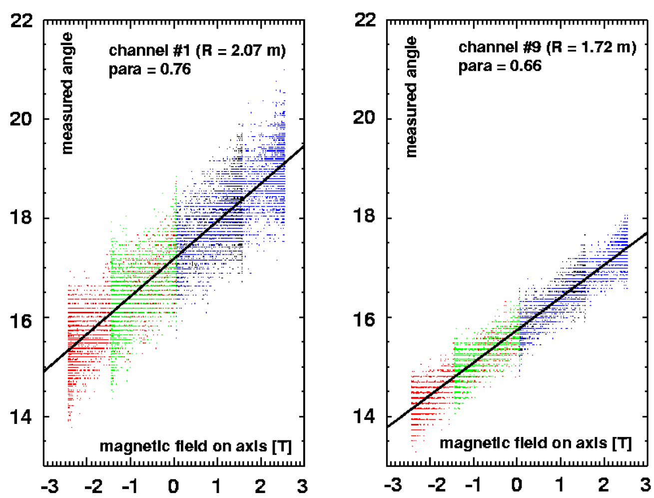
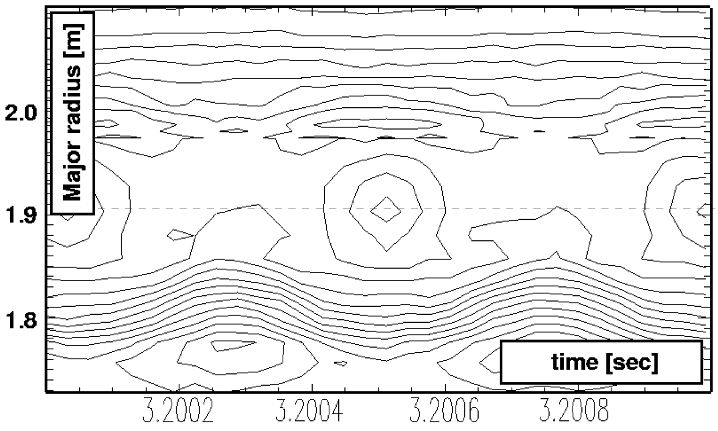


Figure 2: Dependence of measured angle on field (4 ramps from 0 to -2.5T, -1.5T, 1.5T and 2.5 T)

The final step for a complete calibration involves the determination of a reference direction for each channel to better than the desired accuracy of 0.2 degrees. This translates to an absolute offset (b_1) of the measured angle value, which can be understood as the angle between the reference zero (horizontal, beam, etc.) and the alignment of the PEM axis after projection through the optical system for each of the different lines of sight. Even if the direction of the used polariser can be defined, it is experimentally difficult to align this direction within the desired 0.2° for each line-of-sight in the same way. Another source of error lies in the orientation of the PEM set-up projected across a necessary mirror relative to the desired horizontal or beam-aligned zero. This is in general different for each line of sight. For a fixed polariser orientation, the measurement indeed shows a linear change of the absolute angle with channel impact radius. By using the approximation of a linear fit for this, the statistical uncertainty in terms of a standard deviation from linearity can be estimated. For the most recent measurement, it amounts to 0.56°.

The current method of calibrating this constant offset for each channel is based on CLISTE reconstructions. CLISTE knows the proper geometry of the MSE diagnostic, calculates the diagnostic response assuming the calculated magnetic field and finds the best matched result by using a least-squares fit iteratively. This calculation needs the full equilibrium which includes the current density profile and consequently, the profile of the safety factor q(r). When a magnetic mode (e.g. neoclassical tearing mode, NTM) can be attributed poloidal and toroidal mode numbers m and n by means of Mirnov coil signal analysis, the value of the safety factor q at the position of the developing magnetic island is known to be $q_{mode} = m/n$. By independently localizing the magnetic island with fast ECE measurements whose positions only depend on the toroidal magnetic field, a constraint for the absolute position of the corresponding q value can be found. Only when the equilibrium reconstruction produces a safety factor profile compatible with the separately acquired position of q_{mode}, is the absolute

value of the last calibration constant of the MSE diagnostic assumed to be correct. A selection of four discharges (time-frame ranging between April 2005 and March 2006) with good magnetic measurements, edge pressure profiles and fast particle pressure as determined by FAFNER [3], was used to generate a set of calibration constants, which are then used in further reconstructions to validate the results. The CLISTE based determination of this reference zero yields a standard deviation from linearity of 0.54°, which is the analog of the independently determined value (see above) from in-vessel measurements. Thus, the presently used method has about the same channel to channel jitter as the dry set-up which is the approximately achieved accuracy. Figure 4 shows a discharge, which was not part of the calibration set, but was used for the check of consistency between q-profile and NTM island location.
Since there is no generally acceptable way of determining this constant, we have employed the described approach utilizing CLISTE, which involves a full solution of the magnetic equilibrium.



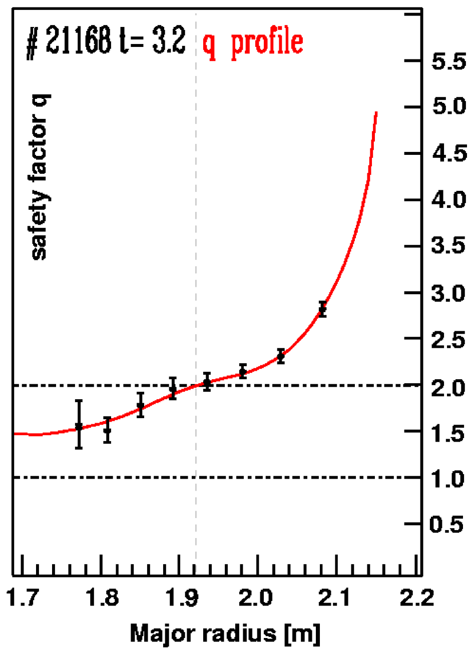


Figure 3:
Above: *Contour plot of ECE temperature versus major radius (direct mapping from toroidal field)*
Right: *q-profile reconstruction at same timepoint from magnetics + MSE data only*

The combination of the four calibration parameters in the applied procedure enables MSE measurements, which constrain CLISTE reconstructions enough that the calculated magnetic equilibrium yields q-profiles with good agreement of mode positions and predicted q-value at the relevant positions without the need for extra data besides magnetic probes and MSE. This step allows to revisit more than 12 months of experiments during which the MSE has now a validated calibration, which is expected to stay valid as long as hardware does not change.

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[3] G.G. Lister et al., IPP report 4/222 (1985).