Separatrix displacement in the presence of 3D external magnetic perturbations on ASDEX Upgrade

J. C. Fuchs[1], E. Strumberger[1], W. Suttrop[1], L. Barrera Orte[1], M. Cavedon[1], G. Birkenmeier[1],
R. Fischer[1], L. Giannone[1], L. Guimarais[2], P. J. McCarthy[3], V. Nikolaeva[2], E. Wolfrum[1],
J. Vicente[2], E. Viezzer[1] and the ASDEX Upgrade Team[1]
[1]*Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany*
[2]*Instituto de Plasmas e Fusão Nuclear, IST, Lisboa, Portugal*
[3]*Department of Physics, University College Cork, Ireland.*

Introduction

At ASDEX Upgrade non-axisymmetric magnetic perturbations produced by 16 in-vessel saddle coils have successfully been used to mitigate the plasma energy loss and peak divertor power load caused by Edge Localized Modes (ELMs), whereas concerning confinement and impurity concentration both unperturbed ELMy reference discharges and plasmas with mitigated ELMs show a similar behaviour [1]. The installed saddle coils allow magnetic perturbations with toroidal mode numbers up to $n = 4$, with varying relative phase between the upper and lower rings and varying toroidal orientation.

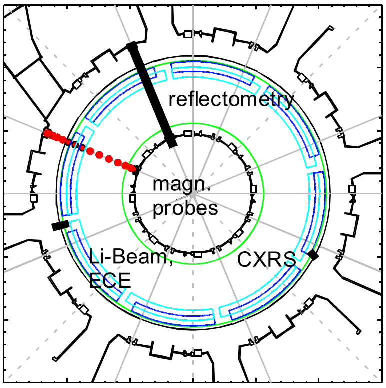

Figure 1: Toroidal view of ASDEX Upgrade with the position of the upper (dark blue) and lower (light blue) perturbation coils, separatrix at the midplane (green), and of some diagnostics used in this paper.

Measurements of the separatrix displacement

In order to measure the separatrix displacement with magnetic perturbations, several discharges have been performed. To check if there is any resonant field amplification in dependence of β_N, it was tried to achieve high β_N values. Due to NTMs only β_N values between 1.3 and 2.6 could be achieved. The perturbation coils were used in $n=1$ and $n=2$ configuration, and the arrangement of coils has been varied in 45° steps during and between discharges. Special care has been taken to choose configurations where the influence of the perturbation field on the magnetic probes used for the equilibrium reconstruction (figure 1) is as small as possible. The discharges have been performed with B_T=-2.5T and perturbation coil currents of $|I_{MP}|$ = 5 kA·turns, resulting in perturbation fields at the last closed flux surface up to 0.35% of B_T. Perfect 2D equilibrium field-aligned (resonant) or non-field-aligned (non-resonant) phasings between the upper and lower coil sets have been chosen, which resulted in values for b^r_{res}, the effective radial resonant field component [3] of the applied perturbation normalized to the toroidal field at q_{95}, between 0.01% and 0.05% for non-resonant configurations and up to 0.25% for resonant configurations. Furthermore data from other discharges with neither perfect resonant or non-resonant phasing and b^r_{res} between 0.1% and 0.15% have also been used.

For measurement of the separatrix displacement several edge diagnostics have been compared in time ranges shortly before the perturbation coils have been switched on, and shortly after the coil currents have reached their maxima. In particular electron density profiles from the Lithium beam and from reflectometry, electron temperature profiles from ECE and ion temperature profiles from CXRS measurements have been evaluated (figure 1). With the exception of the Li-beam diagnostic at z=0.326 m all of these measurements are near the midplane, and all of them are at the low-field side. Additionally from reflectometry also measurements at the high-field side were used. For ECE measurements, which need the total magnetic field for mapping temperatures on real space coordinates, the perturbation field has not been taken into account in the mapping since it is negligibly small at the position of these measurements.

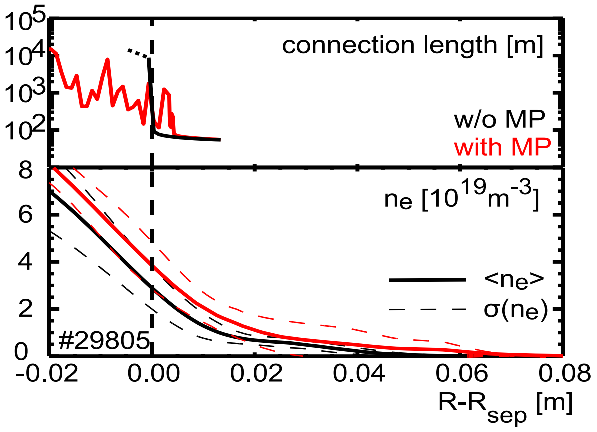

Figure 2: Bottom: Averaged edge density profiles between ELMs measured by the Lithium beam diagnostic (solid) with standard deviation bands (dashed), as a function of the distance to the separatrix of the unperturbed equilibrium, in time intervals shortly before the MP coils are switched on (black) and shortly after the MP coil currents have reached their maxima (red). Top: Connection lengths from the measurement positions of the Lithium beam to the inner and outer divertor without (black) and with (red) MP coils.

In all of these measurements a shift of the edge profile against the separatrix position of the unperturbed equilibrium was observed in the magnitude of mainly 2-3 mm, which corresponds to ca 0.5% of the minor radius, and 5-6 mm in some rare cases, however with quite large error bars in the measurements (figure 2, bottom).

Comparison with equilibrium reconstruction

The main tool for the equilibrium reconstruction at ASDEX Upgrade is the CLISTE interpretative code which numerically solves the Grad-Shafranov equation as a best fit to a set of experimental measurements, especially from magnetic probes and flux loops. Since the Grad-Shafranov equation assumes toroidal symmetry of the plasma, any effects of the non-axisymmetric magnetic perturbations of the saddle coils on the equilibrium is not taken into account. The magnetic probes in ASDEX Upgrade which measure the poloidal component of the magnetic field are all located at one toroidal position, where a dense set of 40 probes around the torus inside the vessel and 32 probes outside the vessel are available. A second, smaller set of magnetic probes at a different toroidal position was found to be insufficient to reconstruct the full three-dimensional equilibrium with a sufficient accuracy due to their limitations in number and position [2]. Therefore, further methods have been applied to get the perturbed 3D equilibrium.

An easy way is to start from an unperturbed, toroidal symmetric equilibrium and to add the vacuum field of the perturbation coils. Using a three-dimensional field line tracing code and measuring the connection length of field lines between various starting points and the target plates, an estimation of the perturbed separatrix can be constructed [2] (figure 2, top). This perturbed separatrix varies around the unperturbed separatrix with displacements of a few mm at the low field side, the displacements calculated at the positions of the profile measurements agree with these measurements within the error bars (figure 3).

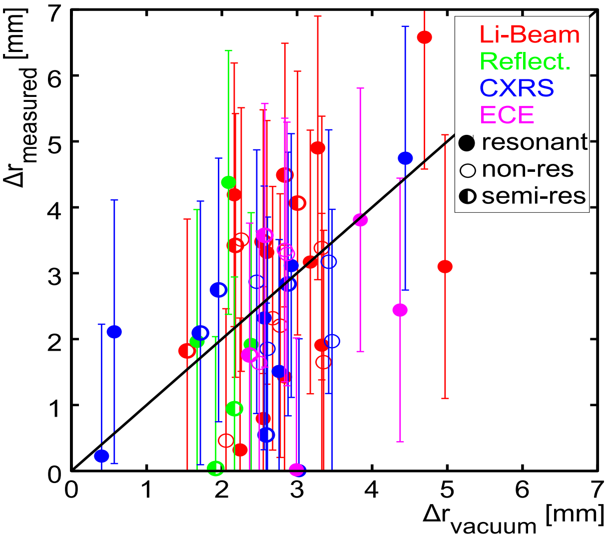

Figure 3: Mesasured displacement of the separatrix from various edge profile measurements at the low field side as a function of the calculated displacement by vacuum field line tracing.

This vacuum field approach does neither take into account any shielding currents by the plasma, nor the plasma equilibrium response to the perturbation field. It allows that the field lines can penetrate arbitrarily into the plasma which leads to a dissolution of the flux surfaces and a formation of a 'stochastic' region with islands, whose depth depends on the configuration of the perturbation coils. A more detailed reconstruction of the perturbed equilibrium in respect of a consistent balance of forces, which incorporates the plasma equilibrium response to the perturbation field has also been performed using the NEMEC equilibrium solver. This code calculates ideal MHD equilibria by minimizing the total plasma energy W_P in a toroidal domain [4]. Since it assumes nested flux surfaces inside the plasma it does not permit any formation of a stochastic layer. The displacements of the separatrix calculated by NEMEC are consistent with those calculated with the vacuum field approach.

Separatrix displacement at the high field side

Although the (vacuum) perturbation field at the high field side (HFS) separatrix is small compared to that on the low field side, an even larger effect on the separatrix deformation was found also on the HFS in some configurations: Figure 4 (right) shows a shift in the density profiles measured with the HFS reflectometry of about 1cm, which is consistent with the results from connection lengths calculations using field line tracing both with the vacuum field approach and with NEMEC equilibria (figure 4, left). Results from NEMEC calculations suggest that these deformations are not due to the separatrix displacement, but may be parts of an island chain at the edge (Since NEMEC calculates the flux inside the

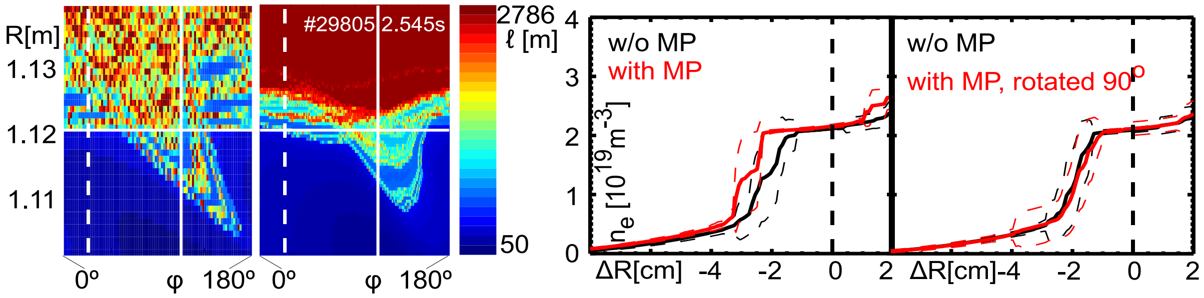

Figure 4: Left picture: connection lengths ℓ calculated with vacuum field approach (left half) and from NEMEC equilibrium (right half) for field lines starting from a horizontal plane half around the torus at the high field side at the height of the reflectometry diagnostic to the target plates. The radial position of the separatrix from the unperturbed equilibrium at the high field side is indicated by the horizontal lines. The toroidal position of the reflectometers is indicated by the solid vertical lines, the dashed vertical lines gives the position of the reflectometers when the coil configuration is rotated by 90°.
Right picture: averaged n_e profiles at the high field side measured by the reflectometry diagnostic (solid) with standard deviation bands (dashed), as a function of the distance to the separatrix of the unperturbed equilibrium, in time intervals shortly before the MP coils are switched on (black) and shortly after the MP coil currents have reached their maxima (red), in the second picture the MP coil configuration has been rotated by 90°.

plasma boundary and assumes closed flux surfaces, no possible islands can be reconstructed there. Outside the boundary however islands can be found when using the self consistent magnetic field from NEMEC equilibria). The shift in the density profiles can be seen if the measurements are at the O-point of the island, but not if the coil configuration is rotated by 90° and the measurements are at the X-point.

Dependence of the separatrix displacement on plasma parameters

Correlations between the measured separatrix displacements and various plasma parameters have been examined, especially in order to check if there is any field amplification e.g. in high β_N discharges. However, no clear dependence could be found within the error bars. Even during a time interval with applied MP, where mode activity caused a β_N ramp, the measured displacement of edge profiles remained nearly fixed (figure 5). According to [5] one would expect a clear effect only when β_N reaches values near the ideal β limit, which was not reached in these discharges. Results from NEMEC show that the deformation of internal flux surfaces grow with rising β_N, whereas the edge is less affected.

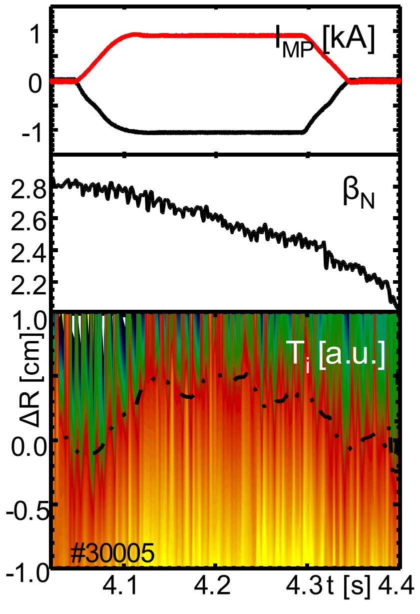

Figure 5: Contour plot of the edge ion temperature profile measured by CXRS as a function of time and distance to the unperturbed separatrix (bottom) during a phase with perturbation coils (top) and a β_N-ramp due to mode activity (middle). The dashed line in the contour plot indicates the course of T_i=250eV, the ion temperature value at the separatrix just before the MP coils are switched on.

References

[1] W. Suttrop et al., *PPCF,* **53**, 124014 (2011)
[2] J.C. Fuchs et al., EPS conference, **36F**, P4.010 (2012)
[3] E. Nardon et al., *JNM* **363–365**, 1071-1075 (2007)
[4] S.P. Hirshman, *Comput. Phys. Com.* **43,** 143 (1986)
[5] V. Igochine, this conference, P5.147