Effect of magnetic perturbations for ELM control on divertor power loads, detachment and consequences of field penetration in ASDEX Upgrade

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Abstract

Magnetic perturbation (MP) fields are currently studied in ASDEX Upgrade and many other tokamaks in terms of edge localized mode control and the implication onto steady state divertor power load and access to detachment. Previous studies at ASDEX Upgrade in low density, attached L-mode (Faitsch et al 2017 Plasma Phys. Control. Fusion 59 095006) are combined with high density L- and H-mode studies (Brida et al 2017 Nucl. Fusion 57 116006). A consistent interpretation is presented for the steady state power load variation due to the 3D MP. The deviation from an axisymmetric power load is reducing with increasing density, being an effect of the increasing broadening in the divertor region. No deleterious effect on the access to a detached divertor regime is found. Experimental results from ASDEX Upgrade reveal similar power load profiles for plasmas without and a toroidal averaged profile in presence of an external MP. EMC3-Eirene modeling is showing agreement only if screening currents in the plasma as a response to the external magnetic field are added. In plasma scenarios with field penetration and locking of internal modes a fundamentally different power load pattern is observed. The pattern is in agreement with edge ergodization and the extent can be used to determine the magnitude of current needed to describe the internal mode.

Keywords: magnetic perturbation, infrared thermography, scrape-off layer, power exhaust

(Some figures may appear in colour only in the online journal)

1. Introduction

The control of transient power loads induced by edge localized modes (ELMs) in H-mode is fundamental to the success of ITER and other future tokamaks. Applying a non-axisymmetric external magnetic perturbation (MP) is one technique that is studied in order to mitigate or suppress large ELMs in next step fusion devices such as ITER [1, 2]. Many of today’s tokamak experiments are equipped with magnetic coils to study the physics and feasibility of ELM mitigation/suppression with an external MP field, e.g. ASDEX Upgrade [3], DIII-D [4], EAST [5], JET [6], KSTAR [7], MAST [8], NSTX [9]. Such 3D MP fields lead to toroidal asymmetries in the power load pattern in the divertor [9–13] that cause further challenges for future devices. It is discussed that for ITER it might be necessary to rotate the external MP field in order to prevent local over-heating due to the toroidally asymmetric power load [2].
2. Divertor power load in presence of an external MP

In this section experimental and modeled heat flux profiles are presented and compared. The influence of increasing density from attached conditions towards detachment is here in focus. The analyzed data is mainly from L-mode experiments as the IR system did not provide reliable data in H-mode conditions due to a vibrating in vessel mirror excited by ELMs. Together with the lack of spatial resolution of the LP compared to IR no in depth analysis was possible in H-mode and is left for future studies with improved diagnostics capability.

2.1. Ad hoc heat flux model

The resulting 2D heat flux structure in attached L-mode conditions are compared to an ad hoc model presented in [16]. This model uses field line tracing starting at the outer divertor target up to the OMP. The magnetic field used is the axisymmetric equilibrium field superimposed with the magnetic field induced by the currents inside the MP coils. No plasma response is taken into account, therefore this is called the vacuum field approximation. Note, that the field line tracing is starting at the target and mapping the first intersection with the OMP to the target. This is different from the often used connection length that follows the OMP to the target. This is different from the often used connection length that follows the OMP to the target. This is different from the often used connection length that follows the OMP to the target.

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2.2. Experimental observations

The heat flux profile at the divertor target under attached conditions without MP is described by the 1D diffusive model presented in [22]:

\[
q(s) = \frac{q_0}{2} \exp\left(\frac{S}{2\lambda_q^2} - \frac{s}{\lambda_q f_\phi}\right) - \text{erfc}\left(\frac{S}{2\lambda_q^2} - \frac{s}{S^* f_\phi}\right) \text{[W m}^{-2}\text{]}, \tag{1}
\]

with \(s\) target location, \(S\) divertor broadening, \(\lambda_q\) power fall-off length, \(f_\phi\) poloidal (effective) flux expansion between OMP and target and \(q_0\) unbounded peak heat flux density at the strike line position (\(s = 0\)). A typical divertor heat flux profile for the outer divertor target is shown in figure 1 with the blue dotted profile together with a fit using (1) shown with the solid blue line. The fitting parameters \(S\) and \(\lambda_q\) are presented in figure 1. The divertor broadening in ASDEX Upgrade can be altered by changing the density at the plasma edge [23] and is thought to be due to the reduction of the temperature in the divertor region leading to a reduction of the parallel heat flux [21]. The presented discharge is designed to have a small \(S\) value compared to \(\lambda_q\) by having a low edge density of \(n_{e,\text{edge}} = 0.8 \times 10^{19} \text{m}^{-3}\). This additionally decreases the uncertainty of the \(\lambda_q\) estimate in the fit of (1).

At ASDEX Upgrade the differential phase between the two rows of coils is used to change the poloidal spectrum of the applied MP field and with this the alignment with the \(q\) surfaces. This spectrum has been shown to have significant influence on the discharge behavior. For example the degree of ELM mitigation and density pump-out [24], the ability for ELM suppression [25] or the loss of fast particles [26] vary with the differential phase. For the discharge parameter of #32217 the differential phase of \(\Delta \phi = -\frac{\pi}{2}\) is field line aligned at the edge (\(q = 5\) surface) and is therefore called the
(vacuum) resonant configuration [3]. The heat flux profile in presence of a resonant external MP field is shown with the red profile in figure 1. The pattern deviates from the profile without MP field by exhibiting multiple distinguishable local maxima and minima as a consequence of the non-axisymmetry. We note here that the occurrence of this structure is not necessarily a sign of edge ergodization, as further discussed in section 3. This phenomenon is often called strike line splitting, e.g. [10, 11], or lobe structure, e.g. [9, 16, 27] and hereafter.

In order to quantify the changes in the divertor power load, the steady state divertor target heat flux profile is treated as a superposition of a toroidally averaged heat flux \( \langle q(s) \rangle _{\phi} \) and toroidal variation \( q'(s, \phi) \):

\[
\langle q(s) \rangle _{\phi} = \frac{n}{2\pi} \int_{0}^{2\pi/n} q(s, \phi) d\phi,
\]

\[
q'(s, \phi) = \frac{q(s, \phi)}{\langle q(s) \rangle _{\phi}},
\]

\[
\Gamma(s) = \max(q'(s, \phi)),
\]

\[
\sigma = \Gamma(s = \lambda_p)
\]

with \( n \) toroidal mode number, \( \Gamma(s) \) named toroidal maximum and \( \sigma \) named toroidal peaking, consistent with earlier studies [13, 16]. This allows to characterize the profile with only one additional parameter compared to the axisymmetric profile if \( \langle q(s) \rangle _{\phi} \) is similar to the axisymetric profile without MP. Consequently, the averaged profile in attached conditions is described by the 1D diffusive model, (1), used for the axisymmetric profile without MP in attached conditions.

An averaged heat flux profile over one complete rotation period of the MP field is shown in figure 1 with black dots. The profile is described by the 1D diffusive model shown as solid black line. Further, the fit exhibits similar parameters for both transport qualifiers \( S \) and \( \lambda_p \) comparing the axisymmetric profile without and the averaged profile in presence of an external MP field. This means that the presence of the MP field does not significantly increase overall cross-field heat transport in these conditions [13, 16].

2.3. Comparison between modeling and experiment

The rigid rotation of the MP field and the steady plasma conditions allow to infer a 2D divertor target heat flux profile that can be compared to modeling results. Note, the rotation of the MP field together with the eight coils in toroidal direction leads to a variation of the dominating \( n = 2 \) and 6 Fourier components of the order of 5% in time and is neglected in the following. The measured heat flux and the heat flux inferred from the model described in section 2.1 are shown in figure 2. It is seen that both the heat flux pattern as well as the absolute amplitude of heat flux within the 2D structure are in agreement. A comparison between 1D profiles is shown in figure 3. It can be seen that the lobe structure is well captured within the model. However, further away from the strike line the modeled heat flux is more peaked than the experimental. This is explained by a non uniform divertor broadening along the divertor location [16]. Modeling using the EMC3-Eirene code [28] is in agreement only if screening currents are taken into account reducing the extent of the ergodized layer at the plasma boundary and minimizing the broadening due to the MP field [17, 29].

The plasma screening of the external MP field is further inferred from experiments using electron cyclotron resonance heating heat pulses deposited at the plasma edge. A detailed description of these experiments is presented in [30]. EMC3-Eirene modeling predicts a measurable propagation time difference in the vacuum field approximation and a similar behavior when screening of the MP field by the plasma is assumed. No change of the heat pulse propagation is measured in these experiments, consistent with plasma screening.

In H-mode, the plasma response is thought to be more important than in L-mode due to the steep edge pressure gradient, forming the H-mode pedestal, and the associated
bootstrap current [31, 32]. This is confirmed by experiments showing that the largest density pump-out and separatrix corrugation occurs not at the vacuum field resonant differential phase but at the phase with the largest calculated resonant field including plasma response [24, 27, 33].

2.4. Increasing divertor broadening and detachment

A set of three L-mode discharges with identical plasma parameters except of density were performed at ASDEX Upgrade. As previously mentioned the increase in edge density increases the divertor broadening. The toroidal peaking (see (5)) with varying divertor broadening is shown in figure 4. In the modeling (black dots) a fixed value of \( \lambda_q \) is used from \# 32217 (low density). The blue dots use the value for \( \lambda_q \) from the corresponding discharges. In L-mode \( \lambda_q \) increases with decreasing edge temperature [21, 34] which was a consequence of the increase in density. The change of \( S \) is significantly larger than the change of \( \lambda_q \) in this set of discharges. In table 1 the values for edge density, power fall-off length \( \lambda_p \) and divertor broadening are summarized for the reference profiles without MP and the toroidal averaged profiles. Note here, that all three discharges have an attached outer divertor, the detachment role-over density for this scenario is in the order of 1.8 \( \times 10^{19} \text{m}^{-2} \) [35, 36]. The toroidal peaking significantly decreases with increasing divertor broadening \( S \). \( \lambda_q \) does not change this trend. The measured toroidal peaking for the inferred divertor broadening \( S \) for the three different density steps (shown in red) is in agreement with the modeled values. In an additional set of discharges the density was increased further in order to study the influence of an external MP on detachment. Due to the high level of bremsstrahlung in the divertor region the IR thermography system is not reliable at high density and Langmuir probes are used to calculate heat flux and to monitor the divertor conditions [17]. It it shown that the toroidal maximum reduces with increasing density complementing the studies with an attached divertor towards detachment [17]. Further, no influence of an external MP field on the detachment process is observed at ASDEX Upgrade [17]. A detailed description of detachment in similar scenarios without MP field is presented in [36].

3. Field penetration and internal mode locking

In a parameter regime characterized by low densities (collisionsality) and low rotation velocity [37], an external MP field can penetrate the plasma and lead to full magnetic reconnection generating magnetic islands at resonant flux surfaces [38]. These small islands can act as a seed perturbation for neoclassical tearing modes reducing confinement or leading to disruptions [39–42].

Such islands are often described by a helical current defect on the resonant flux surface. Due to the radial distance between the scrape-off layer and the resonant flux surface one can approximate the current as a delta function instead of having a finite radial width. The modes often lock and amplify the external MP. The effect on the 2D heat flux pattern at the divertor target is shown in figure 5 for a MP with \( n = 1 \) in L-mode. Exceeding a threshold in the MP coil current of 250 A < \( r_{\text{threshold}} \times 400 \text{ A} \) leads to a significant change of the heat flux pattern. The vertical blurry pattern, visible in e.g. figure 5(b) between a toroidal angle of \( \frac{\pi}{2} < \phi < \frac{3\pi}{2} \) and figure 5(c) between \( \frac{\pi}{2} < \phi < \frac{\pi}{2} \), are due to reflections from the inner divertor target in the IR signal caused by the large radial extent of the heat flux pattern. This artificial heat flux prevents the analysis of the integrated heat flux.

Figure 6 shows a comparison between (a) the 2D heat flux profile from the IR measurement, (b) the one from the model described in section 2.1 and (c) the connection length using the vacuum field approximation. The measured heat flux extent is significantly larger than the model prediction and the connection length profile.

However, scaling the target location axis, equivalent with increasing the MP amplitude, reveals remarkable similarity between measured heat flux pattern and the pattern of the connection length, shown in figure 6(d). A scaling factor of 2.5 is used in order to match the extent along the target location of measured heat flux.

This onion like structure is not reproduced using the model described in section 2.1 (see figure 6(b)). It is observable in connection length calculations due to an ergodization of field lines at the plasma boundary with neighboring field lines having significant different connection length [43–45].

Table 1. Parameters of the ASDEX Upgrade discharges.

| \( n_{\text{edge}} \) \( (10^{19} \text{m}^{-2}) \) | \( \lambda_q \) \( ^{\text{w/0}} \) \( (\text{mm}) \) | \( S^{\text{w/0}} \) \( (\text{mm}) \) | \( \lambda_p \) \( (\text{mm}) \) | \( S \) \( (\text{mm}) \) |
|---|---|---|---|---|
| 0.8 | 3.64 | 0.30 | 3.67 | 0.29 |
| 1.5 | 4.43 | 0.88 | 4.08 | 0.85 |
| 1.8 | 6.02 | 1.38 | 5.50 | 1.23 |

Figure 4. Toroidal peaking depending on the divertor broadening \( S \) for ASDEX Upgrade L-mode discharges. Reproduced from [16]. © IOP Publishing Ltd. All rights reserved.
Figure 5. Experimental 2D heat flux patterns for discharges with $n = 1$ MP with different amplitude—(a) $I_{\text{coil}} = 0.25$ kA, (b) $I_{\text{coil}} = 0.4$ kA and (c) $I_{\text{coil}} = 1.0$ kA. The heat flux patterns change significantly for MP coil currents $250 \, \text{A} < I_{\text{coil}}^{\text{threshold}} < 400 \, \text{A}$, attributed to exceeding a threshold leading to field penetration.

Figure 6. 2D divertor target patterns for $\# 33080$ with $n = 1$, $I_{\text{coil}} = 1.0$ kA. (a) Measured heat flux pattern, (b) modeled heat flux pattern using the ad hoc model with the vacuum field approximation, (c) connection length using the vacuum field approximation and (d) connection length using the vacuum field approximation, target location scaled by a factor 2.5.
This ergodization pattern has a characteristic extent with a clearly defined boundary. Such a structure is not observed in the experimental observations and modeling in the sections before. The model uses field line tracing in the vacuum field approximation to map 2D target location to 2D OMP location. The MP in the vacuum field approximation leads to an ergodization of the plasma boundary which can be seen in the connection length in figure 6(c). However, the model uses only the field line between the outer divertor target and the first intersection of the OMP which leads to a non-ergodic pattern which is in line with measured heat flux in the previous sections but deviates from the observations in this section.

In order to mimic the field penetration and the resulting internal mode, current filaments are added along field lines at the resonant surface. These current filaments are treated the same way as the current inside the coils producing the external MP; solving Biot–Savart’s law and using the vacuum field approximation. We use a current of the form

\[ I_{\text{filament}} = \hat{I} \cos \left( \frac{\Phi_{\text{OMP}} - \Phi_0}{n} \right) \]

with \( \hat{I} \) amplitude, \( n \) toroidal mode number and \( \Phi_{\text{OMP}} (\Phi_0) \) toroidal phase of the field line (mode) at the OMP.

Here, a mode at the \( q = 2 \) surface is assumed with \( m = 2 \) and \( n = 1 \), \( m \) being the poloidal mode number. This position is inferred from the electron temperature profile, shown in figure 7, measured with an electron cyclotron emission system [33, 46]. The temperature profile at the measurement position is flattened around the \( q = 2 \) surface as marked with an arrow. The profile is similar for the time points \( t = 4.4 \) and \( 5.4 \) s, being 1.0 s apart from each other, interpreted as the locking of this mode to the external MP rotated at 1 Hz. The profile at \( t = 4.9 \) s shows no flattening which is interpreted as the X-point of the mode. A second mode is present at \( \rho_{\text{pol}} \approx 0.95 \). This corresponds to the \( q = 3 \) or \( q = 4 \) surface.

The calculated effect on field lines intersecting the divertor target is shown in figure 8 for two different current amplitudes on the \( q = 2 \) surface. Note, no additional external MP field is applied for this comparison.

The divertor connection length foot print is similar for internal and external MPs, with the extent about the same for an external MP current of \( I_{\text{coil}} = 1 \) kA and an internal one with \( \hat{I} = 15 \) kA at the \( q = 2 \) surface. The characteristic extent of the foot print, the largest target location \( s \) of the well defined boundary—e.g. 100 mm in figure 6(a), along the divertor target for different \( \hat{I} \) is presented in figure 9.

Increasing the internal perturbation amplitude \( \hat{I} \) linearly increases the divertor foot print

\[ \Delta s_{\text{internal}}(\text{mm}) = 3 \cdot \hat{I} (\text{kA}), \]

in line with e.g. [47] showing a linear increase of the divertor foot print with increasing perturbation amplitude. Thus, it is possible to estimate the current that is needed to explain the measured heat flux pattern having both an internal as well as an external MP simultaneously. Assuming that the external and internal MP are in phase—the internal mode locks to the external MP field and is a resonant effect—and using a linear superposition, the foot print extent can be expressed as

\[ \Delta s_{\text{IR}} = \Delta s_{\text{MP}} + \Delta s_{\text{internal}}. \]

The visible extent from IR measurements is \( \Delta s_{\text{IR}} = 100 \) mm. The foot print reaches up to \( \Delta s_{\text{MP}} = 40 \) mm from field line tracing using the external MP field. Thus, \( \Delta s_{\text{internal}} = 60 \) mm is deduced. Using the linear regression presented in (7), a current of \( \hat{I} = 20 \) kA is needed at the \( q = 2 \) surface.

4. Conclusions

The implications for next step devices, especially ITER, is a crucial question of present day experiments. The results obtained at ASDEX Upgrade presented in this paper suggest that the heat flux profile, although being non-axisymmetric exhibits a similar toroidal averaged profile in the presence of an external MP and without MP field. No diminishing effect on the access to detachment was observed at ASDEX Upgrade. However, in similar experiments in other machines deviating effects are reported. For example a reduced peak heat flux in presence of an external MP field, e.g. [48] and references therein, or a re-attaching of the outer divertor target due to the application of an external MP field, e.g. in NSTX [48].

EMC3-Eirene modeling predicts a broadening of \( \lambda_q \) for conditions with small \( \lambda_q \) compared to the extent of the edge ergodic region [29]. This is expected for ITER conditions with an extrapolated \( \lambda_q \leq 1 \) mm [22] and an increased edge ergodic region compared to ASDEX Upgrade. Previous EMC3-Eirene modeling for ITER used diffusion coefficients that lead to a significantly larger power fall-off length \( \lambda_q \geq 4 \) mm [49]. This might reduce the influence of the MP field on the broadening compared to the axisymmetric heat flux profile without MP field. However, experimental evidence for the broadening is still missing at ASDEX Upgrade.
exploring dominantly regimes with larger $\lambda_q$ relative to the extent of the edge ergodic region so far. Further, the extent of the edge ergodic region also depends on the plasma response, e.g. the strength of the plasma screening [29]. Thus, extrapolations towards ITER regarding the influence of the external MP towards the scrape-off layer transport need to be taken with care. Future studies in ASDEX Upgrade with smaller $\lambda_q$ due to operation in H-mode and higher poloidal magnetic field are foreseen to validate the EMC3-Eirene predictions.

Field penetration, as observed in low density L-mode discharges with an external $n = 1$ MP field, leads to a fundamentally different heat flux pattern at the divertor target compared to discharges without field penetration at ASDEX Upgrade. The measured heat flux structure is in line with connection length calculations due to an ergodization of field lines at the plasma boundary with neighboring field lines having significantly different connection length. From the extent of the heat flux pattern it is possible to infer the current within the magnetic island.

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References

[1] Lang P et al 2013 Nucl. Fusion 53 043004
[2] Loarte A et al 2014 Nucl. Fusion 54 033007
[3] Suttrop W et al 2011 Phys. Rev. Lett. 106 225004
[4] Evans T E et al 2004 Phys. Rev. Lett. 92 235003
[5] San Y et al 2016 Phys. Rev. Lett. 117 115001
[6] Liang Y et al 2007 Phys. Rev. Lett. 98 265004
[7] Jeon Y M et al 2012 Phys. Rev. Lett. 109 035004
[8] Kirk A et al 2010 Nucl. Fusion 50 034008
[9] Ahn J-W et al 2010 Nucl. Fusion 50 045010
[10] Jakubowski M et al 2009 Nucl. Fusion 49 095013
[11] Harting D et al 2012 Nucl. Fusion 52 054009
[12] Thornton A et al 2014 Nucl. Fusion 54 064011
[13] Faitsch M et al 2017 Nucl. Mater. Energy 12 1020
[14] Suttrop W et al 2009 Fusion Eng. Des. 84 290
[15] Siegl B et al 2015 Rev. Sci. Instrum. 86 113502
[16] Faitsch M et al 2017 Plasma Phys. Control. Fusion 59 095006
[17] Brida D et al 2017 Nucl. Fusion 57 116006
[18] Faitsch M et al 2015 Plasma Phys. Control. Fusion 57 075005
[19] Sun H J et al 2015 Plasma Phys. Control. Fusion 57 125011
[20] Sun H J et al 2017 Plasma Phys. Control. Fusion 59 105010
[21] Siegl M et al 2016 Plasma Phys. Control. Fusion 58 055015
[22] Eich T et al 2011 Phys. Rev. Lett. 107 215001
[23] Siegl M et al 2013 Plasma Phys. Control. Fusion 55 124039
[24] Suttrop W et al 2017 Plasma Phys. Control. Fusion 59 014049
[25] Suttrop W et al 2018 Nucl. Fusion 58 096031
[26] Garcia-Munoz M et al 2013 Plasma Phys. Control. Fusion 55 124014
[27] Kirk A et al 2015 Nucl. Fusion 55 043011
[28] Feng Y et al 1997 J. Nucl. Mater. 241 930
[29] Brida D et al 2018 Nucl. Mater. Energy submitted
[30] Brida D et al 2017 Nucl. Mater. Energy 12 831
[31] Liu Y et al 2016 Nucl. Fusion 56 056015
[32] Ryan D A et al 2017 Plasma Phys. Control. Fusion 59 024005
[33] Willensdorfer M et al 2016 Plasma Phys. Control. Fusion 58 114004
[34] Faitsch M et al 2018 Plasma Phys. Control. Fusion 60 045010
[35] Carralero D et al 2014 Nucl. Fusion 54 123005
[36] Potzel S et al 2014 Nucl. Fusion 54 013001
[37] Fitzpatrick R 1998 Phys. Plasmas 5 3325
[38] Fielt S et al 2015 Nucl. Fusion 55 013018
[39] Hender T et al 1992 Nucl. Fusion 32 2091
[40] Koslowski H et al 2006 Nucl. Fusion 46 L1
[41] Yu Q et al 2008 Nucl. Fusion 48 024007
[42] Fitzpatrick R 2012 Plasma Phys. Control. Fusion 54 094002
[43] Nguyen F et al 1997 Nucl. Fusion 37 743
[44] Finken K et al 1998 Nucl. Fusion 38 515
[45] Eich T et al 2000 Nucl. Fusion 40 1757
[46] Rathgeber S K et al 2013 Plasma Phys. Control. Fusion 55 025004
[47] Cahyna P and Nardon E 2010 arXiv:1005.3663
[48] Ahn J-W et al 2017 Plasma Phys. Control. Fusion 59 084002
[49] Schmitz O et al 2016 Nucl. Fusion 56 066008