First Observation of ELM Suppression by Magnetic Perturbations in ASDEX Upgrade and Comparison to DIII-D Matched-Shape Plasmas


1Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543-0451 USA
2Max-Planck-Institut für Plasmaphysik, D-85740 Garching, Germany
3CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, U.K.
4General Atomics, PO Box 85608, San Diego, California 92186-5608, USA
5UC San Diego, 9500 Gilman Dr, La Jolla, CA 92093, USA
6Oak Ridge National Laboratory, 1 Bethel Valley Rd, Oak Ridge, TN 37831
*Full author list in references 12, 13
E-mail contact of main author: rnazikian@pppl.gov

Abstract. ELM suppression by n=2 Magnetic Perturbations (MPs) is observed for the first time in ASDEX Upgrade (AUG) following a shape matching identity experiment with DIII-D. AUG is the first all metal wall machine to achieve robust ELM suppression with MPs. ELM suppression is achieved for ≈50 τE limited by the duration of the neutral beam injection. Throughout ELM suppression the AUG plasma maintains ITER relevant performance parameter: βn=1.8, pedestal νp=0.25, H98(y,2)=0.95. This accomplishment follows a coordinated experiment between AUG and DIII-D to access similar plasma parameters in a shape-matching identity experiment: AUG increased triangularity from δ=0.2 to 0.3 while DIII-D reduced triangularity from the standard ITER shape (δ=0.5) to the AUG matching shape (δ=0.3). The DIII-D experiment demonstrated the accessibility of ELM suppression in the AUG matched shape; the AUG experiment demonstrated the advantages of increased plasma shaping to access ELM suppression at higher pedestal pressure. The long duration of ELM suppression in AUG with n=2 MPs demonstrates the effectiveness of tungsten (W) transport by MPs; no significant D2 gas injection was required during the ELM suppression phase. The conditions for achieving ELM suppression are similar in the two devices despite large differences in the impurity content and main ion dilution (Zeff≈ 1.5 in AUG and Zeff≈ 4.5 in DIII-D). These results demonstrate the feasibility of operating high confinement long pulse discharges with ITER relevant parameters in a metal wall machine and strengthen confidence in the physics basis for ELM suppression by MPs in ITER.

1. Introduction

ELM suppression with 3D magnetic perturbations (MPs) is obtained for the first time in low collisionality ASDEX Upgrade plasmas following shape-matching experiments on DIII-D. These experiments demonstrate the importance of low pedestal collisionality and increased shaping to access ELM suppression in AUG and revealed the minor role played by the impurity species even with large differences in the wall material and plasma dilution [1]. Previous experiments on AUG only achieved ELM mitigation at low pedestal collisionality (νp<0.3) [2] where the peak ELM induced heat flux is substantially reduced but not eliminated. These observations are quite different from ELM suppression obtained on DIII-D with similar collisionality [3,4] raising questions concerning the physics basis for ELM suppression in DIII-D and its applicability to ITER. This is particularly important given that the ITER internal coil design is largely based on the DIII-D empirical scaling [5]. The joint
experiment between DIII-D and AUG aimed to carefully match the plasma shape while operating in a similar collisionality range in the pedestal. The hypothesis was that increasing plasma shape on AUG would allow access to higher pedestal pressure, producing more edge kink drive by the MPs and hence reducing the MP threshold for ELM suppression. The DIII-D part of the experiment was to demonstrate that ELM suppression could be achieved in an AUG matching shape with comparable MP level to AUG. After the successful demonstration of ELM suppression in DIII-D in the AUG matched shape then experiments were performed on AUG at higher shaping ($\delta=0.3$). This proved successful in generating robust ELM suppression for the first time in AUG.

2. Plasmas Performance in ELM Suppression

ELM suppression is obtained using $n=2$ MPs in AUG with an upper vacuum resonant field strength very near the upper range achievable on DIII-D, of the order 1 mT. This gives a vacuum MP in the range $\delta B/B\approx 5 \times 10^{-4}$ at full toroidal field strength in both devices. The use of $n=2$ is based by the coil geometry on AUG, where there are two rows of eight coils, one above and one below the midplane. While $n=3$ and $n=4$ can be used, the resonant field amplitude in the plasma is lower than for $n=2$. On DIII-D, $n=3$ MPs are used as DIII-D has two rows of six coils and the $n=3$ configuration is found to be optimal for ELM suppression. DIII-D can operate in $n=2$ but operationally the conditions for ELM suppression are marginal with $n=2$ compared to $n=3$. Both DIII-D and AUG typically operate close to the upper limit of the available MP coil current for ELM suppression studies.

With stronger shaping in AUG (#33353 in Fig. 1) the plasma is observed to enter into a robust long duration of ELM suppression ($\approx 50 \tau_E$) with good confinement ($H_{98y2}\approx 0.95$), ITER relevant beta ($\beta_N\approx 1.8$) and collisionality ($\nu_e*\approx 0.25$). The small events during ELM suppression shown on bolometer measurements from the inner divertor in Fig. 2b are due to sawteeth and are not ELMs. These sawteeth seldom trigger ELMs. The confinement factor is very similar to the matched-shape DIII-D plasma with $\delta=0.3$ shown in Fig. 1c (#164362). The matching DIII-D discharge is more marginal to ELM suppression than the AUG plasma (Fig. 1d), likely due to some small level of mixed harmonics in the DIII-D coil configuration.
The stationary phase of ELM suppression in AUG with good plasma performance is quite remarkable given that there is essentially no deuterium gas injection during ELM suppression. This suggests that W is prevented from accumulating in the plasma core by a combination of factors associated with the elimination of ELMs and the enhancement of particle transport by the MP. The application of the MP early in the ELMing phase of the discharge is also helpful to maintain the ELM frequency, which helps to prevent radiative collapse in between unmitigated infrequent type-I ELMs, before full ELM suppression. Fig. 2 shows that the RMP induced particle transport is very effective to remove W in AUG; it appears even more effective for metallic impurities than for low-Z impurities studied on DIII-D. In the DIII-D studies, fluorine gas injection is used to measure the particle confinement time for F-IX on the core Charge Exchange Recombination (CER) channels [6]. These studies yield \( \tau_p/\tau_E \approx 2 \). In contrast, a similar investigation of W transport using pulsed power to the ICRF antenna and tuned to maximize W generation, demonstrates a very favourable result \( \tau_W/\tau_E \approx 1.2 \) for tungsten. Transport analysis of the controlled injection of both low and high-Z impurities in DIII-D and AUG give added confidence in the effectiveness of MPs to control impurities in future machines such as ITER.

An important consideration for ITER and indeed for all tokamaks is the compatibility of ELM control methods with high pedestal pressure operation. High pedestal pressure is required in order to access high core pressure for producing fusion power. An important question is whether there is any significant systematic difference between metal wall and carbon wall experiments in terms of access to ELM suppression and in terms of the impact of the MPs on the pedestal pressure in ELM suppression. Figure 3 shows a remarkable similarity in the pedestal electron temperature and density in the matched shape AUG and DIII-D plasma in ELM suppression. On the other hand a large difference is also seen in the ion temperature due to very different levels of main ion dilution by impurities in the two experiments. For the two discharges in Fig. 1 the pedestal electron density and pressure during ELM suppression is
very similar for the two experiments (Fig. 3a,b). The pedestal density $n_{e,\text{ped}}$ is a little lower in DIII-D, but compensated by a little higher pedestal electron temperature than in AUG. The major difference is in the ion temperature arising from carbon dilution of the matched shape DIII-D plasma (Fig. 3c). In the DIII-D matched shape plasma $Z_{\text{eff}} \approx 4.5$ due to a strong carbon source, perhaps due to the heating of a tile edge on the lower shelf. This leads to a low main ion pedestal density $n_{D,\text{ped}} \approx 30\% n_{e,\text{ped}}$. From power balance analysis, equal power flows through the electron and ion channel in the pedestal, so that the ion temperature $T_{i,\text{ped}}$ should be roughly $3x$ the electron temperature, as measured. On the other hand the impurity content in AUG is much lower, with $Z_{\text{eff}} \approx 1.5$ due mainly to boron impurities. In this case $n_{D} \approx n_{e}$ and the electron and ion temperatures are well matched. Given the relation between main ion dilution and ion temperature it is not perhaps surprising that there is only a small difference in the pedestal pressure in the two experiments. Figure 3d shows the total pressure for DIII-D compared to the total pressure for AUG in these two time slices. The total pressures agree within $10\%$ at the top of the pedestal despite the large difference in main ion density and impurity concentration. A more careful analysis shows that the collisionality at the top of the pedestal is well matched in the two experiments. This is because the effect of lower $Z_{\text{eff}}$ on collisionality in AUG is offset by the effect of lower $T_{e,\text{ped}}$ and higher $n_{e,\text{ped}}$. Thus it is perhaps not surprising that the pedestal pressures are well matched in these plasmas based on our understanding of the effect of shape and collisionality on pedestal pressure [7].
The Effect of Plasma Shape on ELM Suppression and Pedestal Pressure

A key aspect of this study was the modification of the plasma shape to access ELM suppression in AUG at higher triangularity. The key physics concept behind this experiment was as follows. It is well known that increasing plasma shaping also tends to increase the pedestal pressure (and edge current density) in ELMing discharges. This is a well known consequence of the stabilizing effect of shaping on the edge peeling ballooning mode [8]. It then follows that if we operate near the threshold of ELM suppression, by adjusting the pedestal transport to stay close to but not to exceed the current density limit for peeling mode onset at low collisionality, then we can support a higher pedestal pressure (and higher global beta) in ELM suppression with stronger shaping. Just as important, a higher pedestal pressure can also allow for a stronger kink response and therefore a stronger edge resonant response of the plasma to the applied MP, as demonstrated numerically [9,10]. Therefore there are in principle two positive attributes of ELM suppression, first access to higher edge pressure and current density in an ELM stable regime will enhance plasma kink response and thus lower the threshold MP level for the onset of ELM suppression (in principle). Second, the stronger shaping can in principle allow for higher pedestal pressure in an ELM stable regime and thus improve the performance of the plasma. It is possible that a combination of these factors is affecting the achievement of ELM suppression in AUG by increasing plasma shaping, even by a modest amount, from $\delta=0.2$ to 0.3.

There is considerable empirical evidence that this conceptual model has some validity, however there is also some challenges to the model based on the DIII-D experiments. In support of the model, we note that the pedestal pressure is indeed considerably higher in the matched shape AUG plasma with full ELM suppression and $\delta=0.3$ (#33353) compared to the lower shape ($\delta=0.2$) ELM mitigated plasma (#31128). Figure 4 compares the total pressure profile for the ELM mitigated case (blue) vs the ELM suppressed case (red), as well as the two plasma shapes corresponding to each case. The pedestal pressure is $\approx$30% higher in the

![Figure 5. Comparison of (a) edge pressure profile for ELM suppressed plasma with \(d=0.3\) (red) and ELM mitigated plasma with \(d=0.2\) (blue), (b) plasma boundary shape for the two cases in (a) showing the main change in the upper triangularity.](image)

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Figure 6. (a) Edge pressure and current profile in DIII-D from kinetic equilibrium analysis for low ($\delta=0.3$ red) and high ($\delta=0.5$ black) shaping; the plasma flux surfaces and boundary for low (red) and high (black) shaping, (c) VMEC analysis of the surface displacement to the $n=3$ MP in DIII-D amplified by 20x, using a fixed pressure and current profile and modifying the plasma shape from low to high $\delta$.

stronger shaped plasma, indicating the likelihood for stronger edge kink response and stronger edge resonant response to the applied $n=2$ MP.

However, it is interesting that the pedestal pressure did not significantly increase in DIII-D going from the AUG matched shape $\delta=0.3$ to the ITER shape $\delta=0.5$. The threshold MP level for ELM suppression also did change, remaining close to $\delta B/B \sim 3 \times 10^{-4}$. Given that the plasma shape was modified while the pressure and edge current density remained essentially unchanged, it is evident that shaping alone is not the key parameter for accessing ELM suppression but rather a combination of factors, including shape, that contribute to increased pedestal pressure and global confinement. Figure 6 shows the pressure and current density profile in the edge of DIII-D for the AUG matched shape (red) and ITER shape (black), indicating minimal change ($\sim 10\%$ reduction) in edge pressure and core confinement. The two shapes are shown in Fig. 6b for $\delta=0.3$ (red) and $\delta=0.5$ (black). It is in fact interesting that the plasma beta decreased from $\beta_N=1.8$ in the ITER shape to 1.6 in the matched shape, perhaps a consequence of the reduced triangularity of the plasma.
In order to address whether shape alone can significantly affect the MP coupling to the edge kink, we performed a shape scan using the ideal nonperturbative MHD VMEC code [11] on a fixed set of profiles for the AUG matched shape plasma in DIII-D. Two cases are shown in Fig. 6c based on one axisymmetric kinetic equilibrium in the AUG matched shape on DIII-D (δ=0.3) and varying the plasma shape numerically by modifying a lower poloidal field coil current. The plasma kink response to the MP is calculated and the radial displacement of the plasma surface is amplified 20x for visual inspection. The net effect of the shape variation with unchanged q-profile and pressure profile is minimal. This is consistent with the working hypothesis that shaping is important for accessing ELM suppression in AUG by enhancing the edge pressure and increasing the kink response.

The identification of complete ELM suppression in AUG is an important milestone in the research towards ELM control in fusion plasmas. The accomplishment is particularly important for demonstrating the compatibility of ELM suppression by MPs in metal wall devices and in demonstrating that ITER relevant parameters can be achieved for long durations with minimal accumulation of high-Z impurities. The demonstration of effective particle transport by the RMP raises confidence that MPs provide a path forward for controlling impurities in present and future reactors. The shape matching experiment with DIII-D and the achievement of ELM suppression with closely matched pedestal and machine parameters gives increased confidence in a common physics basis for ELM suppression. The role of shaping was explored and the observations are broadly consistent with the beneficial effect of increasing pedestal pressure so as to increase the coupling of the MP to the edge kink. This is also a positive result both for ITER and for future strongly shaped fusion experiments. Finally, the good performance of these AUG plasmas and their stationary behaviour is encouraging both for future optimization studies and for detailed scientific investigations on the underlying physics of ELM suppression.

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