Enhancement of Helium Exhaust by Resonant Magnetic Perturbation Fields

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Abstract:
Sufficient exhaust of helium as a fusion born plasma impurity is a critical requirement for future burning plasmas. We demonstrate in this paper that resonant magnetic perturbation (RMP) fields can be used to actively improve helium exhaust features. We present results from the TEXTOR tokamak with a pumped limiter and from the LHD heliotron with the closed helical divertor. In both devices RMP fields are applied to generate a magnetic island located in the very plasma edge and this magnetic island has a noticeable impact on the helium exhaust. Also, the effect of the intrinsic stochasticity at the X-point of the LHD plasma on helium exhaust is investigated. Reduced helium fueling efficiency accompanied by enhanced outward transport is shown to facilitate enhanced helium exhaust from the system under RMP application. 3-D fluid plasma edge transport and kinetic neutral gas modeling with the EMC3-EIRENE code generally support these experimental findings.

1 Introduction

Exhaust of helium as a fusion born plasma impurity is a critical requirement for future burning plasmas. The effective total helium confinement time $\tau^*_{p,He}$ must not exceed the energy confinement time τ_E by more than an order of magnitude to avoid dilution of the fusion fuel [1]. We demonstrate in this paper that resonant magnetic perturbation (RMP) fields can be used to actively improve helium exhaust [2]. Results from TEXTOR-DED are shown as an example for a tokamak with a pumped limiter and results from the Large Helical Device LHD with the closed helical divertor as an example for a heliotron/stellarator device. In addition, the impact of the level of magnetic field stochasticity at the X-point and around the last closes flux surface at LHD was investigated in dedicated experiments manipulating the level of stochasticity at the X-point [3]. The fully 3-D plasma fluid and kinetic neutral transport code EMC3-EIRENE was used [4] to interpret the measurements.

The results in combination provide evidence that application of RMP field inducing edge magnetic islands as well as fine tuning the level of plasma edge stochasticity yield significantly enhanced helium exhaust. This suggest important additional functionality of the ITER RMP ELM control coils and dedicated experiments on present day devices like DIII-D, EAST or KSTAR which obtained full ELM suppression by RMP field application are motivated. In this paper, the results published very recently in [2, 3, 4] on helium exhaust with RMP fields are surveyed and linked together. In order to do so we apply in the analysis a global particle balance view. Here, the effective helium confinement time $\tau^*_{p,He}$ is the result of a core confinement time for the fusion born α-particle τ_α and the absolute helium confinement time τ_{He}, connected to $\tau^*_{p,He}$ by the recycling coefficient R through $\tau^*_{p,He} = \tau_\alpha + R/(1-R)\tau_{He}$. Confinement and outward exhaust of α particles is an important topic in particular in heliotron and stellarator devices in which an inward directed neoclassical impurity transport can occur. However, generally only moderate helium exhaust efficiencies are found in nowadays fusion devices. Also for ITER, which will deploy activated charcoal coatings on cryo-pumps, helium pumping efficiencies of $3-5\%$ are expected. Hence, the second term for $\tau^*_{p,He}$ describing the link between recycling and the absolute helium confinement is the target of the analysis presented as it is expected to define $> 90\%$ of the helium particle balance.

2 Helium exhaust with an edge magnetic island

At TEXTOR, the RMP field is applied by the Dynamic Ergodic Divertor (DED). The resulting magnetic topology is shown in figure 1 with a Poincare plot (black dots) and the magnetic field connection length as color coded 2-D contour plot. In general, the DED induced stochastic edge layer features a helical scrape-off layer of short connection length flux tubes embedded into a stochastic domain [5]. In this contribution we investigated the impact of a toroidal/poloidal mode number $m/n = 4/1$ magnetic island located at $r/a = 0.95$ in the stochastic layer on helium transport and exhaust. This situation is seen in figure 1 (a), obtained from field line tracing from a linear superposition of the plasma equilibrium with the RMP fields. This approach is used throughout this paper for both TEXTOR and LHD and also for the EMC3-EIRENE modeling. The edge magnetic island at TEXTOR is located in the close vicinity of the DED target representing the dominating recycling source for plasma fueling. It was found that the RMP induced particle pump out (reduced N_{tot} in the plasma with RMP fields) is strongest in this very configuration with edge magnetic island [6]. In particular, even with a large increase (factors of 10-20) of the gas fueling of RMP discharges with edge magnetic island at TEXTOR, no recovery of the original N_{tot} value was possible. This regime was studied concerning helium exhaust and transport. The magnetic topology of the comparative case at LHD is shown in figure 1(b) as result of a $m/n = 1/1$ RMP at an RMP current of $I_{RMP} = 3.3kA$. This yields penetration of a $m/n = 1/1$ island located very close to the last closed flux surface

(LCFS). This magnetic field configuration (called "penetrated magnetic island state") will be discussed predominantly. However, also tow RMP configurations are discussed in which the plasma response avoided island penetration.

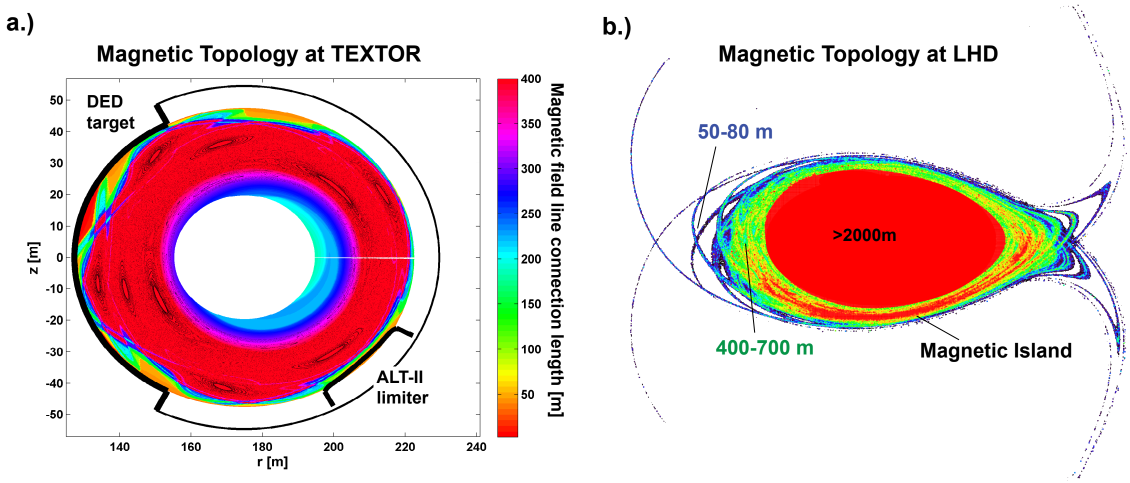

FIG. 1: Magnetic topologies addressed at TEXTOR-DED (figure a, left side) and LHD (figure b, right side) showing the magnetic wall to wall connection length L_c.

This is seen for RMP fields with $m/n = 1/1$ base mode at $I_{RMP} = 1.9kA$ and also for core resonant modes with $m/n = 2/1$ base mode and $I_{RMP} = 3.5kA$. For both, no signatures of island penetration were detected in measurements like the electron temperature profiles. Moreover, for both RMP configurations, a significant magnetic response amplitude from the plasma was measured by pickup coils featuring a phase shift to the external field of $160-180$ *degree*. This is usually taken as clear sign for island healing by internal response currents [7, 8]. Hence, we will discriminate for the LHD discussion the RMP situation of penetrated edge magnetic island from the healed edge and core magnetic island.

The 3-D plasma boundary induced by RMP fields on both, TEXTOR and LHD result in reduced values of $\tau^*_{p,He}$ as shown in figure 2. Here, a direct comparison of the measured $\tau^*_{p,He}$ from both devices is shown for several different magnetic field configurations. On both devices, puff/pump studies were conducted by injecting a short ($\approx 200ms$) helium gas pulse with a moderate particle flux of $\approx 2.0-4.0\times10^{19}$ particles/second. Both devices used Turbo-Molecular pumps for particle exhaust. A small increase of the plasma density was seen after the gas pulse, which can be used to measure the effective, overall particle confinement. Spectroscopy on $He-I(\lambda_{He-I} = 667.8nm)$ and $He-II(\lambda_{He-II} = 468.1nm)$ lines [14] is then used to infer $\tau^*_{p,He}$ accompanied by CXRS measurements at LHD [15] to quantitatively discuss the $He/(He + H)$ ratio or He^{2+}/H ratio, respectively. For TEXTOR, the noRMP situation and three RMP cases, each one with a different phasing of the DED currents is shown. This phase shift yields movement of the helical scrape-off layer structure and hence results in a different coupling to the toroidally symmetric pumping device. In [2] it is shown in detail, that adjacent ALT-II pump ducts show deviating neutral pressure values which point towards a 3-D neutral recycling distribution with RMP applied. This then yields a difference in the overall reduced values for $\tau^*_{p,He}$

which feature a reduction from 13% down to as much as 43%. Comparing this to the results in [9], we see that the RMP fields would be able to enhance the helium exhaust possibly enough to make the helium exhaust with the ALT-II limiter compatible with a maximal ratio $\tau_E/\tau^*_{p,He} > 10$ being sufficient [1] to maintain the helium contamination on an acceptable level for a burning plasma. This motivates to re-asses helium exhaust in poloidal divertors as discussed in [10, 11, 12] under RMP conditions to see if this aids a more reliable helium sufficieny across all divertor recycling regimes.

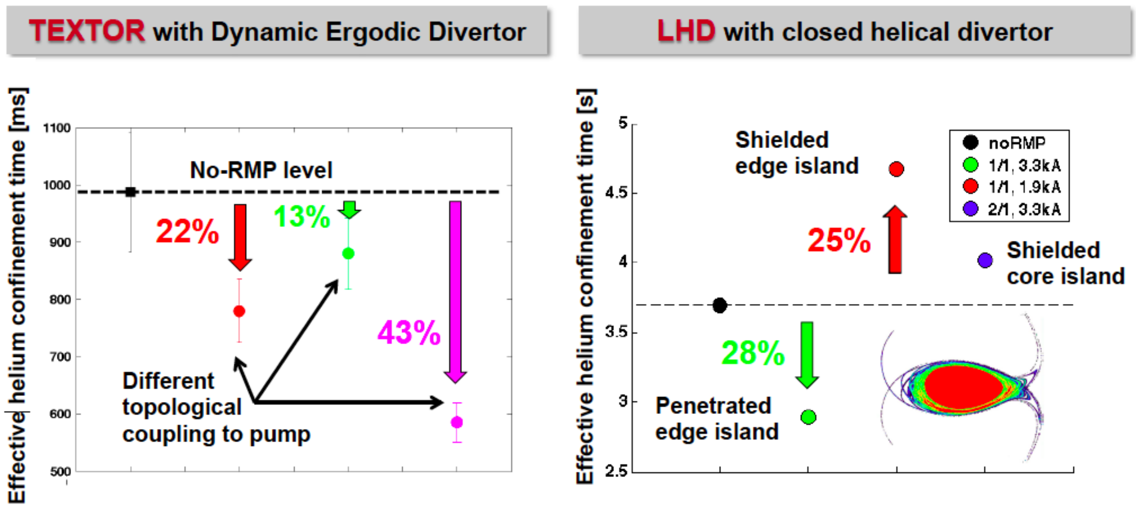

FIG. 2: Comparison of $\tau^*_{p,He}$ at TEXTOR (left side) and LHD (ride side). For TEXTOR three different orientations of the 3-D boundary with respect to the ALT-II limiter pump device is shown. For LHD, results for a penetrated edge island case (green) is compared to the noRMP situation in black and two RMP cases where island healing occurred.

At TEXTOR it was found that with RMP fields, the penetration of the helium in the plasma core was reduced with a resulting increase of the neutral pressure around the plasma [2]. This addresses an important point in the helium particle balance as discussed before. As typically the helium pumping efficiency is below 10%, it is important to identify any means to enhance the retention of helium in the plasma periphery and avoid helium penetration back into the plasma core. The RMP fields foster on both devices this helium retention in the plasma periphery which is another beneficial feature of RMP fields as tool for fine control of a wide set of plasma edge and divertor physics issues.

The results at LHD resonate with these findings at TEXTOR. As seen in figure 2(b), it is seen that the overall value of $\tau^*_{p,He}$ is a factor of $3.5-4$ higher in LHD compared to TEXTOR before RMP fields are applied. This is considered to be a result of neoclassical "ion-root" impurity transport which yields a negative electric field featuring an inward transport of impurities. This regime is one out of five characteristic impurity transport regimes at LHD as described in [2] and [13]. The results of this paper show that even in this adverse impurity transport regime in highly 3-D systems RMP fields yield improved impurity transport features. In figure 2(b), it is shown that the penetrated edge island case yields a reduction of $\Delta\tau^*_{p,He} = 28\%$ while in the two other RMP cases with healed magnetic islands, the level of helium accumulation in the plasma is even increased. This finding is not understood yet, but might be a result of enhanced 3-D deformation of flux surfaces near the internal plasma current which cancel the external RMP field in the island healing process. This additional deformation might affect the ion-orbit losses and hence enhance the inward directed neoclassical impurity flux.

Presence of a magnetic island in the plasma edge is the central characteristic feature of these perturbed magnetic topologies which feature improved helium exhaust. At the same time, this was identified to be a regime with substantial RMP driven particle pump out. Hence, it is important to discriminate if the improved helium exhaust is a result of the overall reduced particle confinement or if a selective reduction of $\tau^*_{p,He}$ can be shown. This was possible at LHD, where the radial profile of the $He/(He + H)$ ratio was measured. Analysis of $d/dt(He/(He + H))$ showed that the helium decontamination even features a faster decay time then $\tau^*_{p,He}$ with the magnetic island present. The decay time constant of $He/(He + H)$ - called He dilution time - was reduced by 68% for this situation which shows that a preferentially enhanced exhaust of helium was measured even beyond any impact of the RMP fields on the global hydrogen particle confinement [2].

3 Impact on stochasticity on helium exhaust

In the previous section, magnetic islands in the plasma edge was discussed as specifically impact-full magnetic topology under RMP application on helium transport and exhaust. However, LHD features an intrinsic stochastic layer around the last closed flux surface. The width of this stochastic layer depends on the position of the magnetic axis of the LHD plasma considered. It was found that both configurations have strongly different helium exhaust and transport features [3]. This is shown as example in figure 3, left column. The upper row of figures shows the magnetic topology, $n_H/n_{He}(t)$ and $n_H/n_{He}(r_{eff}/a_{99})$ for the inward shifted configuration with small level of stochasticty. The lower row shows the same assembly for the outward shifted configuration with increased stochasticty. Both configurations did not include a magnetic island in the plasma edge as discussed before. The inward shifted configuration with $R_{ax} = 3.60m$ are characterized by a slim stochastic layer while for $R_{ax} = 3.90m$, the stochastic layer width is at least $4-5$ times as wide. The measurements of the ratio of the helium density n_{He} to the hydrogen ion density n_H shown in the middle and right column are obtained in similar puff/pump studies as described before. In these cases, the helium gas injection started at $t = 3300ms$ and was kept constant during the remainder of the discharge as shown by the black dashed line in the middle column showing the time traces of both density functions considered. Comparing now $(n_{He}/n_H)(t)$ for the case with $R_{ax} = 3.60m$ (figure 3(a)) to those for $R_{ax} = 3.90m$ (figure 3(c)), we find that the helium content is reduced for $R_{ax} = 3.90m$ with a wide stochastic layer to almost half of what it was for $R_{ax} = 3.60m$ with a slim stochastic layer. This is also visible when comparing the profiles of $(n_{He}/n_H)(r_{eff}/a_{99})$ shown in figures 3(b) and (d). In particular the helium content at the last closed flux surface is reduced in the situation of a wide stochastic layer at $R_{ax} = 3.90m$. This configuration also features hollow n_{He} profiles deeper inside of the plasma. This strong impact of the stochasticity at the last closed flux surface was also used to stabilize detachment in LHD [16] and hence is in line with a generally very beneficial impact of the LHD stochastic layer on edge transport characteristics and divertor performance.

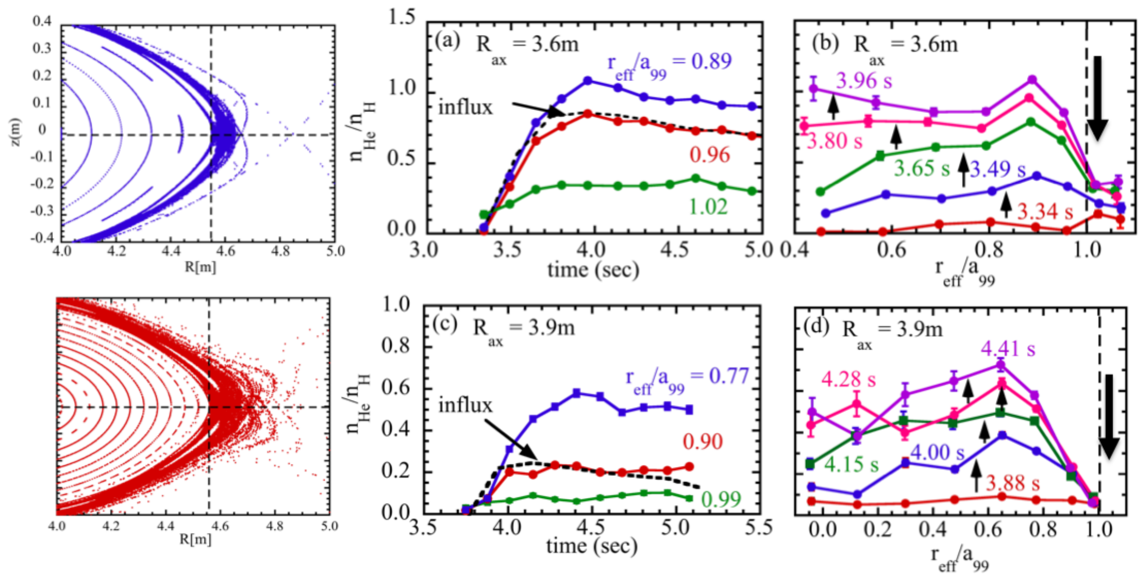

FIG. 3: Impact of the stochasticity at the X-point in the fishtail plane at LHD [3].

4 Interpretative modeling with EMC3-EIRENE

EMC3-EIRENE modeling was performed for the LHD situation to understand the helium particle balance with RMP fields in both, the RMP case with magnetic island as well as for different width of the intrinsic stochastic layer at LHD. Two important findings have been obtained which shed light on the helium fueling terms with RMP fields and the inward transport by the competition between friction and thermal forces in the plasma edge region. Concerning the fueling terms it was seen that a recycling source must be assumed in order to reconstruct the experimentally obtained emission distributions from neutral helium lines. This is opposed to the alternative of a source term at the puff location. This is shown in figure 4. Here, the spectroscopically measured 2-D distribution of neutral helium emission at $\lambda = 667.8nm$ is shown on the left and compared to a synthetic reconstruction of this emission in EMC3-EIRENE [4]. A successful reconstruction of the general emission distribution is only possible when assuming a distributed helium neutral source from recycling on the divertor targets (a simplified divertor target representation has been used (see [4])). This provides important support for the helium recycling term being dominant in the helium particle balance. However, at the same time attempts to reconstruct the experimentally measured profiles of $n_{He^{2+}}/n_{H^+}(r_{eff}/a_{99})$ failed when using only this recycling source. At LHD, in inward directed transport of helium was seen as discussed. The helium level accumulated in the core plasma of LHD represents a helium source into the EMC3-EIRENE modeling domain which covers ($r_{eff}/a_{99} \approx 0.8-1.1$). Hence, including a core fueling level of helium to the modeling domain is required to match the experimental helium concentration profiles. Without any contribution from inside the inner simulation boundary, only flat helium density profiles are seen [3]. These results on the helium recycling term and the helium core term point out, that the RMP fields affect the recycling term directly which results in reduced core fueling and consequently a reduced helium core fueling level in the modeling.

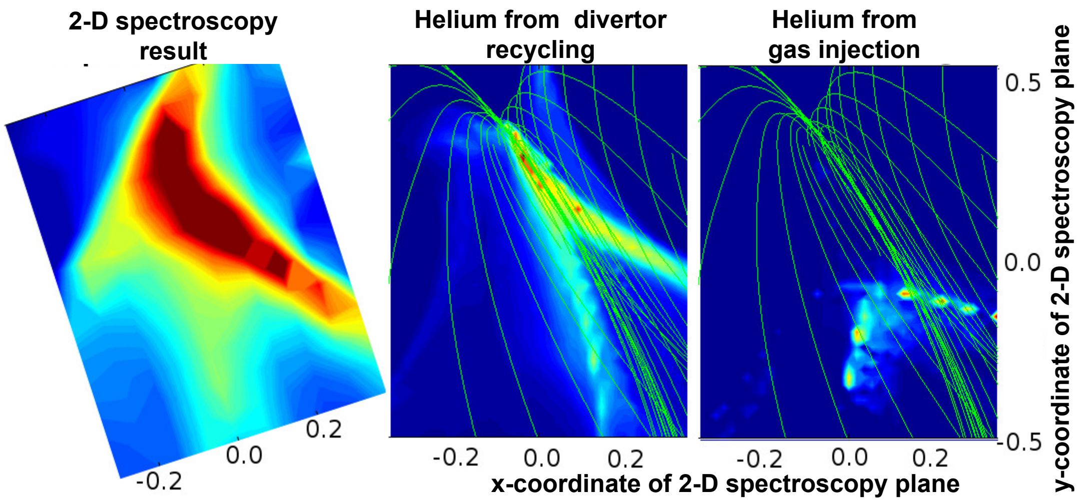

FIG. 4: 2-D images of the neutral helium emission at $\lambda = 667.8nm$ *from a new 2-D imaging spectroscopy (left side) and from synthetic modeling with EMC3-EIRENE[4]. Fueling from divertor recycling was compared to fueling solely from the gas injection.*

This again supports the notion that one of the most critical elements in controlling helium confinement and exhaust is commanding the recycling source from helium long enough such that accumulation in the plasma core is prevented. In addition to these results from fully 3-D plasma edge modeling for the LHD case, it was found for TEXTOR, that the specific size and location of the magnetic island in the plasma edge introduce a local electron-root like solution for the outward impurity flux. This was investigated with the ORBIT Hamiltonian guiding center drift model [17]. Implementing the $m/n = 4/1$ magnetic island in the plasma edge causes non-ambipolar drifts of electrons and ions which are led by fast electron losses along open field lines balanced by ion currents across the island domain. The size of the island defines in the ORBIT model the effectively resulting jump step of the drifting ions. In the T_e/T_i ratio of TEXTOR, the dominant loss channel was established by the fast electron losses and hence an electron-root like electrical field behavior is expected aiding the outward transport of impurities. The EMC3-EIRENE results for LHD, however, point out that with RMP fields the friction term on impurities is increased compared to the thermal-force[4]. More complete impurity transport analysis is required to identify the governing physics term in 3-D edge layers.

5 Concluding discussion

The results surveyed here and discussed in detail in [2], [3] and [4] demonstrate that helium exhaust can be enhanced by manipulating the plasma edge of fusion devices. Results from

TEXTOR as example for a tokamak with RMP fields and from LHD as fully 3-D system with intrinsic magnetic field stochasticity have shown that these results are generic and apply to both devices types. We found a selectively enhance outward helium transport combined with a reduced helium re-fueling efficiency, which yields reduced $\tau^*_{p,He}$ as a very beneficial feature of RMP application. It was seen that both, a localized magnetic island in the plasma edge and increased stochasticity can yield such a beneficial characteristics with a stronger reduction in $\tau^*_{p,He}$ born from the magnetic island. In particular the higher helium retention in the plasma periphery, which was seen in experiment and identified in 3-D modeling as a major contributor to the result, is promising for improved helium pumping by RMP fields in nowadays high-performance tokamaks with RMP ELM control and also for ITER. In addition, the results are promising for devices like Wendelstein 7-X which use a magnetic island in the plasma edge as the actual divertor structure. Hence, investigating the interaction of this island with the helium particle balance is a key element for qualification of the island divertor concept in optimized stellarators.

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