Modeling of Helium Transport and Exhaust in the LHD Edge

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Experimental results from LHD show a reduction of helium concentration in the plasma with the introduction of a magnetic island on the $m/n = 1/1$ resonant surface in the plasma edge. Simulations of the plasma with and without the island are carried out with the coupled code EMC3-EIRENE and compared to Charge Exchange Recombination Spectroscopy measurements of ionized core helium, and Visible Spectroscopy measurements of edge neutral helium. The numerical simulations indicate that the experimental parameters lie in a high density regime where the impurity transport is dominated by the outward directed friction force. The EMC3-EIRENE simulations capture the reduction in helium transport well and indicate that: 1) the reduction in core helium is a result of increased outward transport caused by the magnetic island and an increased opening of the edge-surface layer to the divertor plates; 2) the dominant source of neutral helium is best modeled by recycled helium at the targets; and 3) ionized helium density profiles are best matched in the simulations when there is a large core helium source in addition to a smaller edge source.

I. INTRODUCTION

Experiments performed on the Large Helical Device (LHD) [1, 2] have shown that the presence of a large island in the edge region has significant effects on core helium accumulation. Specifically, it has recently been demonstrated [3] that the presence of a $m = 1$, $n = 1$ island correlates to a reduction in the core helium content in response to helium injection (i.e. a puff/pump study) [3]. In this paper we will provide numerical simulations of these LHD configurations with and without the edge island and show that introducing an edge island into the simulation shows a reduction of helium content in agreement with the experimental results described in [3]. The numerical study presented here is based on the experiment description provided in [3] and both together support the implication that magnetic geometry can be used to alter the helium content of a stellarator.

Characterizing edge impurity transport is critical for operation of next generation fusion devices. Impurity presence in the edge may be necessary in sufficient quantities in order to isotropically radiate enough of the heat flux that escapes through the Last Closed Flux Surface (LCFS) [4, 5]. However, those impurities must not penetrate into the main plasma, where the increase in Z_{eff} can cause radiation collapse [6–8]. Also, in a fusion reactor, the exhaust of helium is of key importance. It has long been known that buildup of helium in the core plasma prevents accessibility to breakeven conditions [9]. Therefore, there must be a pathway to remove helium from the core plasma and pump it out of the vessel.

This paper attempts to elucidate the mechanisms that govern the reduction of helium transport in the presence of the edge magnetic island in LHD. Using numerical simulations we directly test the effect that the change in magnetic geometry has on the transport of helium in the edge plasma. The numerical simulation package EMC3-EIRENE includes the magnetic structure of the island, the change in the open field line geometry, and any edge stochastic regions. The fluid model in the code employs a Braginskii approximation for parallel transport but neglects cross-field fluid flows and the effects of electrostatic potentials, instead modeling cross-field transport with anomalous diffusion terms. In this paper it is found that geometric changes alone are able to show a reduction in helium content on the order seen in the experiments.

The outline of the paper is as follows. Section II describes the experimental setup in brief. Section III gives details for the simulation parameters. Section IV provides the comparisons between the experimental data and the experiment. The first part shows comparisons between experiment and a new synthetic diagnostic for line radiation of excited states of neutral helium. The second part shows comparisons of ionized helium concentration using experimental data from Charge eXchange Recombination Spectroscopy (CXRS). Section V discusses the results and explains the physics that governs the reduction of helium transport as understood from the simulation results. Finally we conclude in Section VI.

II. EXPERIMENTAL SETUP

LHD is a 10 period heliotron with major radius and averaged minor radius of 3.9 and 0.65 m [1]. It is equipped with non-symmetric coils capable of producing magnetic perturbations that can induce a large $m/n = 1/1$ island in the region just outside the LCFS. The island is clearly visible in Figure 1, where the connection lengths are plotted for the configurations with and without islands. A region of increased connection lengths is visible inside the separatrix of the magnetic island when the Resonant Magnetic Perturbation (RMP) coils are energized, indicating that the edge stochasticity is reduced in the vicinity of the island O-point. Additionally, the overall extent of the stochastic layer is enhanced with the presence of the magnetic island which can be seen as a reduction of the core confined (red) region in Figure 1. For this paper, both configurations, with and without the island have magnetic axis values of $R_{ax} = 3.90$ m.

Various diagnostics are used to provide information about the helium content in LHD and these are shown in Figure 2 in order to show the relation of the modeling domain to the diagnostic locations. A helium gas valve is located at the bottom of the torus, and is used to introduce helium impurity ions into the plasma.

The helium ions can be measured using several different diagnostics. Specifically, this paper addresses measurements of ionized helium and neutral helium. The ionized helium is represented as the ratio of He^{2+}/H^+ in the core plasma, which is determined from CXRS [10, 11]. Measurements of neutral helium are provided using visible spectroscopy of the region just inside and outside the LCFS. A 130 channel system provides measurements of line radiation from atomic transitions [12]. The viewing location of the diagnostic is shown in Figure 2. In this paper we examine the results from a transitions of neutral helium at 667 nm corresponding to a $1s3d\,^1D_2 \rightarrow 1s2p\,^1P_1$ transition.

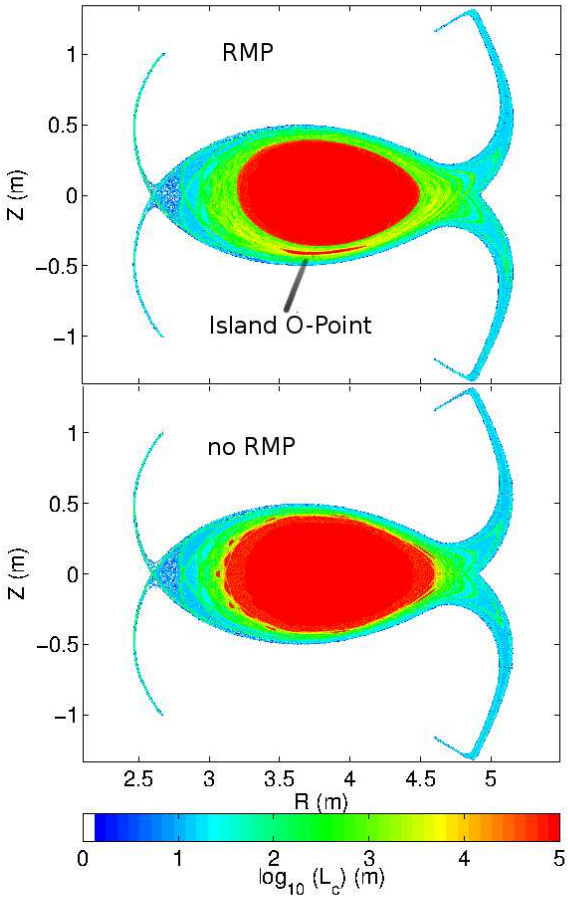

FIG. 1. Connection length plots of the configuration, $R_{ax} = 3.90$ m, with an RMP induced magnetic island (top) and without (bottom). The island is visible as an area of increased connection length in the lower half of the top plot.

An experiment to measure the transport of helium in configurations with and without magnetic islands were carried out on the LHD heliotron [3]. Two plasma discharges were compared, corresponding to configurations without any RMP coils and thus no magnetic island, and with 3.3 kA in the RMP coils which produce a radial magnetic field with relative magnitude to the main toroidal field, $B_r/B_t \approx 10^{-3}$. These are discharges #128405 (no RMP induced island) and #128391 (with RMP induced island). At ∼3.8 seconds, helium was puffed into the plasma from gas valves located at the bottom of the machine. The helium was injected at a flux density of $\Gamma_{He} = 2.0 \times 10^{19}$ particles/s and lasted for ∼150 ms, after which helium appears in spectroscopic measurements as well as in the CXRS absolute helium and hydrogen concentrations in the plasma. The two most noticeable changes induced

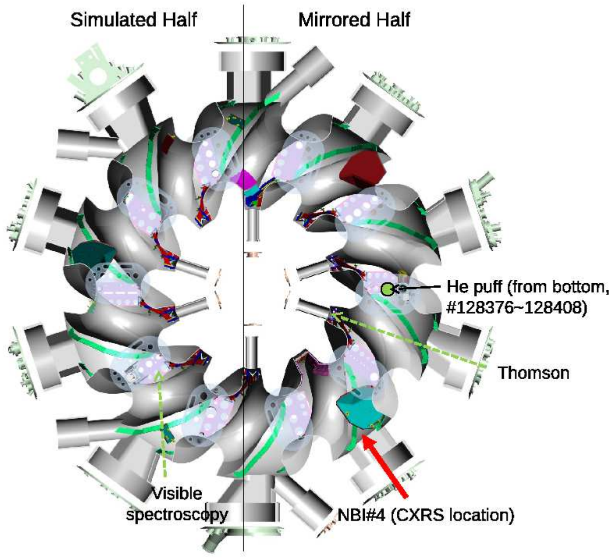

FIG. 2. Schematic of LHD with relevant diagnostics labeled

by the presence of the magnetic island were: 1) a reduction of the plasma core helium content from ≈ 50% to ≈ 20% and 2) a reduction of the helium emissivities in the visible spectroscopy. Both results strongly support reduced helium content in the plasma core and plasma edge when the island is present. Moreover, the effective helium confinement time $\tau^*_{p,He}$ was extracted from the experiment using exponential fits to the helium emissivities. With the magnetic island present, $\tau^*_{p,He}$ was reduced by 22%. For further details of the experimental findings, the reader is referred to reference [3]. In this paper we attempt to understand the underlying physics mechanisms by 3-D modeling of the helium concentration in the edge layer using EMC3-EIRENE. Direct comparisons to the experiment will be shown later in the paper.

III. SIMULATION SETUP

The LHD plasmas are simulated with the coupled code EMC3-EIRENE. EMC3 is a fluid Monte-Carlo [13, 14], EIRENE is a kinetic neutral code [15]. Coupling the two codes provides a self-consistent solution for the edge plasma.

For the configuration with a 1/1 island it is necessary to simulate a half torus, invoking stellarator symmetry on the toroidal ends. Therefore, half the torus is simulated by mirroring the simulated half (see Figure 2). For purposes of consistency we also simulate a half torus for the configuration without an island as well. Both configurations have 1 degree toroidal resolution. The simulation with an island has 89 radial and 600 poloidal cells. The configuration without an island has 75 radial and 600 poloidal cells. The input power for both configurations is 8 MW, divided equally between electrons and ions, equivalent to the heating power in the experiment.

Comparisons with electron temperature and density profiles from Thomson scattering are used to constrain the transport parameters of the simulation. We adjust the electron density at the inner simulation boundary, (close to the LCFS), and the global values of the anomalous perpendicular particle diffusivity, $D_\perp$, and the electron/ion thermal diffusivities $\chi_{\perp,e}, \chi_{\perp,i}$. Comparisons to Thomson Scattering are shown in Figures 3. For the configuration with an island, $D_\perp = 0.8$ m^2/s and $\chi_{\perp,e} = \chi_{\perp,i} = 1.1$ m^2/s. For the configuration without an island, $D_\perp = 1.0$ m^2/s and $\chi_{\perp,e} = \chi_{\perp,i} = 0.8$ m^2/s. Despite the simplicity of the transport models, EMC3-EIRENE can reproduce the profile data from Thomson scattering relatively well. There is an apparent disagreement between the experiment and the simulation in the density profile in the far outboard side (around R=4.76 m). The peaked profile in density is accompanied by a reduction of T_e at the far outboard edge which produces a nearly constant pressure, a feature not reproduced in the simulation. The reason for the behavior in the experiment is not yet understood, but one possible explanation would be that it represents a change to the magnetic field structure due to a plasma response, which has been observed in LHD discharges with RMP fields [16, 17].

The effects of the island on the plasma density and temperature are clearly visible in both the Thomson data and the numerical reconstruction by examining the highlighted region of the plots in Figures 3c and 3d. The island causes a flattening of the temperature profile and a local increase in the density. The flattening of the temperature is caused by there now being a direct parallel pathway between the inside and outside of the island that is considerably shorter than the pathway through the stochastic region. The local increase in density internal to the island is possibly a consequence of the closed field line structure of the island. Any neutral particles that ionize within the island are forced to perpendicuarly diffuse out, a process which is slower than transport through the stochastic layer [18]. Nevertheless, it is clear from the Thomson scattering results that the bulk plasma parameters are comparable between the two configurations.

In the present simulation, the last few meters along the divertor legs are omitted due

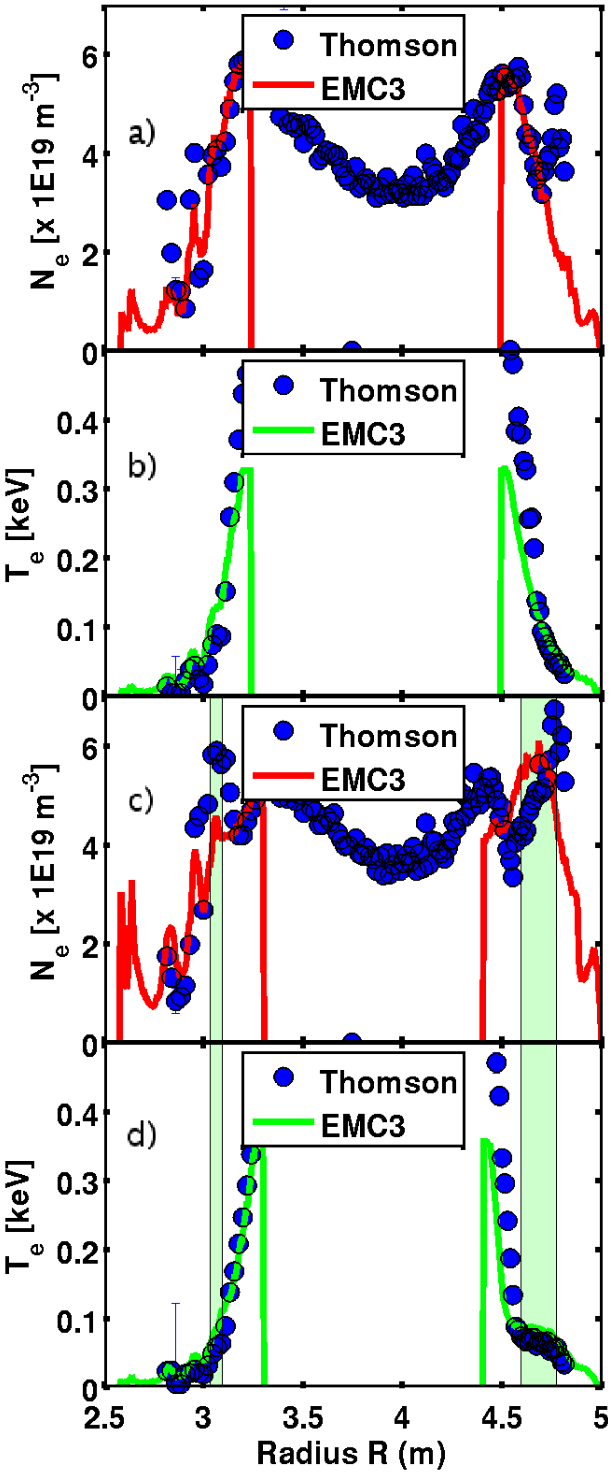

FIG. 3. Comparison of simulation with Thomson scattering measurements. a) and b) are comparisons of n_e and T_e without the RMP induced island (discharge #128405), c) and d) are comparisons of n_e and T_e with the RMP induced island (discharge #128391). The shaded region in c) and d) represents the position occupied by the island.

to the difficulty of treating the deformation of flux tubes caused by strong magnetic shear. Instead, the last cell of the divertor legs in the plasma domain is traced along field lines to the divertor surface, providing the particle deposition pattern on the divertor plates [19–21]. The recycling neutrals are released from the divertor surfaces weighted properly to account for the particle deposition distribution [22].

Impurities are handled in EMC3 as a trace species. The only effect from impurities on the main plasma is through an impurity radiation source term in the electron energy equation [14]. Because of this limited feedback, impurity behavior scales linearly with the impurity concentration. Increasing or decreasing the impurity concentration tends to only linearly increase or decrease the impurity density or radiation and overall has small effects on the main plasma. This remains true as long as the impurity radiation fraction is small relative to total power balance. The limitation of trace impurity modeling has consequences for the analysis presented in this paper. In the experiment, the core helium concentrations are often significantly higher than trace impurity levels. In the simulations for both discharges, $D_{\perp,\mathrm{He}}$ $= 1.0\ \mathrm{m}^2/\mathrm{s}$.

IV. COMPARISON OF SIMULATION AND EXPERIMENT

A. Neutral Helium

There are several options for impurity source specification in the simulation model which affect the distribution of neutral helium. The most common option is "divertor sourcing" where impurity particles are sourced from target surfaces in proportion to the hydrogen neutral recycling flux, Γ_p. The proportional variable is akin to a chemical sputtering coefficient, $S_{ch} = 0.02$ for the simulation without RMP. The total helium production rate can be calculated by the product, $\Gamma_{\mathrm{He}} = \Gamma_p S_{ch}$. To ensure that the total helium source is the same, S_{ch} is adjusted so as to account for any variations in Γ_p between the two configurations, i.e. $S_{ch}^{\mathrm{RMP}} = S_{ch}^0 \Gamma_p^0 / \Gamma_p^{\mathrm{RMP}}$, where the "0" superscript denotes no RMP induced magnetic islands. For these simulations the adjustment is significant since the ratio $\Gamma_p^0/\Gamma_p^{\mathrm{RMP}} \approx 0.5$, and therefore the value of $S_{ch} \approx 0.01$ for the simulation with RMP. In these LHD simulations, the impurities sourced from the divertor will be sourced from the same locations as the neutrals, with the same relative weights.

Impurities can also be sourced from pre-specified locations, allowing for local impurity sources from gas puffs to be modeled directly. This allows a second option for the impurity sourcing, one located at the physical location of the helium puff valves on LHD.

Future fusion devices will need to account for the comparably weak pumping efficiency of helium. Therefore, helium produced in the device will be outwardly transported to the edge and then recycle multiple times in the plasma edge before being pumped away. It is critical that recycling helium be retained in the plasma periphery and not penetrate back into the core plasma. The EMC3-EIRENE code is perfectly suited to study the mechanism of outward transport, recycling and refueling of helium. In order to resolve the role of helium recycling for the concentration of helium impurity inside the edge surface layer, we performed modeling with helium sourced from the gas inlet only (puff source) and compared it to a case where the helium influx was provided from the recycling surface (divertor source). We compare the results of these two scenarios using the visible spectroscopy measurement described above and shown in Figure 4, and a newly developed synthetic diagnostic implemented in EMC3-EIRENE [23]. The synthetic diagnostic produces a line integrated measurement through the LHD simulation domain. At each point in 3D space it calculates a line emission intensity using the ADAS database. These emission values are then integrated over the line of sight producing a view similar to that of the visible spectroscopy diagnostic.

The results from the synthetic diagnostic for impurity fueling using local (puff) sourcing and global (divertor) sourcing are shown in Figure 4. As is clearly visible, the divertor source simulation better matches the experimental data in shape. In addition, the magnitude of the radiation in the puff fueling is several orders of magnitude below the divertor fueling, and drops off many orders of magnitude between the puff location and the location of the visible spectroscopy diagnostic.

From the knowledge of the diagnostic viewing geometry and the information from the divertor sourcing simulation we can characterize the radiation profile by overlaying magnetic field lines on it. It can be seen from the center plot of Figure 4 that the main radiation bundle appears to lie near the helical x-point line, with smaller radiation values appearing along the divertor legs.

It is clearly shown that the inclusion of divertor recycling of helium is a key process to reproduce the experimental observation. The helium puffed in the experiment is recycled many times so that by the time the experimental data are taken, they are roughly uniformly

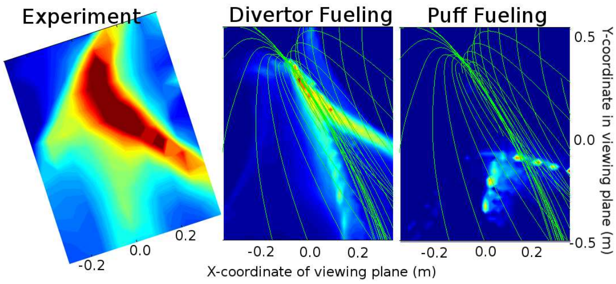

FIG. 4. Line radiation from 667 nm He line for configurations without the magnetic island. Shown are experimental results from discharge #128405 (left), Synthetic diagnostic using EMC3-EIRENE data with divertor sourcing (middle), and synthetic diagnostic using EMC3-EIRENE data with puffed fueling (right). For the simulated data, guide lines indicating the paths of magnetic fields in the divertor legs are added in green. Color scale is arbitrary.

distributed toroidally. The neutral helium seen in the experiment is primarily sourced from helium ions that neutralize at the wall and recycle back into the plasma. This is an important finding to characterize the migration of helium in the vessel.

B. Ionized Helium

Turning to ionized helium and the results from charge exchange analysis, we discuss the experimental results which show that there is a strong reduction of the helium content relative to the main plasma species in the core. The comparison is constrained in several ways. First, EMC3-EIRENE only simulates the edge regions, and the overlap only appears close to the vicinity of the 1/1 island. Second, the magnitude of the helium impurity in the simulation needs to be such that the trace impurity assumption in the code is met. The experimental core concentrations reach values much higher than trace impurities, which complicates the comparison.

Nevertheless, the simulation does indeed show a reduction in the ratio of He^{2+}/H^{+} across the entire edge plasma when the divertor source is specified. These results are shown in Figure 5. In the vicinity of the island (in the shaded region) the simulation predicts a reduction in the ratio of He^{2+}/H^{+} of about 25%. The experimental reduction is around 60%, although the error bars are large enough that a 25% reduction is within the margin of error. Also, in Figure 6, the He^{2+} density over the entire poloidal cross section is shown. The reduction in helium content is most clearly seen in the confined plasma region near the

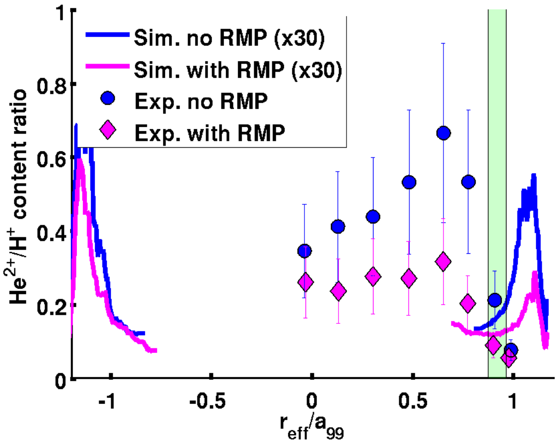

FIG. 5. He^{2+}/H^{+} ratio as calculated by EMC3-EIRENE along the CXRS viewing line for case without island (blue) and with (magenta), along with the experimental results without island (blue diamond) and with (magenta circle). The location of the island is shaded in green.

LCFS. In this region, the configuration with the RMP shows a reduction of around 40% of He^{2+}. The simulation indicates that it is the total helium concentration that is reduced, not just the ratio of He^{2+}/H^{+}.

The reduction of the helium ratio in the presence of the island is reproduced in the simulation. However, there is a discrepancy between experiment and simulation with regards to the radial profile. The experimental data (see [3] and Figure 5) show that helium content decreases monotonically with minor radius in the simulation region, ($r/a > 0.7$). On the other hand, the divertor fueling has a peak helium concentration in the island and then a sharp fall-off on either side.

The magnitude of the helium content is also an issue when the helium is fueled from the divertor. It is possible to increase the magnitude in the simulation by adjusting the source coefficient. However, to reach the values of helium concentration in the island, the helium recycling source would need to increase by a factor of 10-20. The best way of constraining the magnitude of the neutral source given the experimental data at hand is by an absolute comparison of the magnitude of the neutral line radiation (Figure 4) but this is beyond the scope of this paper.

It is possible to improve the agreement of the radial profile between the simulation and the charge exchange diagnostic by better modeling the helium source profile. In the experiment the core helium concentration is high, with He^{2+}/H^{+} in the configuration without

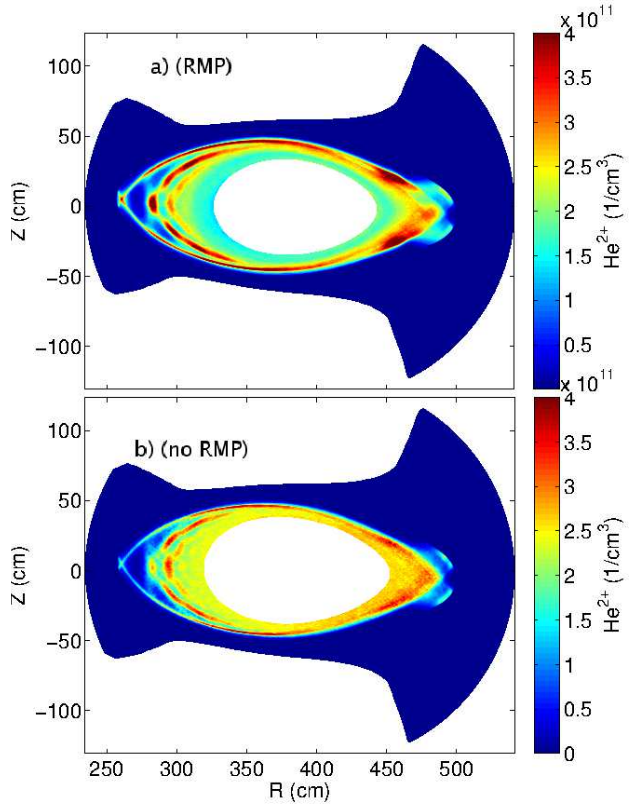

FIG. 6. Plots of simulated He^{2+} from EMC3-EIRENE both with (top) and without (bottom) an RMP induced island

the RMP reaching above 70%. These large values of measured helium indicate that the core plasma operates as a helium reservoir. It is not possible to simulate the core helium self-consistently with EMC3-EIRENE at this point. However, we can approximate a core reservoir by including a source of He^{+} ions at the inner simulation boundary. This internal source combines with the smaller recycling source at the wall to produce the full helium profile.

With internally sourced helium, a better profile agreement can be seen in the edge plasma between the experiment and the simulation as seen in Figure 7. Here we inject exactly the same amount of helium in both the cases with and without the RMP induced island. Both the experiment and simulation show a reduction of the He^{2+}/H^{+} ratio at about the same relative order of magnitude. It should be noted that the helium content is still more diluted in the simulation because of the trace impurity requirement and is multiplied by 2 in Figure 7. Even though the amount of helium is large in these results, it is still being handled as a

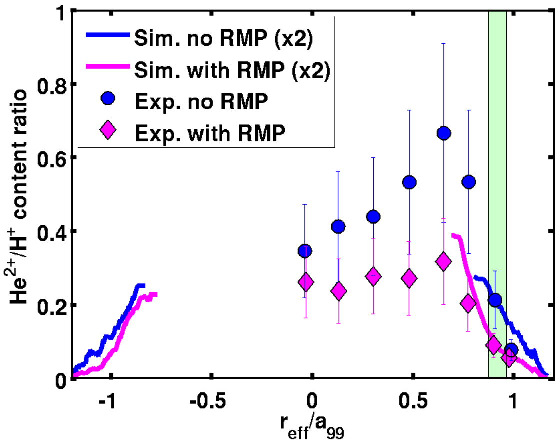

FIG. 7. Comparison He^{2+}/H^{+} of between experiment (points) and scaled simulation (lines) with (magenta, discharge #128391) and without (blue, discharge #128405) the RMP induced island

trace species (i.e. impurity-impurity collisions are not included.)

Matching both the visible spectroscopy and the charge exchange diagnostic is only currently possible by a superposition of the two impurity sourcing options, using the divertor source to reproduce the distribution of neutral helium and the internal source to reproduce ionized helium. It is important to note that altering the core helium content produces no effect on the neutral line radiation profiles seen in Figure 4. This is because EMC3-EIRENE has no recombination pathway for ionized helium to neutralize. The only source of neutral helium in the simulations is the wall source. Similarly, as long as the magnitude of the wall source is smaller than the internal source, the change in the ionized helium profile is negligible.

V. DISCUSSION

Given the above results it is possible to provide a framework for a physical explanation for the bulk of the experimental observations. To explain both the reduction in He^{2+}/H^{+} ratio seen by charge exchange, and the reduction in core helium content, it is suggested that the island enhances the outward transport of helium in the vicinity of the edge surface layer. This enhanced transport allows for the flushing of impurities from the main plasma which explains the reduction in core impurity content in both simulation and experiment.

The possible causes for the increase outward transport are discussed here. The EMC3-

EIRENE modeling suggests increased outward transport due to an enhanced opening of the edge surface layer by inserting the 1/1 island into this important core-edge interface region. This enhanced opening of the edge surface layer is visible in Figure 1 where the presence of the island produces shorter connection lengths on average in the edge stochastic region. The level of magnetic field line opening from the radial region surrounding the island is increased relative to the stochastic edge without the island. As a result, a larger outward particle flux, manifested in the code by a factor of two increase in the particle recycling flux, Γ_p, is supported by the larger amount of open field lines.

The same topological changes also affect the background plasma parameters. The RMP coils produce an increase in the radial magnetic field, B_r in the edge. Both configurations, with and without the island, lie in a high density regime for LHD, where the ion friction force is large compared to the thermal gradient force [14]. Figure 8 shows a comparison of the poloidally and toroidally averaged absolute values of the friction force to the thermal gradient force for both configurations with and without RMP. The configuration without RMP shows that the friction force is approximately 2 times the thermal gradient force in the edge region. The friction force is even more dominant in the RMP configuration, with the friction force up to 8 times the thermal gradient force. In such regimes, impurity content is seen to be reduced in the core (see Figure 13 in [24]). In the friction dominated regime the addition of the enhanced B_r can increase the impurity outflow velocity and thereby decrease the impurity retention in the stochastic layer.

VI. CONCLUSION

The puffed helium experiments provide useful information for the transport of impurities in the edge of LHD in the presence of a magnetic island. It is found, from comparisons with the synthetic diagnostic of impurity line radiation, that the neutral helium profile is best matched with a source from the divertor, while the ionized helium is best reproduced by helium sourced inside the LCFS. In the experiment this can be described as a reservoir of core helium, where some helium leaves the confined plasma through the stochastic layer and is recycled back into the plasma after reaching the divertor plates.

To explain the reduction in helium concentration with the island presence, it is suggested that the RMP coils produce an additional magnetic field line loss which is represented by

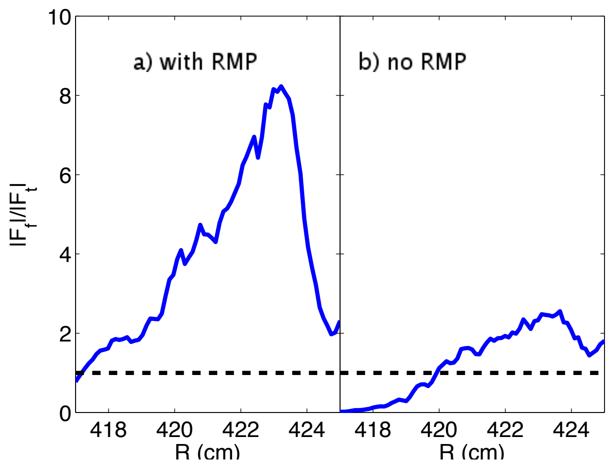

FIG. 8. Comparison of impurity force balance in configurations with (a) and without (b) RMPs. The plot shows the ratio of the friction force to the thermal gradient force. The absolute values of the forces are toroidally and poloidally averaged and then mapped back to the midplane radius value.

an increase in the extent of the stochastic region. Additionally, in the high density regime where the friction force is dominant, the outward flow of plasma and thus impurities is strengthened. Both effects cause a flushing of impurities from the main plasma, and weakens the stochastic layers ability to retain helium impurity ions in the stochastic layer, yielding a reduction in impurity concentration across the entire plasma.

VII. ACKNOWLEDGMENTS

Work supported by grants from US DOE-SC0006103 and DOE-SC00013911. Supported also from JSPS KAKENHI Grant No. 25420893 and by startup funds from the Department of Nuclear Engineering, University of Wisconsin-Madison.

[1] Ohyabu, N *et al* 1994 Nuc. Fus. **34** 387

[2] Ida, K *et al* 2015 Nuc. Fus. **55** 104018

[3] Schmitz O. *et al* 2016 "Enhancement of helium exhaust by resonant magnetic field perturbations at TEXTOR and LHD" accepted for publication in Nuc. Fus

[4] Ongena J *et al* 1999 Plasma Phys. Control. Fusion **41** A379

[5] Kotschenreuther M. *et al* 2007 Phys. Plasmas **14** 072502

[6] Krasheninnikov S I *et a;* 1999 J. Nuc. Mat. 266, 251-257

[7] Feng Y *et al* 2005 Nuc. Fus. **45** 89-95

[8] Kobayashi M *et al* 2010 Phys. Plasmas **17** 056111

[9] Reiter D *et al* 1991 Plasma Phys. Control. Fusion **13** 1579

[10] Ida K *et al* 2015 Rev. Sci. Inst. **86** 123514

[11] Ida K *et al* "Helium transport in the core and stochastic edge layer in LHD" *this issue*

[12] Kobayashi M *et al* 2015 "Relation between impurity/hydrogen emissions and edge stochastic magnetic structure at detachment transition observed in LHD divertor region" 20th Intl. Stellarator and Heliotron Workshop SR-01

[13] Feng Y *et al* 1997 J. Nuc. Mat. 241, 930

[14] Feng Y *et al* 2004 Contrib. Plasma Phys. **44** 57

[15] Reiter D *et al* 1992 J. Nuc. Mat. **80** 196

[16] Kobayashi M *et al* 2013 Nuc. Fus. **53** 093032

[17] Narushima Y *et al* 2013 Plasma Fus. Res. **8** 1402058

[18] Hegna C C and Callen J D 1992 Phys. Fluids B **4** 4072

[19] Morisaki T *et al* 2005 J. Nuc. Mat. 337, 154-160

[20] Feng Y *et al* 2008 Nuc. Fus. **48** 024012

[21] Masuzaki S *et al* 2010 Contr. Plas. Phys. **50** 629

[22] Kobayashi M *et al* 2013 Nuc. Fus. **53** 033011

[23] Frerichs H *et al* 2010 37th EPS Conference on Plasma Physics P2.127

[24] Feng Y *et al* 2011 Plas. Phys. Control. Fus. **53** 024009