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ABSTRACT

We report first direct measurements of divertor exhaust gas impurity enrichment, η_{exh} = (exhaust impurity concentration)÷(core impurity concentration), for both unpumped and D_2 puff-with-divertor-pump conditions. The experiment was performed with neutral beam heated, ELMing H–mode, single-null diverted deuterium plasmas with matched core and exhaust parameters in the DIII–D tokamak. Neon gas impurity was puffed into the divertor. Neon density was measured in the exhaust by a specially modified Penning gauge and in the core by absolute charge exchange recombination spectroscopy. Neon particle accounting indicates that much of the puffed neon entered a temporary unmeasured reservoir, inferred to be the graphite divertor target, which makes direct measurements necessary to calculate divertor enrichments. D_2 puff into the SOL with pumping increased η_{exh} threefold over either unpumped conditions or D_2 puff directly into the divertor with pumping. These results show that SOL flow plays an important role in divertor exhaust impurity enrichment.

1. INTRODUCTION

Deliberate addition of impurities to increase radiated power is a frequently proposed technique to radiate a large fraction of the power exiting a magnetically confined, fusion core plasma before it reaches a divertor target. Because core impurities both dilute and cool the fusion fuel, it is desirable to enrich the divertor impurity concentration and radiation relative to the core.

The retention of impurities in a divertor is determined by both the distance a neutral impurity atom travels before being ionized and the forces acting on the impurity ion in the scrape-off layer (SOL) and divertor plasma. Dense, ionizing divertor and SOL plasmas screen the core from impurities. The net electric and collisional thermal forces drive impurity ions up the temperature gradient, away from the divertor. Frictional drag with the hydrogenic plasma is large and is toward the divertor near the target, where most of the hydrogen is recycled and re-ionized. However, plasma flow toward the divertor is slow upstream of the recycle region, and the thermal force typically dominates there. Furthermore, on some magnetic surfaces the re-ionization plasma source can be excessive and drive some plasma upstream away from the recycle region.

One possible means to overcome impurity flow away from the divertor is to increase the SOL plasma flow toward the divertor by puffing D_2 into the SOL while simultaneously pumping the same amount of D_2 from the divertor, so-called puff and pump. The first puff and pump experiment on DIII–D demonstrated up to a twentyfold reduction of core Ar impurity by puffing about 1.2×10^{22} D/s in ELMing H–mode [1]. However, because the large D_2 puffs decreased core temperature while increasing the core, SOL and exhaust gas densities, and the ELM frequency, the experiment could not distinguish the effect of SOL flow from other parameter changes. Furthermore, there were no suitable diagnostics available to measure divertor impurity content. More recent experiments on ASDEX-U in completely detached H–mode (CDH–mode) [2] reported a divertor exhaust neon enrichment η_{exh} of 5.6 during D_2 puff and pump vs. only 1.5 without it [3]. Additional experiments with matched core and divertor parameters, in which only the puff and pump rate was varied, concluded that η_{exh} in CDH–mode depended mainly on the divertor neutral gas density and little on either magnitude or location of external D_2 puffing [4,5]. However, divertor impurity content was not measured in the ASDEX-U experiments, but was calculated from a multi-compartment model to match the observed temporal decay of impurity spectral lines.

The experiment described in the present paper obtained the first *direct* measurements of neon in a tokamak divertor exhaust. The data show η_{exh} dependent on both puff and pump and the point of D_2 injection in DIII–D ELMing H–mode discharges with attached divertor. Furthermore, the data show transient storage of Ne in a reservoir, thought to be the target graphite, which effect would influence the calculation of η_{exh} from decay rates alone. Although the ultimate parameter of interest is divertor *plasma* impurity enrichment, its calculation is excessively model dependent using only data available from the present DIII–D diagnostic set. Future experiments will attempt to overcome this limitation.

2. EXPERIMENT

All of the measurements were performed in lower-single-null diverted ELMing H–mode discharges with R_0 = 1.68 m, a = 0.60 m, elongation = 1.8, I_p = 1.3 MA, B_T = 1.9 T (ion grad-B drift toward divertor target), q_{95} = 4.1, neutral beam heating = 6.5 MW. The exhaust plenum D_2 pressure was kept at 0.28–0.32 Pa by adjusting the position of the plasma outer strike point (OSP) relative to the pump plenum inlet aperture. This pressure yielded an exhaust rate of $\approx 6 \times 10^{21}$ D/s when the divertor liquid-He-cooled cryocondensation pump was activated. Neon was the chosen impurity because it was the easiest impurity to diagnose among those that recycle and can be cryocondensed. (The pumping speed of both D2 and Ne in the presence of D2 have been calibrated.)

Four different D_2 flow geometries were studied and are illustrated in Fig. 1. Case A had neither active pump nor D_2 puff. The plasma rapidly attained the "natural" ELMing H–mode density, determined by equilibrium between wall absorption and desorption of D_2. Cases B–D had pumping plus steady D_2 puffing at $\approx 6 \times 10^{21}$ D/s during the pumping phase. Case B puffed the D_2 from a single, calibrated gas valve located in the upper outer corner of the vacuum vessel. Case C puffed the D_2 from a set of 16 capillaries distributed toroidally near the midplane, offering greater toroidal gas symmetry and a SOL only about half as thick as at the Case B puff location. Case D puffed the D_2 from a single calibrated valve into the divertor private flux volume, for which little SOL flow is expected. Trace neon was puffed into either the divertor private flux (Cases B–D) or upper vessel (Case A) volumes via a calibrated valve. All plasmas were well matched for core and SOL density and temperature profiles prior to Ne injection, but the neon raised the core electron density slightly, especially in Cases C and D. All cases had about the same electron temperatures ($\approx$40 eV) and densities (1.5–2 $\times 10^{19}$ m^{-3}) in the SOL at a divertor Thomson scattering view point a bit outward from the separatrix X-point, and both inner and outer divertor legs were well attached to the floor. The temporal evolutions of selected waveforms for Cases A and B are shown in Fig. 2. The D_2 puffs were steady from $t \approx 1.5$ s until $t \approx 5$ s. The Ne puff started at t = 2.0 s. In Case A it was a short 80 ms puff, but in Cases B–D it was steady until t = 4.0 s.

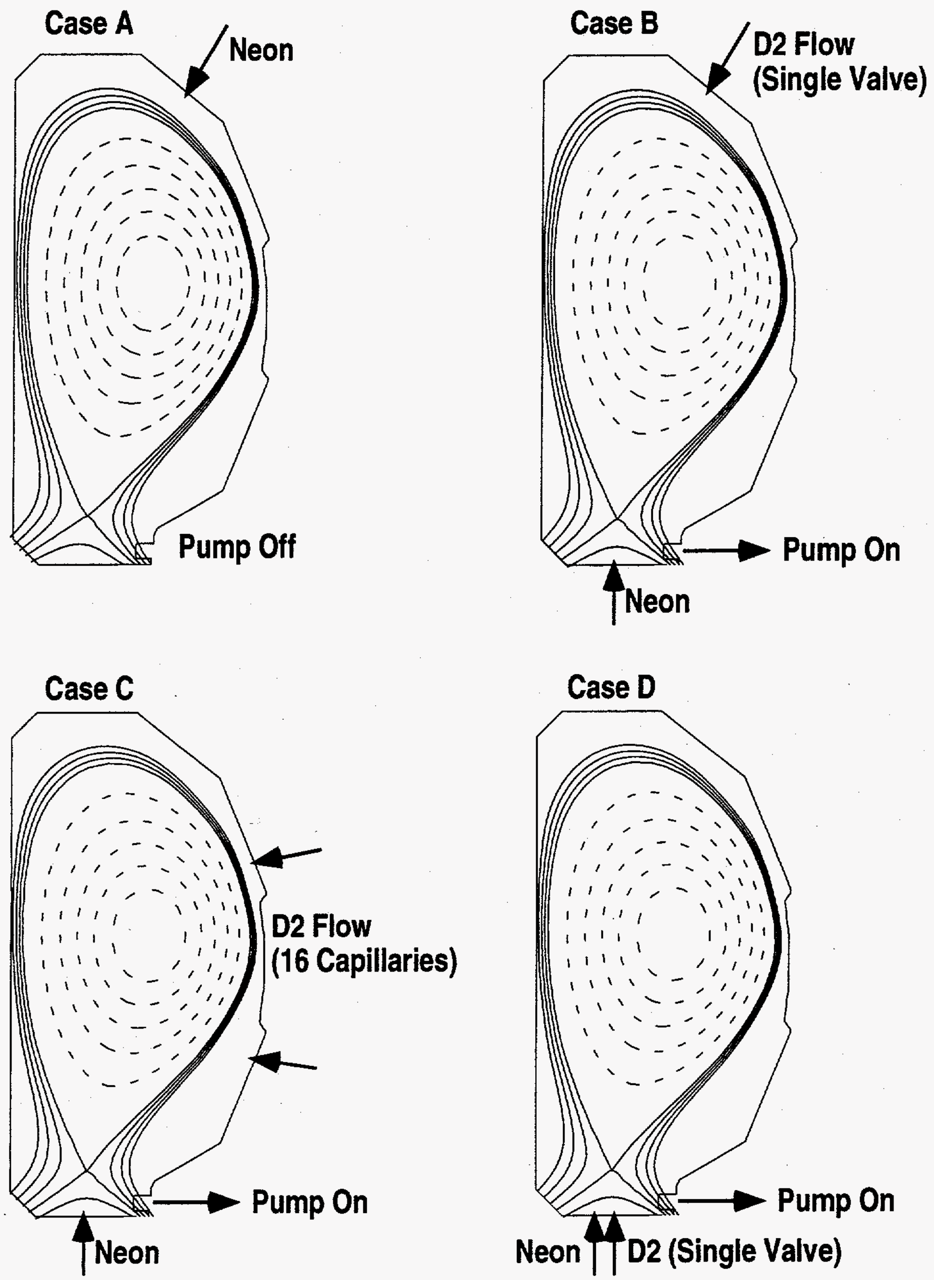

Fig. 1. Schematic of the four experimental gas puff and divertor pump combinations. Shot numbers of Cases A–D are 86907, 86912, 86921, and 86923, respectively.

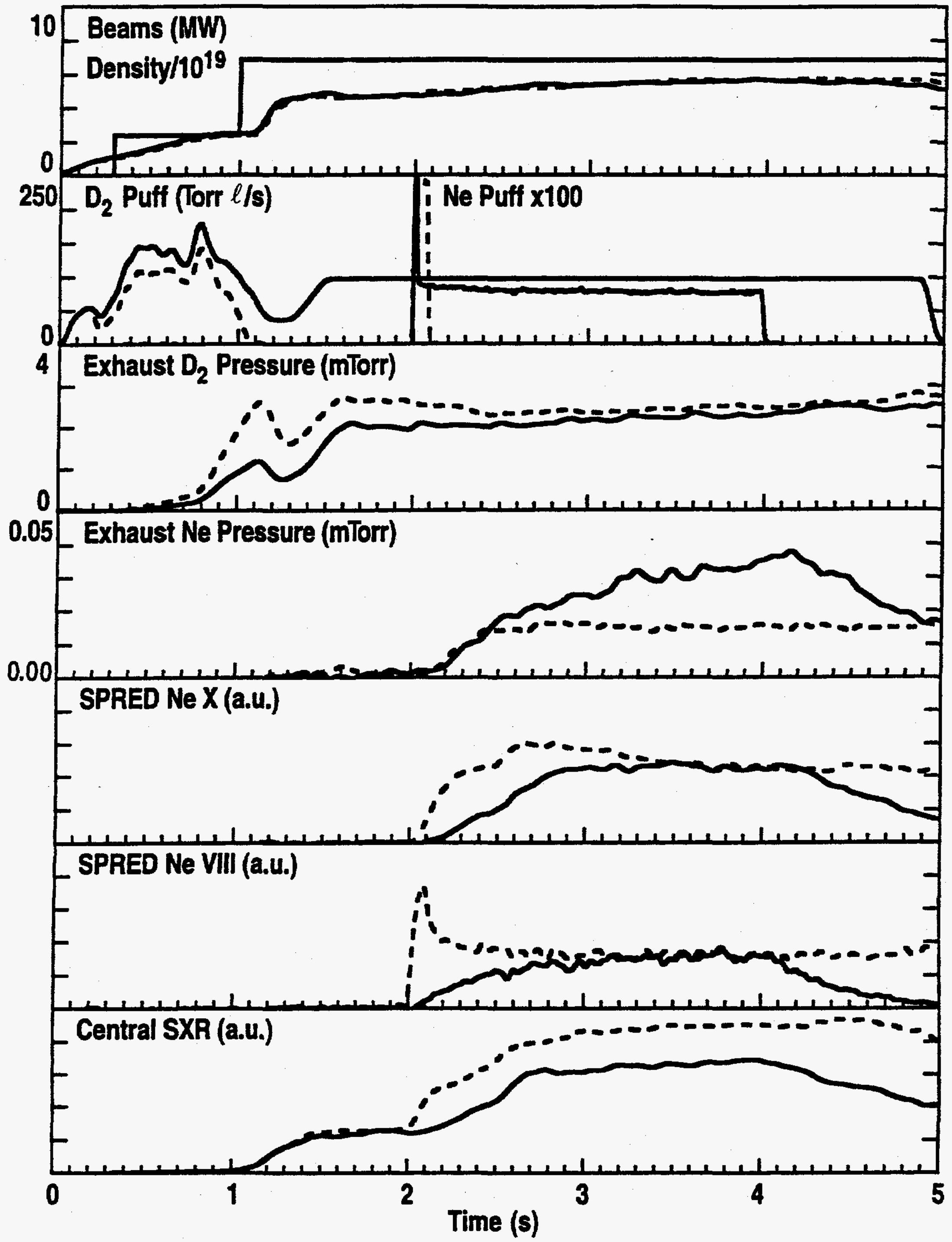

Fig. 2. Time traces from Case A (dashed) and Case B (solid) discharges.

The Ne^{+10} density profile in the core was calculated from measurements of the Ne X n = 11–10 transition at 524.9 nm excited by charge exchange recombination (CER) with energetic deuterium neutrals from the heating beams, using a 32-spatial-channel, high resolution, absolute intensity spectrometer array [6]. The principal uncertainty is the accuracy of the charge exchange excitation rates, which for neon are presently based on computational models. Therefore, these rates were checked in a set of separate discharges by comparing the measured line-integrated bremsstrahlung measured by the same 32-channel spectrometer array in a band near 523 nm against bremsstrahlung calculated from the measured electron density and temperature profiles provided by Thomson scattering and the carbon and neon density profiles calculated from the CER measurements, using tabulated excitation rates [7]. The carbon rates are well established, and there were no other significant impurities in these plasmas. The puffed Ne increased Z_{eff} by ~1 (Ne^{+10} concentration ~1%). This comparison showed that the tabulated neon excitation rates must be increased by a factor ≈1.7 [6,8].

The neon content in the exhaust gas was measured by a modified Penning gauge [9]. Hydrogenic and neon visible line intensities from the Penning discharge were measured. The line intensities are non linear functions of the D_2 and Ne pressures and are not independent of the species mix. The gauge is differentially pumped to operate in its optimum range, and the gauge was calibrated *in situ* over a wide range of pressures and Ne/D_2 mixtures [10]. Total plenum gas pressure was also measured by a capacitance manometer and an ionization gauge, and the data were in agreement. Figure 2 shows the uncorrected Ne exhaust pressure from the Penning gauge.

3. RESULTS

Divertor exhaust enrichment, η_{exh}, is defined as f_{exh}/f_{core}, where $f_{exh} = p_{Ne}/(2p_{D_2})$ and $f_{core} = n_{Ne^{+10}}/n_e$ are the exhaust and core neon concentrations, respectively. We evaluate f_{core} at normalized minor radius $\rho = 0.7$, which is interior of the ELM zone, yet close enough to the edge to respond rapidly to changing divertor conditions. MIST modeling shows that essentially all of the neon is Ne^{+10} at this radius.

Figure 2 illustrates the qualitative behavior of Ne in the experiment. After Ne is puffed, it appears in the SOL and edge (Ne VIII, 77.04 nm, SPRED UV spectrometer) and core (Ne X, charge exchange line at 18.73 nm; thin foil filtered soft x-ray diode). It also appears in the divertor exhaust plenum gas (Penning gauge, response time ≈200 ms). Neon enters the plasma more slowly with puff and pump (Case B). Neon leaves the plasma after the Ne puff at about the same rate it enters in Case B, while in Case C, and especially in Case D, (not shown) the Ne decay rate is slower.

Values of η_{exh} for each of the experimental cases at $t = 4$ s are given in Table 1. Neon exhaust enrichment increased by a factor 2–3 in Cases B and C, with SOL puff and pump, relative to the unpumped "natural" Case A. In contrast, D_2 puffed into the private region (Case D) yielded no improvement over "natural" enrichment. Thus, the DIII–D results shows an increase of exhaust enrichment with SOL puff and pump.

Divertor recycling was not controlled in this experiment, and it varied among the four cases. Recycling produces a strong plasma flow in the neighborhood of the target that collisionally entrains impurities. It has been calculated that the effects of this local entrainment are still appreciable far upstream in the SOL [11], so the variable recycling might affect the core Ne content and thus the exhaust enrichment. Outer strikepoint recycling can not presently be measured in DIII–D when the OSP is in the exhaust aperture for pumping. Therefore, in Table 1 we present three other indicators of recycling: H_α emission from the inner strikepoint, gas flux under the X-point (measured by an ionization gauge), and the peak private region plasma density (measured by divertor Thomson scattering). The private plasma temperature did not vary within measurement uncertainty. The data suggest that recycling was greatest in "natural" Case A and was also large in X-point puff Case D, both low enrichment cases. However, theory [11] and the ASDEX-U CDH–mode results [3–5] predict high divertor enrichment from high recycle. Thus, the higher η_{exh} observed in DIII–D Cases B and C with SOL puff and pump occurred despite their lower recycling.

ELM frequency also was not controlled in this experiment. Frequent ELMs expel edge plasma with its impurity content into the SOL, and the additional SOL plasma increases flow toward the divertor and SOL screening. These effects ought to increase exhaust enrichment. Table 1 gives the ELM frequencies. The two low-η_{exh} Cases A and D had the lowest and the second highest frequencies, respectively, which suggests that the variable ELM frequency did not determine the enrichments. However, among the pumped Cases B–D, enrichment is approximately proportional to ELM frequency, so it is possible that ELM frequency is an important parameter if the low η_{exh} in the unpumped case was determined by other processes.

Table 1
Neon enrichment experiment at $t = 4$ s.

Parameter		Case A	Case B	Case C	Case D
$f_{exh} = p_{Ne}/2p_{D_2}$	(%)	0.31	0.75	1.19	0.45
$f_{core} = n_{Ne}/n_e$	(%)	0.46	0.39	0.87	0.65
η_{exh}		0.67	1.92	1.37	0.69
H_α at ISP	(photon s^{-1} m^{-2} $ster^{-1}$)	1.6×10^{20}	1.1×10^{20}	0.7×10^{20}	1×10^{20}
Gas flux under X-point	(molec m^{-2} s^{-1})	5×10^{21}	2.5×10^{21}	2×10^{21}	4×10^{21}
Peak private plasma density	(m^{-3})	7×10^{19}	2.5×10^{19}	2×10^{19}	5×10^{19}
Private region temperature	(eV)	2	3	3	3
ELM frequency	(s^{-1})	47	55	38	21

Quite unexpectedly, the quantitative time histories of injected, exhausted and core Ne inventories yielded a substantial Ne deficit in Cases B–D. Figure 3, which presents Ne inventory time histories for Case B, shows a Remainder = (Total Inventory) – (Core Ne) – (Plenum Ne) of about 1.5×10^{19} Ne atoms, where the (Total Inventory) = (Puffed Ne) – (Pumped Ne). The deficit is not in the divertor plasma, because then the corresponding $n_{Ne} \sim 10^{19}$ m^{-3} would be unmistakably manifested by a much larger divertor radiation than is in fact observed. Figure 3 shows that injected Ne is sequestered rapidly at the beginning of the Ne puff and then more slowly through the rest of the puff. The sequestered Ne is released without long-term storage after the puff. The Ne evolution can be approximated by a four-chamber model consisting of core and divertor plasmas, plenum gas and a hypothesized "wall" or target reservoir. The data are insufficient to determine all the unknown parameters, but the model requires "wall" Ne storage times ~10 ms [6]. Long-term Ne holdup in a limited discharge was reported previously [12].

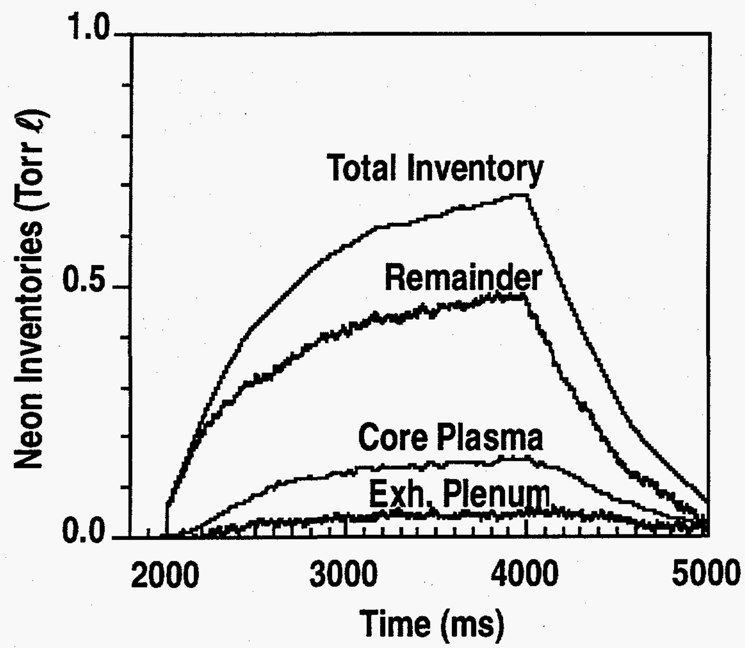

Fig. 3. Neon inventory time histories in the Case B discharge. Shown are core, plenum and total (= puffed – pumped) Ne inventories, and remainder = total – core – plenum.

4. DISCUSSION AND CONCLUSION

The present DIII–D results show that D_2 puffed into the SOL with matched exhaust pumping increased exhaust neon enrichment by 2–3 times over either unpumped conditions or D_2 puffed directly into the divertor, supporting the hypothesis that SOL flow plays an important role in divertor impurity enrichment. In contrast, ASDEX-U experiments [3–5] concluded that η_{exh} depended mainly on the divertor neutral flux and little on either the external D_2 puff magnitude or location, supporting the hypothesis that divertor neutral gas and/or plasma density plays the principal role in enrichment. However, the two sets of experiments were done with very different plasmas. The DIII–D experiment used H–mode plasmas with Type I ELMs (relatively large), fully attached divertor legs and low, nonperturbing Ne densities. The ASDEX-U experiments had completely detached H–mode plasmas with Type 3 ELMs (small, near H–mode power threshold) and large Ne densities. Further experiments and numerical modeling are needed to better understand divertor impurity enrichment.

Neon gas in the DIII–D puff and pump shots was temporarily stored in an unidentified reservoir, hypothesized to be the divertor targets, for ~10 ms. A possible mechanism might consist of: 1) implantation of ~100 eV Ne ions a few atoms deep in the graphite target, and 2) Ne release as the target erodes. DIII–D target erosion, measured at ~150 Å/s by the divertor materials exposure system [13], would release the trapped Ne in ~10 ms as required. If such Ne retention is commonplace, then calculation of divertor enrichment by particle accounting methods alone is suspect, and direct measurements of the impurity distribution are necessary.

In summary, we report first direct measurements of divertor exhaust impurity enrichment. D_2 puff into the SOL with matched pumping increased exhaust neon enrichment by 2–3 times over either unpumped conditions or D_2 puff directly into the divertor. Much of the puffed neon entered an unmonitored temporary reservoir, inferred to be the graphite divertor target.

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