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HELIUM COMPRESSION AND ENRICHMENT WITH POLOIDAL DIVERTOR

(Doublet-III Experimental Report, 7)

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The helium ash enrichment function of a divertor has been experimentally demonstrated. Helium atoms accumulate in the divertor region, as the electron density of main plasma increases. With a helium allowance of 1% of electron density in the main plasma, neutral helium at the divertor region is as high as 3.6×10^{-5} Torr. A factor of 2.4 helium enrichment in the divertor region was also observed. This experiment indicates the possibility of helium ash exhaust in an alpha-heated, diverted tokamak using practical-sized pumping ducts.

Keywords; Helium Exhaust, Divertor, Helium Compression, Tokamak, Doublet-III

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ポロイダル・ダイバータによるヘリウム圧縮と濃縮
（ダブレットⅢ実験報告・7）

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ダイバータのヘリウム灰濃縮機能が実験的に示された。主プラズマの電子密度が増すと，ダイバータ領域にヘリウム原子が集積する。ヘリウムの主プラズマ中への混入量を1％に抑えても，ダイバータ付近のヘリウム分圧が3.6×10^{-5} Torrに達する。またダイバータ領域で2.4倍のヘリウム濃度が観測された。実現可能な大きさの排気孔を用いて，ダイバータ付きトカマク型核融合炉のヘリウム灰排気の可能性がこの実験から示される。

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目次なし

Helium ash exhaust is one of the most important issues in thermonuclear fusion research. The alpha particles will, unless exhausted, dilute the fuel particles and deteriorate fusion reactivity since total particle density is limited by the maximum available β. A simple divertor is proposed for the INTOR tokamak by Shimomura et al.,[1-3]. Their calculation showed the helium pressure at the divertor plate to be 1×10^{-5} Torr, the pumping speed then required becomes 5×10^{5} ℓ/s, which is an engineering possibility. Helium enrichment is also important from the viewpoint of tritium inventory.

We wanted to test the feasibility of using a divertor to concentrate neutral helium by experiments in diverted plasmas in Doublet III[4,5]. Figure 1 shows the experimental setup. The diverted plasma is formed in the upper half of the Doublet III vacuum vessel. This simplified divertor has the divertor coils outside the vacuum vessel and there is no special divertor chamber or divertor throat. Helium gas is injected into the vacuum vessel from the upper port in a pulse of 5 msec duration at ~ 600 msec in the discharge. The discharge lasts for 900 msec. The amount of helium gas corresponds to a helium particle density of 4.1×10^{12} cm^{-3} if distributed uniformly in the plasma.

A quadrupole mass analyzer installed at the bottom chamber is used to monitor neutral helium density during and after the discharge. The vacuum time constant of this mass analyzer system is ~ 100 msec. An ionization gauge was used to detect the total pressure (hydrogen molecule pressure) in the lower chamber. Figure 2 shows the density dependence of the total, and helium partial pressure with and without divertor. Both the total and helium pressure are strong increasing functions of electron density. This experiment was done with a constant amount of helium injection. The amount of helium in the main plasma decreased while the helium pressure in the lower chamber increased (Fig. 3). The maximum observed pressure of helium was 3.6×10^{-5} Torr, with a helium allowance of 1% of electron density in the main plasma. This result shows that ash exhaust is realistic in an alpha-heated, diverted tokamak, with a practical-size pumping system. The pressure of helium without divertor is lower by one order of magnitude than that with divertor.

Helium enrichment is also an important problem from the viewpoint of tritium inventory. The helium enrichment factor, defined by:

$$\eta = (p_{He}/p_{H_2})_{\substack{\text{lower}\\ \text{chamber}}} / (n_{He}/n_e)_{\text{plasma}}$$

is presented in Fig. 3 vs. electron density in the main plasma. This figure shows that helium is enriched in the lower chamber by a factor of 2.4 (a factor of 1.2 in addition to a gain by a factor of two due to the definition of η) in high density diverted discharge.

There was some concern that most of the injected helium particles were directly swept out to the divertor region so that this experiment did not simulate an alpha-heated tokamak in which helium is generated from the hot core. In order to investigate this possibility, helium gas was injected before the divertor was turned on. The helium density in the lower chamber showed no difference from the case in which helium atoms were injected after the divertor was turned on. Therefore, the experiments presented in this letter should simulate those in an alpha-heated plasma.

The physical phenomenon of the helium removal function of a divertor appears to be basically the same as the suppression of impurity backflow from a divertor to the main plasma as demonstrated in DIVA[2, 6]. The possible mechanisms for helium concentration at the divertor are: localized recycling, friction force, pre-sheath field and temperature gradient along the field line. We will present experimental observations related with these mechanisms.

Recycling of helium is localized at the divertor region. The ratios of helium line intensities along the chord through the divertor to that along the central chord are shown in Fig. 4. From this figure it is clear that recycling of helium is localized in the divertor region and is even more concentrated in high density discharges. Helium backflow to the plasma, particularly near the divertor is suppressed by the friction force due to collisions with protons flowing along the field line. Electron density at the divertor region measured with a 2 mm microwave interferometer is $> 5 \times 10^{13}$ cm^{-3} in high density diverted discharges. A doppler broadening measurement of H_α light at the divertor indicates that ion temperature is ~ 2 eV in high density discharges. Assuming that the electron temperature is close to the ion temperature, the plasma is very collisional at the divertor region. The flow velocity of helium atoms was measured by a time-of-flight measurement with HeI line-filtered photodiodes; one looking through the central chord, and the other looking at the divertor. The flow velocity of helium was close to the proton flow velocity, (~ 0.3 C_s, C_s is ion sound velocity), which supports the hypothesis that plasma is collisional at the edge region. Localized recycling and friction force must be important since momentum transfer time from helium to proton is less than 0.1 μsec and transit time to the divertor plate is several tens of microseconds, for particles recycling near the divertor.

If we consider helium pressure balance in a long distance range along the field line, friction force may not be important because the helium flow velocity is very close to the proton flow velocity except at the very initial stage of travel along the field line. Helium concentration is possible even if the friction force is not strong. The presence of a pre-sheath electric field and temperature gradient along the field line is a possible mechanism. When the ion temperature at the divertor is ~ 2 eV, the ion temperature measured by a doppler broadening of the Balmer beta line is ~ 20 eV along the central chord. If we assume that the electron temperature is close to the ion temperature, this result shows the presence of an electron temperature gradient along the field line.

Let us consider the pressure balance along the field line for fully stripped helium species.

$$-\nabla_{\parallel} P_{\alpha} + 2en_{\alpha}E_{\parallel} = 0$$

where P_{α}, e, n_{α}, $E_{\parallel}$ are the pressure of fully stripped helium, electronic charge, density of fully stripped helium, and the electric field along the field line. Here, friction force is assumed to be negligible. $E_{\parallel}$ is a pre-sheath field[2], which is necessary to equate the flow of electrons and ions along the field line. From the equation above,

$$P_{\alpha 2} - P_{\alpha 1} + 2e(n_{\alpha 2}\Phi_2 - n_{\alpha 1}\Phi_1) = 0$$

where Φ is the electrostatic potential, and the subscripts 1, 2 mean the edge region near the main plasma, and the region near the divertor plate.

Since $\Phi_2 \sim 3\, T_{e2}$ (sheath potential) , and $\Phi_1 \sim \Phi_2 + T_{e1}$, we get

$$\frac{n_{\alpha 2}}{n_{\alpha 1}} = \frac{3}{7}\frac{T_{e1}}{T_{e2}} + \frac{6}{7} \quad (T_i \simeq T_e \text{ is assumed})$$

where T_e is the electron temperature, and T_i is the ion temperature. This equation indicates that if the temperature is lower near the divertor region, fully stripped helium should be denser there than at the edge of the main plasma.

The conclusions are summarized as follows:

1. Without any divertor chamber or divertor throat, neutral helium is concentrated at the divertor region up to 3.6×10^{-5} Torr with a helium allowance of 1% of electron density in the main plasma. Helium enrichment by a factor of 2.4 is also observed.
2. Helium pressure without divertor is lower by one order of magnitude than that with divertor.
3. Helium ash exhaust is realistic in an alpha-heated, diverted tokamak.

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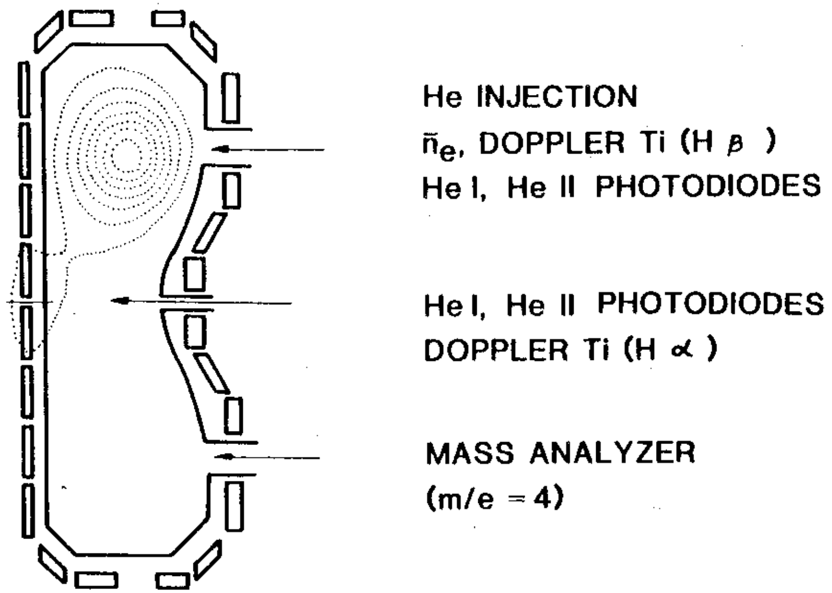
FIGURE CAPTIONS

FIG. 1 Cross-sectional view of the Doublet-III vacuum vessel and the location of the diagnostics, and gas injection system. Diverted plasma is formed in the upper half of the vacuum vessel. Note that divertor coils are outside the vacuum chamber and there is no divertor chamber or throat.

FIG. 2 The helium pressure and total pressure (hydrogen molecule pressure) in the lower chamber vs. electron density in the main plasma, with and without divertor. The solid, and open circles denote helium, and total pressure with divertor. The solid, and open triangles denote helium, and total pressure without divertor. The amount of helium injection was kept constant.

FIG. 3 The fraction of helium density to electron density in the main plasma (open circle), and the helium enrichment factor η (solid circle) $[\eta = (p_{He}/p_{H_2})_{\text{lower chamber}} / (n_{He}/n_e)_{\text{main plasma}}]$ vs. electron density of the main plasma.

FIG. 4 Line intensity ratio of HeI, HeII lines looking at the divertor, and through the central chord vs. line-averaged electron density of the main plasma.



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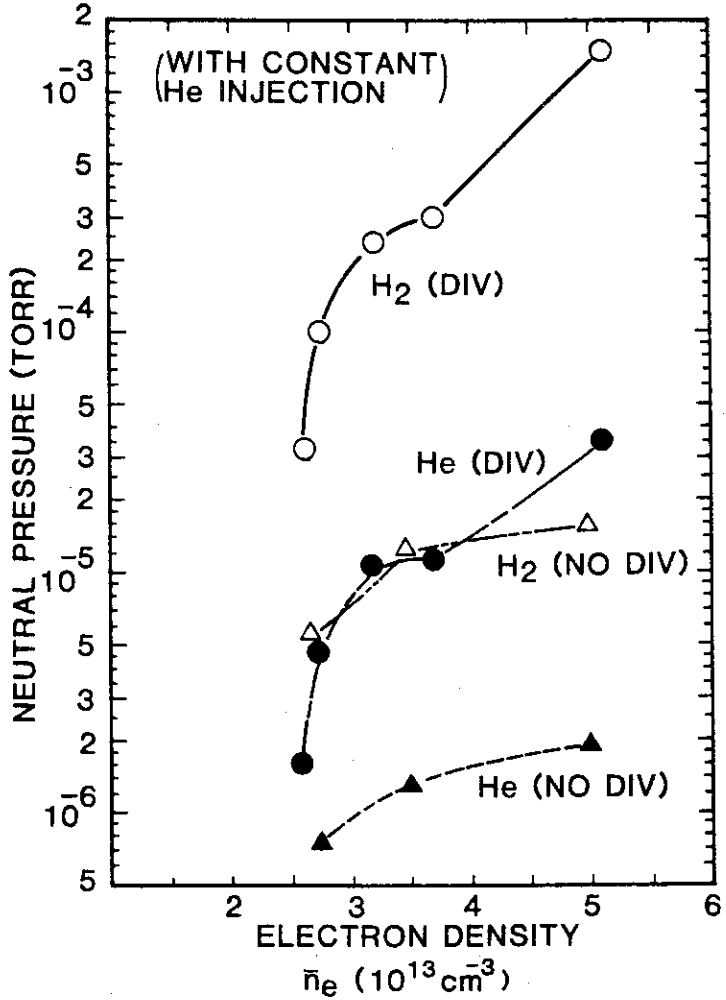

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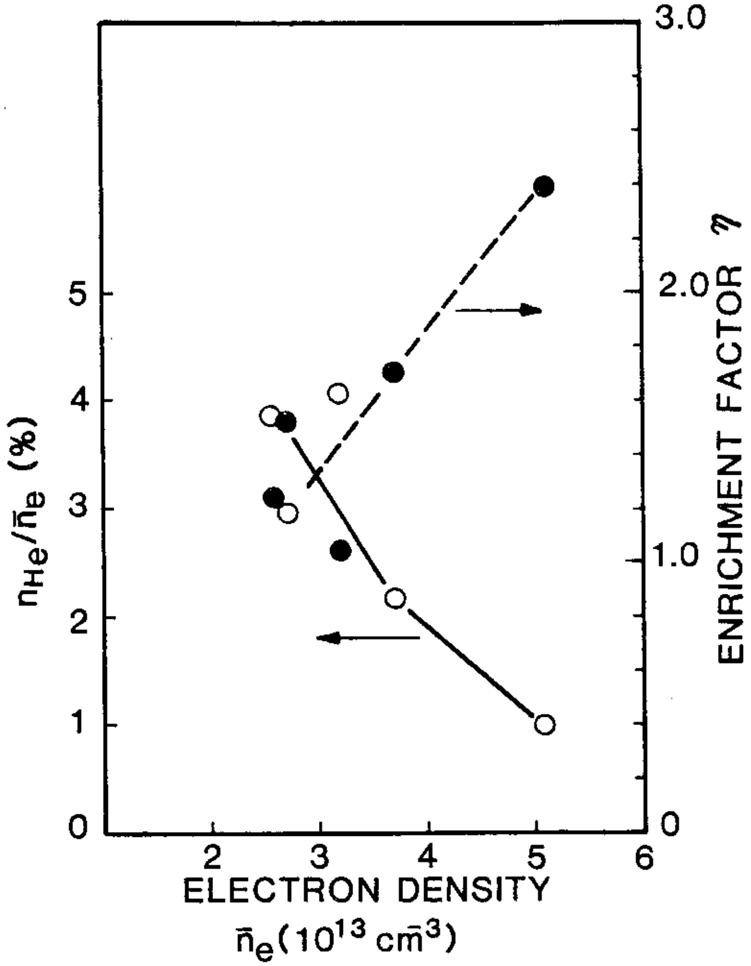

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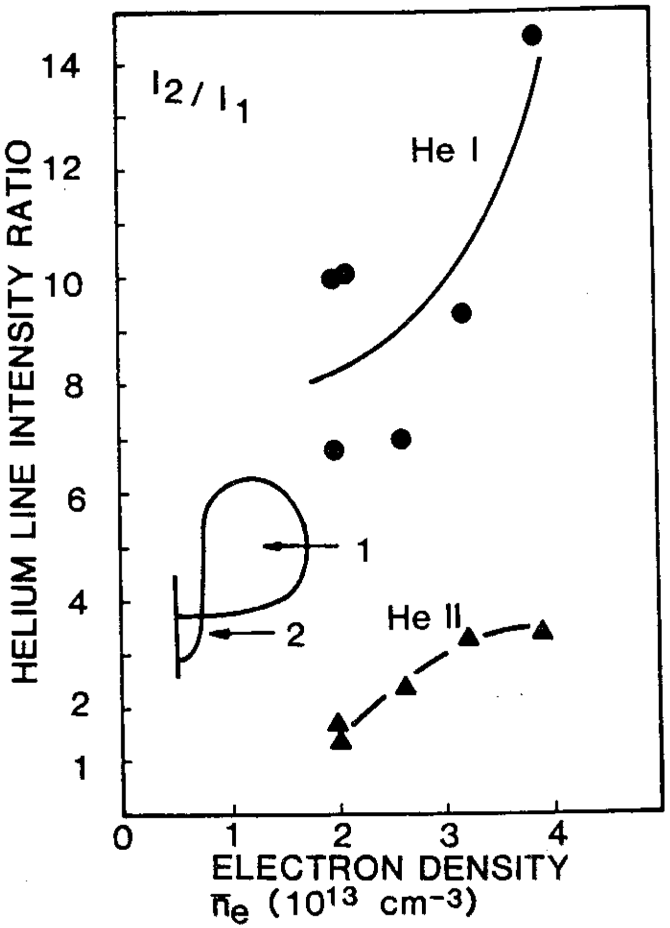

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