ELSEVIER

Journal of Nuclear Materials 241–243 (1997) 883–886

journal of nuclear materials

Study of helium transport in HL-1M edge plasma region

L.L. Peng *, B.Q. Deng, J.L. Luo, S.K. Yang, M. Wang, E.Y. Wang, S.J. Qian

Southwestern Institute of Physics, P.O. Box 432, Chengdu, Sichuan 610041, PR China

---

Abstract

Radial profiles of the emission intensity for H_α and neutral helium line ($\lambda = 5875.7$ Å) are measured to study helium transport and recycling in the HL-1M edge region in the vicinity of the poloidal graphite limiter (at $r = 26$ cm) after previous helium glow discharge cleaning and boronization under different LHCD and ECH conditions. A one-dimensional Monte Carlo neutral helium transport code, 1DHET, is utilized to calculate neutral helium density profile in the same region. The comparisons show that the freshly boronized wall with helium glow discharge cleaning exhibits somewhat selective recycling characteristics between the helium and hydrogen atoms, if ECH power is not applied.

Keywords: HL-1M; Boundary plasma; Helium exhaust and control; Monte Carlo simulation

---

1. Introduction

Helium studies are considered separately from those of other impurities because helium plays a particular role in present tokamak discharge experiment and in future D–T fusion reaction. First of all, helium glow discharge cleaning (He-GDC) is adopted as a routine technique in most of present tokamak devices. This technique is more effective in removing oxygen from wall material surfaces and in depleting the hydrogen absorbed in the wall/limiter. Helium as residual gas stays in the vacuum vessel after He-GDC and it will continue to effect plasma discharge. Helium is not only ionized to contribute electrons directly, but also induces the desorption of hydrogen in the wall leading to enhanced wall fueling. Helium puffing experiments in HL-1 indicated that the time constant of the electron density decay τ_p^* ($= \tau_p/(1-R)$) is three times as long as that with H_2 puffing, where τ_p is the particle confinement time. For the same density, the amount of gas feed is five times less than that with H_2 puffing [1]. On the other hand, from the long-run point of view, helium exhaust is an important issue in the design of magnetically confined D–T fusion plasma. The α particles, the so called helium ash, are produced as a result of the D–T fusion reaction and have to be removed from the system, otherwise the burning fuel will be diluted by the accumulated helium. The pumping systems, such as divertors or pump limiters are designed for this purpose. However not only helium but also fuel particles will be exhausted by the pumping system simultaneously. In order to raise the potential economic benefits and to improve environmental safety of D–T fueled reactor, the tritium dynamic inventory should be reduced as much as possible. Therefore efforts are made to establish some particular edge plasma/wall conditions which ensure the pumping system has a high helium pumping efficiency combined with a low pumping efficiency for hydrogenic species. In other words, a regime where most fuel particles will recycle from wall and back to main plasma, but most of the helium particles will be retained by the 'activated wall' that can be refreshed.

The previous calculations of neutral helium transport in the vicinity of divertor plate using Monte Carlo simulation techniques [2], by considering elastic scattering between neutral helium atoms and hydrogenic ions, have shown that the edge plasma with temperature lower than 10 eV and high density (say $1 \times 10^{14}/\mathrm{cm}^3$) plays filter-like role for helium particle. The helium ions can diffuse from core region to the wall but the neutral helium atoms reflected from wall have lower probability to re-enter the main plasma due to the particular edge plasma conditions, hence, the helium will be accumulated and enriched in the vicin-

---

* Corresponding author. Fax: +86-28 558 1458; e-mail: lizongy@public.bta.net.cn.

PII S0022-3115(96)00625-3

ity of pumping ports so that the helium removal efficiency will be enhanced.

Brooks et al. [3] have performed a helium self-pumping experiment using certain deposited metal (Ni, V, etc.) surface layer of 50 Å on a limiter or divertor plate to trap helium in-situ. They have shown this freshly deposited layer can trap helium much better than hydrogen. In a fusion reactor, high helium trapping and little or no helium detrapping by hydrogen in such a self-pumping divertor plate may reduce the ratio of tritium flux to helium flux exhausted through the pumps, hence reduce tritium inventory and post-processing, reduce total reactor cost and possibly achieve better helium removal. The selective trapping in this deposited layer may potentially provide the new idea for developing an advanced pumped divertors or limiters. The key problem is to maintain an effective trapping layer.

Some kinds of selective recycling properties for helium and hydrogen atoms in HL-1M discharges have been found under He-GDC conditioning and wall boronization by applying a variety of ECH and LHCD power combinations to Ohmically-heated plasmas. These recycling differences will be assessed for different edge plasma conditions in this paper.

2. Experimental description

HL-1M is a modification of HL-1 tokamak, $R = 1.02$ m, $a = 0.26$ m, $B_T = 2$–2.5 T, $I_p = 100$–320 kA, $\bar{n}_e = 7 \times 10^{19}/\text{m}^3$, $T_e(0) \cong 1$ keV and pulse duration $\cong 1$ s for normal operations. Two full poloidal graphite (SMF-800) limiters are mounted at $r = 26$ cm. After the first helium glow discharge cleaning, the wall boronization has been achieved by heating some $C_2B_{10}H_{12}$ solid powder which sublimates in the vacuum chamber at a temperature of about 90°C, the total discharge pressure is about 4–8 Pa, the ratio of partial pressures of $C_2B_{10}H_{12}$ to He is 2:3. Secondary ion mass spectrum (SIMS) analysis shows that the thickness of deposited boronization layer is about 350–700 Å and is a non-uniform deposition on the surface of vacuum vessel and graphite limiter. Before Ohmic discharge starts, the second helium glow discharge cleaning is carried out to remove the newly produced hydrogen in the process of boronization. We have observed the emission intensity profile of He line ($\lambda = 5875.7$ Å) from the residual helium after helium glow discharge cleaning. In order to compare the difference of recycling between the helium and hydrogen atoms from the graphite limiter wall, the emission intensity profile of H_α line ($\lambda = 6562.8$ Å) is also measured by multichannel visible spectrometer to investigate the hydrogen atom distribution in the edge region. During the discharge pulse, three turbomolecular pumps are in operation, pump speed is 1500 l/s for each. In order to analyse the effects of elastic scattering on helium distribution, the edge plasma parameters are measured by Langmuir probe. Two typical groups of data are chosen from two typical discharge cases at $t = 200$ ms: group 1 corresponds to the lower temperature and higher density case, while group 2 corresponds to the higher temperature and lower density case. The data are listed in Table 1.

Table 1
Edge plasma parameters in two cases

r (cm)	Group 1		Group 2	
	T_e (eV)	n_e ($10^{11}/\text{cm}^3$)	T_e (eV)	n_e ($10^{11}/\text{cm}^3$)
24	10.0	8.4	63.0	1.7
25	8.9	5.3	51.0	1.6
26	7.5	3.6	42.0	1.4

3. Monte Carlo simulation

1DHET code [4] is utilized to simulate neutral helium atom transport in HL-1M edge region (using slab model) where the plasma parameters can vary only in radial direction and are uniform in the other directions. The edge plasma parameters are given by probe data, the temperature is ≈ 8 eV and the density is about $3.6 \times 10^{11}/\text{cm}^3$ in the vicinity of limiter. The helium atom source is obtained from the neutralization and reflection of the residual ionized helium particles incident on graphite limiter and wall. The sampling steps of the neutral sources and collisions events are similar to the methods used in reference [2]. A helium ion incident on the limiter has velocity $\vec{v}_i$ chosen from a shifted Maxwellian distribution

$$f(\vec{v}_i) = \left(\frac{m_{\text{He}}}{2\pi kT_{il}}\right)^{1/2} \exp\left[-\frac{m_{\text{He}}}{2kT_{il}}\left(\vec{v}_i - \vec{a}_l\right)^2\right] \qquad (1)$$

where T_{il} is edge ion temperature and a_l is the edge ion flow speed taken equal to the hydrogen ion sound speed. Before helium ion hits the limiter it is accelerated through the sheath potential, $\phi \approx 3T_e$, it will therefore have a total incident energy E_0 given by $E_0 = \frac{1}{2} m_{\text{He}} v_i^2 + 2\phi$. In the edge region, a helium atom is assumed to interact with the plasma either by electron impact ionization or by elastic scattering on hydrogen ions. The modelling of the interactions of ions and/or neutrals with limiter/wall can be considered as consisting of two processes: backscattering and re-emission. Through these processes, hydrogen and helium ions hitting a limiter are neutralized and return back to the plasma. The particle and energy reflection coefficients depend on limiter material and the incident particle and are modelled in the same way as in Ref. [2].

4. Comparisons and discussion

Fig. 1 shows how the calculated neutral helium density distribution varies with the radial position, provided that

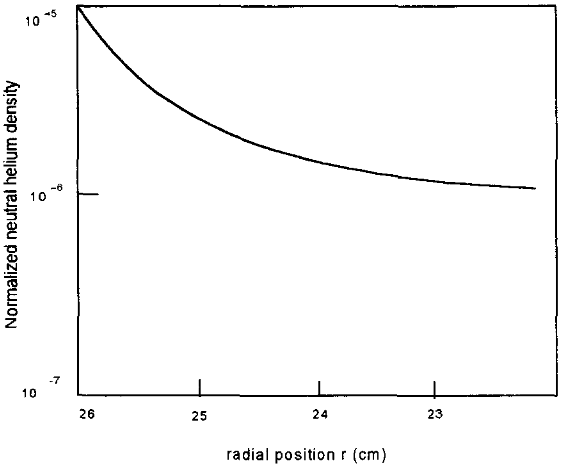

Fig. 1. HL-1M neutral helium profile from 1DHET simulation.

the neutral helium source particles result from the neutralization of helium ions incident upon the limiter, where the densities have been measured under the condition of one source particle/cm$^2 \cdot$ s emitted from limiter. We can see that the helium density is peaked at the limiter and decreases monotonically towards the core region.

The measured neutral helium and hydrogen emission intensity profiles are shown in Fig. 2. We can see that most neutral hydrogen atoms are recycled from limiter, because I_H profile is peaked at the limiter (like Fig. 1) and decreases rapidly in comparison with neutral helium emission profile I_{He} which has a broader profile and peaks about 6 cm apart from the limiter. This implies that helium emission comes from the residual helium atoms, while hydrogen emission comes from recycled neutral atoms. Helium atoms generally have a longer mean free path than the neutral hydrogen atoms and therefore penetrate further into main plasma and form a broad profile. For comparison, the revised neutral hydrogen transport code SPUDNUT [5,6] had also been used to study the neutral hydrogen transport, taking the effects of molecular processes into consideration in HL-1 edge region [7]. The hydrogen recycling experiment investigations in HL-1 edge region had been extensively performed [1]. By comparison, we found the molecular effects in HL-1M edge region are not as important as in HL-1, otherwise the peak of I_H profile would be apart about one mean free path from the limiter. These differences might be caused by boronization with He-GDC in HL-1M. The helium atoms are not recycled from boronized limiter wall, while most of hydrogen atoms, not hydrogen molecules, are backscattered from the limiter. In addition, since the edge electron temperature is lower, the electron impact ionization rate become smaller in the edge region. The elastic scattering of helium atoms with hydrogen ions, whose temperature is lower than 10 eV in the vicinity of limiter, pushes the peak of edge residual helium atom profile inward a few centimeters.

Under the condition of pure inductive discharge, the neutral helium emission intensities are shown in Fig. 3 for two typical different edge plasma conditions given by Table 1. The solid line refers to high edge plasma tempera-

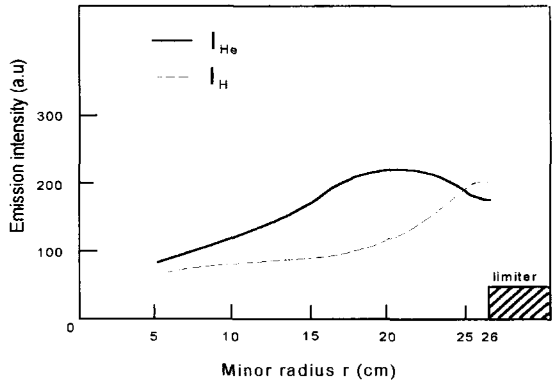

Fig. 2. Helium and hydrogen atom emission intensity profiles in HL-1M.

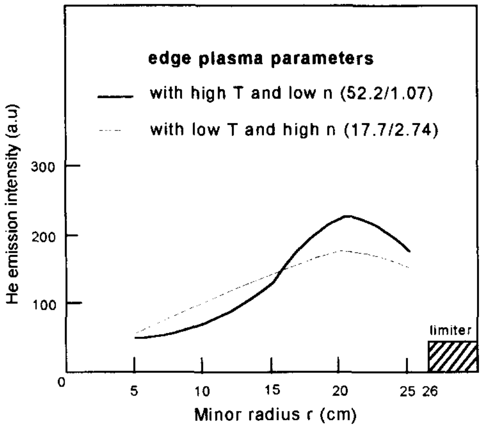

Fig. 3. Helium emission intensity profiles under different edge plasma conditions.

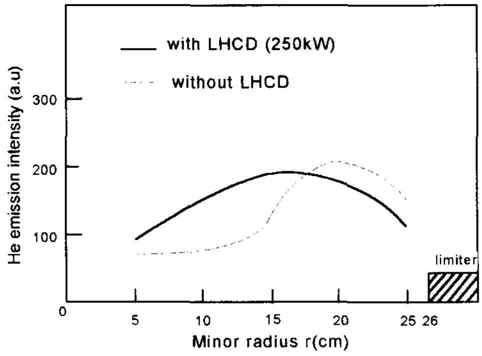

Fig. 4. Comparison of helium emission intensity profiles between with and without LHCD.

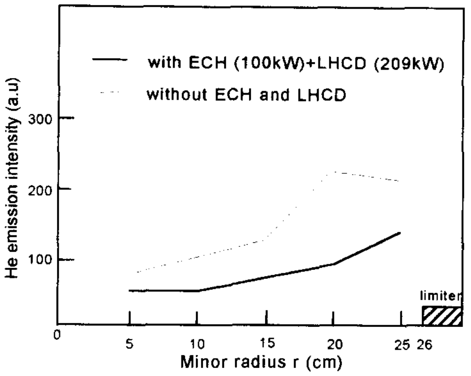

Fig. 5. He emission intensity profiles measured by just before and during ECH + LHCD.

ture and low density, the dotted line is for low temperature and high density case. Both helium emission profiles are peaked at 6 cm away from limiter. We infer from this that the measured intensity of helium emission is mainly due to the residual bulk helium gas contribution and helium recycling is suppressed by boronization combined with helium GDC. Under low temperature and high density condition, the neutral helium profile becomes flattened due to elastic scattering with plasma ions causing a substantial fraction of edge residual helium atoms to move inward.

In the experiment with LHCD (250 kW, $f_{LH} = 2.45$ GHz), an increased He accumulation tendency in main plasma has been observed as the bulk plasma particle confinement is improved. A broader helium profile is formed and the peak shifts inward further, as shown in Fig. 4. This is because plasma current increases due to current drive, the helium particle confinement is enhanced and fewer helium ions strike on limiter and get neutralized, therefore, fewer helium atom recycling events happen on the limiter. During the LHCD pulse duration, the edge electron temperature drops from 24 eV to 8 eV, hence the elastic scattering processes in the edge region are enhanced, as a result, pushing helium atoms inward. On the other hand, the inward pinch driven by the edge electron temperature and density gradient also can make inward peaking of helium profile. However, when LHCD (209 kW, 30 ms, 2.45 Ghz) was launched beginning 10 ms after ECH power (100 kW, 20 ms, 75 GHz) had been injected, the effects are quite different. First, the entire intensity curve of He emission drops by about 50%, secondly, the peak of helium profile shifts to the limiter and the intensity decreases monotonically towards the core as shown in Fig. 5. The former indicates that electron impact ionization is dominant with higher electron temperature, neutral helium atoms from residual gas are more fully ionized. The latter might be related to the sheath potential increase near the limiter due to the elevated electron temperature, some escaped charged particles gain more energy before hitting the limiter. As a result, more helium atoms that were previously trapped in the wall are re-emitted. In this case, the profile is similar to the Monte Carlo simulation result as shown in Fig. 1. Thus the helium atoms are enriched close by the limiter and exhausted more easily. So this auxiliary power combination not only has the advantage of enhanced confinement, but also helps to reduce helium accumulation.

5. Conclusions

The comparisons between the experimental measurements of radial emission intensity profiles of neutral helium and hydrogen in the vicinity of limiter and one-dimensional Monte Carlo simulation of neutral helium transport in the same region seem to indicate the boronized wall (with He-GDC) exhibits somewhat selective recycling property between the hydrogen and helium atoms. The helium atom recycling from the boronized wall is markedly suppressed but the hydrogen atoms seems in quite different way. Another effect which could contribute to the observed differences may be due to the improved confinement of helium except in plasmas that have ECH and LHCD applied simultaneously. This possibility is under investigation.

Acknowledgements

We are grateful to the members of the HL-1M group, especially Dr. Zhang Nianman and Yan Donghai, for their discussion and assistance in the operation and measurements.

References

[1] L.L. Peng, C.J. Yan et al., J. Nucl. Mater. 196–198 (1992) 520–524.

[2] B.Q. Deng, Zh.Y. Xie, H.W. Shi, H.H. Abou-Gabal and G.A. Emmert, Contrib. Plasma Phys. 33(1) (1993) 35–41.

[3] J.N. Brooks, R.E. Nygren et al., J. Nucl. Mater. 176–177 (1990) 635–639.

[4] H.H. Abou-Gabal and G.A. Emmert, Nucl. Fusion 31 (1991) 407.

[5] K. Audenaerde, G.A. Emmert and M. Gordinier, J. Comp. Phys. 34 (1980) 268.

[6] H.C. Howe, Jr., J. Nucl. Mater. 111–112 (1982) 424.

[7] B.Q. Deng, X.R. Duan, L.L. Peng et al., 18th Eur. Conf. on Controlled Fusion and Plasma Physics, 3–7 June 1991, Berlin, Germany, part 3, D2, p. 5.