Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 363–365 (2007) 1340–1345
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Siliconization for wall conditioning and its effect on plasma performance in HL-2A tokamak

X.R. Duan *, Z. Cao, C.H. Cui, X. Cai, H.J. Sun, X.T. Ding, Y.D. Pan, M.X. Wang, Q.W. Yang, X.M. Song, D.Q. Liu, Y. Liu, X.Q. Ji, Z.Y. Cui, Y. Zhou, Yong Liu, HL-2A Team

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

Abstract

Wall conditioning with siliconization has been performed in the HL-2A tokamak to improve the plasma performance. It was based on the plasma chemical vapor deposition by using a four-anode glow discharge cleaning system and gas mixture of 90% He + 10% SiH_4. It was found that the main components of the residual gas were CO, H_2 and H_2O. The amount of H_2O was reduced from 49.5% to 24.5%. After siliconization, the impurity fluxes released from the first wall were reduced, especially the oxygen level (till to 10%) and high z impurities like Cu were decreased significantly. The total radiated power measured by the bolometer was decreased from 70% to 35%. A high density exceeding the Greenwald limit and energy confinement improvement have been achieved. The plasma operational region of HL-2A has been effectively broadened.

PACS: 52.55.−s; 52.40.−w; 52.25.v

Keywords: Plasma facing material; Siliconization; Wall recycling; Density control

1. Introduction

As well known, hydrogenic and impurity influx needs to be controlled to permit density control and minimize radiative losses, and a suitable wall condition is essential to achieve high performance plasma in fusion devices [1]. The deposition of thin films of various materials can modify the composition and surface characteristics of the plasma facing surfaces. These films getter oxygen, resist chemical erosion and lead to tokamak discharges with significantly reduced oxygen and carbon impurities. In recent years progress in wall coatings has been achieved by using boron (boronization) and silicon (siliconization) as the coating material, a few tens nm thick amorphous boron/carbon and silicon/carbon can be deposited on the plasma facing surfaces, thereby reducing high z impurities, increasing the density limit and improving the energy confinement. For example, boronization and siliconization were performed on TEXTOR [1,2] and sequentially

* Corresponding author. Fax: +86 28 82850300.
E-mail address: duanxr@swip.ac.cn (X.R. Duan).

0022-3115/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2007.01.185

reduced the impurities, finally improved the confinement. H-mode or very high H-mode discharges were obtained on JT-60U [3] and JET [4] and D III–D [5] after boronization with materials of $B_{10}H_{14}$ or $C_2B_{10}H_{12}$. Boronization and siliconization were also conducted on HL-1M [6] and HT-7 [7], the plasma performances were improved obviously.

HL-2A began operation in December 2002. The research program is aimed at most of the important issues of fusion physics, such as confinement improvement, divertor physics, wall conditioning and MHD instability [8]. In order to obtain plasma discharges with high performance, siliconization has been used for wall conditioning in the recent years. After siliconization the plasma performance has been improved obviously with respect to density limit, energy confinement and reduction of radiation losses. In this paper the results on the suppression of impurities and improvement of plasma performance are given. After a brief survey of the experimental aspects in Section 2, some details about the siliconization in HL-2A and the properties of the coatings are described. In the fourth section and fifth section, the effect of siliconization on impurity concentration and plasma performance are discussed. Finally, a brief summary is given.

2. Experiments

HL-2A tokamak is characterized by a large closed divertor chamber. The major radius is $R = 1.65$ m and the minor radius is a=0.4 m. The vacuum vessel has a volume of 26 m^3 and a plasma facing area of 46 m^2. The fixed and movable limiters and two domes of the divertors are covered with the graphite tiles [8]. Before the experimental campaign 2005 the surface of the shielding plates for the multipole coils 1 (MP1) and multipole coils 2 (MP2) has been covered with 2-D carbon fibre composite (CFC 1501GS with thickness of 0.7 mm) (about 30% of the first wall), this can protect the first wall, and effectively shield the splash of heavy metal impurity. The main pumping system of HL-2A is composed of 6 turbo molecular pumps (3500 l/s each) and two set of cryopumps. The total leakage rate is 1.2×10^{-5} (Pa m^3 s^{-1}), the highest vacuum has reached 4.6×10^{-6} Pa. The vacuum vessel can be baked up to 120 °C for degassing and a glow discharge device is installed in the vessel for cleaning the inner surface. Hydrogen glow discharge cleaning (GDC) is applied to remove impurities from the wall, and helium glow discharge cleaning for removing residual hydrogen.

About 30 diagnostics have been installed in the main chamber of the device, which include the HCN laser interferometer, electron cyclotron emission (ECE) receiver, Thomson scattering, charge exchange (CX) neutral particle analyzer, vacuum ultraviolet (VUV) spectroscopy, reciprocating probes, and visible spectrometers. The neutral gas pressure is given by fast ionization-gauge. Some multichannel arrays such as Hα detection array, soft-X-ray (SX) arrays and bolometer arrays are installed to supply 2-D measurement [9].

In these experiments, the working gas was hydrogen, the plasma current I_p was up to 400 kA, the torroidal field B_T to 2.6 T and the plasma line averaged electron density n_e up to 6.0×10^{13} cm^{-3}, the discharge duration about 3 s.

3. Siliconization

Siliconization in HL-2A was realized by DC glow discharge with a gas mixture of 90% He + 10% SiH_4. The GDC system in HL-2A is shown in Fig. 1. Four stainless steel anodes, each with a dimension of $\varnothing 25 \times 450$ mm, were installed into the limiter shadow region outside the bulk plasma in the vacuum chamber. Each anode consisted of a stainless steel pole and a shield, which looks like a lamp mantle. The anode pole was connected to its anode mantle via a ceramic insulator. Two anodes shared one power supply system, whose output voltage and current were 0–1200 V and 0–8 A, respectively.

A uniform glow plasma can be achieved by adjusting the amount of the feeding gas and output parameters of the power supply systems and some

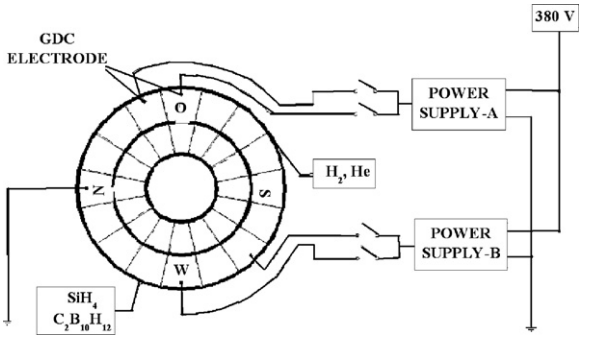

Fig. 1. Schematic setup of the glow discharge cleaning system in HL-2A tokamak.

of the gate valves in the main pumping system. The He GDC parameters were as follows, gas pressure $(3–8)\times10^{-2}$ Pa, anode voltage (420–730) V and current (2.4–5.6) A. After about 60 min of the helium glow discharge cleaning, a stable dc glow discharge could be obtained. The operation parameters for siliconization were: the helium pressure 8.8×10^{-2} Pa, the anode electric voltage 650 V, the electric current 2.4 A, the electric current density of the first walls in the vacuum vessel was 5.3 uA cm^{-2}.

When the density of the silicon alkane was low, SiH_2 and SiH_3 formed in the glow discharge propagate to the wall, and are absorbed by the wall surface [10]. The process continued for about 1.5 h. This was followed by 15 min of He GDC to remove co-deposited hydrogen from the near surface region of the film and reduced the hydrogen influx during subsequent plasma discharges. And this resulted in an α-Si:H (non-crystal silicon) film [1]. During the procedure collection probe is exposed using a manipulator system, and the surface analyzing technique (electron scan microscope) showed a typical thickness of 120 nm for the α-Si:H layer at the midplane.

After siliconization, the residual gas mass mixture analysis indicates a significant reduction of H_2O. The main components of the residual gases were CO and H_2, and the peak value of the H_2O was reduced from 7.9×10^{-6} Pa (49.5%) to 3.9×10^{-6} Pa (24.5%). This provided excellent wall condition for tokamak discharges with higher performance.

4. Effect on impurity

The influence of siliconization on the impurity concentration in HL-2A under limiter and divertor operation has been studied, and it was based on the spectroscopical method. The OMA IV system is a 0.5 m Czerny–Turner spectrometer operating in the range 400–1100 nm. It is equipped with a CCD detector (256×1024, pixel size 19 μm × 19 μm), and can be cooled to −80 °C, hence this system is of low noise. A 300 grooves/mm grating was set to monitor emission lines from different elements before and after siliconization. The VUV monochromater is a Seya–Namioka vacuum one with a wavelength range 20–200 nm. It was used to monitor impurities with higher ionization stages. The viewing line of the VUV monochromater went through the plasma center, whereas the OMA system could detect spectral emission from both the main chamber and the divertor chamber at the same time.

Fig. 2 shows a pair of comparison discharges from 505 to 610 nm before and after siliconization under limiter configuration. Both spectra are normalized by the brightness of Hα emission, and the discharge parameters were as follows: plasma current ~300 kA, loop voltage ~1 V and line averaged density of electron $\sim1.5\times10^{13}$ cm^{-3}. The experimental results have shown that the copper/nickel emission was reduced to below the detection limit of the OMA system. After siliconization oxygen emission was reduced significantly, e.g. O III reduced to below the detection limit, and O IV by a factor of five. The carbon emission was also decreased obviously, C I emission decreased to a very low level, other carbon ions' emission was decreased significantly. It is found that the emission from the lower ionization stages of the impurity like carbon and oxygen was decreased more significantly. Silicon emission lines such as Si III at 574 nm was of relatively high level after siliconization, and it is decreased in the subsequent discharges.

Some spectra measured under divertor configuration is shown in Fig. 3. The dark line with higher emission level represented the spectra before siliconization, the dark line with very low emission level was the spectra 3 shots after siliconization, and the gray line represented the spectra 70 shots after siliconization. These results have shown that the impurities' emission was lower by a factor of 4 than that under limiter configuration. Just after siliconization the main emission from 505 to 660 nm was from Hα, He I, and silicon lines. About 70 shots

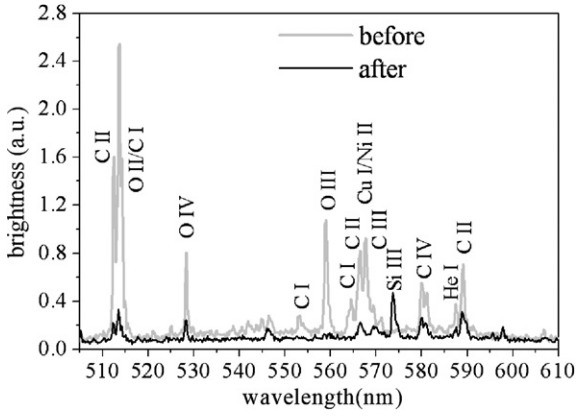

Fig. 2. Comparison of impurity emissions before and after siliconization under limiter operation.

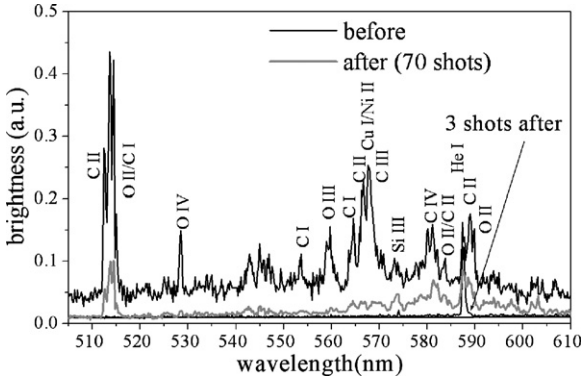

Fig. 3. Comparison of impurity emissions before and after siliconization under divertor operation.

after all emission lines were decreased significantly compared with that before siliconization, the copper/nickel emission was decreased to below detection limit, whereas the silicon line remained detectable. During divertor configuration the silicon concentration is found to be a factor 10 less than that during limiter operation with comparable discharge parameters. This could be partially due to a weaker interaction with the first wall under divertor configuration. During limiter operation the plasma facing surface was exposed to plasma with much higher temperature compared to the divertor, which led to larger erosion yields due to physical sputtering through hydrogen.

Fig. 4 shows the temporal evolution of the Hα emission and O VI emission (103.2 nm) during discharge before and after siliconization. The plasma current and electron density were almost the same, but the integrated Hα was decreased by about 50% and O VI emission was decreased obviously. Fig. 5 is the brightness ratio evolution of O III, C II and Si III over Hα emission as a function of discharge number before and after siliconization. In these discharges, the plasma current I_p was from 230 to 300 kA, B_T was from 2.4 to 2.5 T, line averaged electron density was $(1.7–2.5)\times10^{13}\,\mathrm{cm}^{-3}$. These results have shown that the emission ratio Si III/Hα did not change obviously under divertor configuration, but the impurities' emission O III and C II decreased significantly with the discharge number. About 100 shots later they increased with the discharge number and after about 150 shots the impurities emission increased to the same level as it was before siliconization, i.e., siliconization effect lasted for about 150 shots under those discharge conditions.

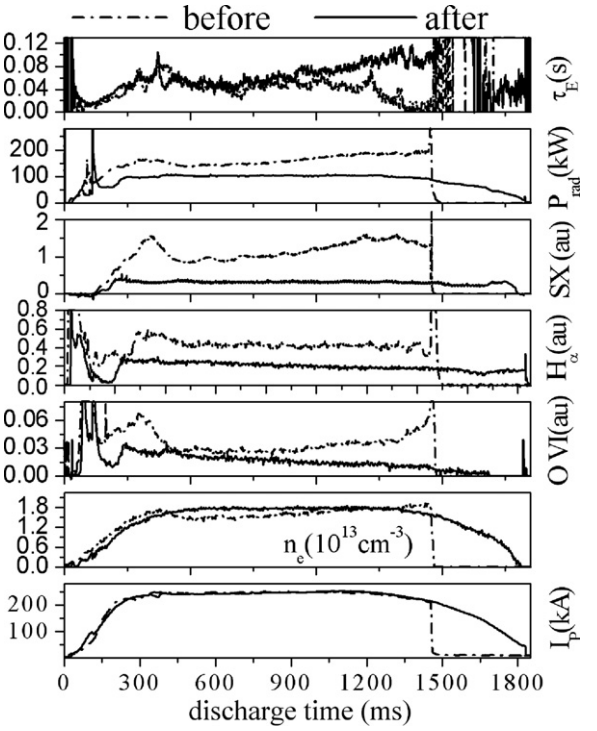

Fig. 4. Comparison of plasma parameters before and after siliconization under limiter configuration. The dashed line refers to the pre-siliconization discharge.

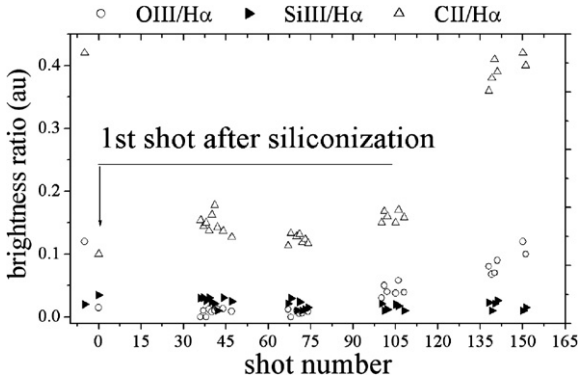

Fig. 5. Brightness ratio evolution of impurities' emission over Hα emission under divertor configuration as a function of discharge number.

5. Effect on plasma performance

The experimental results given in the last section have shown that the impurity concentration, especially oxygen and high z materials, was reduced significantly after siliconization. This led to a better

controllability of plasma density. Besides, the plasma performance was improved obviously.

To study the radiation losses, three bolometer arrays were installed in HL-2A and located at the midplane, lower and upper port 45° from the midplane respectively. The multi-element detector was a 16 channel AXUV diode array and the volume integrated power P_{rad} was obtained from the multichannel measurement. Fig. 4 shows the temporal evolution of the plasma parameters before and after siliconization. The discharge parameters such as I_p and n_e were the same. It is shown that the plasma radiation loss after siliconization was reduced by about 30% compared with that before siliconization. Besides, the radiation measured by SX detector across the plasma core was decreased more significantly. Fig. 6 shows the variation of the radiated power over ohmic power for a line averaged density of $(0.5–5.0)\times10^{13}\,\mathrm{cm}^{-3}$. Before siliconization the radiation loss P_{rad}/P_{OH} was increased more rapidly with the increase of the line averaged electron density. At lower density, the P_{rad}/P_{OH} value was decreased from about 55% before siliconization to ~20% after siliconization, and at higher density, it was decreased from ~70% to ~40%.

After 650 ms, the energy confinement time τ_E was increased slightly for the discharge after siliconization, whereas it remained unchanged for the discharge before siliconization. Due to the strong radiation loss it led finally to a major disruption. This was a typical case, i.e. the major disruption happened more frequently before siliconization. As shown in Fig. 4, the Hα emission was decreased obviously after siliconization under the same discharge condition, this indicated that the recycling was decreased. Fig. 7 is the dependence of the neutral gas pressure before and after siliconization on the line averaged electron density. After siliconization the neutral gas pressure was relatively low compared with the pressure before siliconization, and it was decreased by about 30% at high electron density and to 40% at lower density. This was the result of the improvement of the energy confinement and the reduction of the recycling.

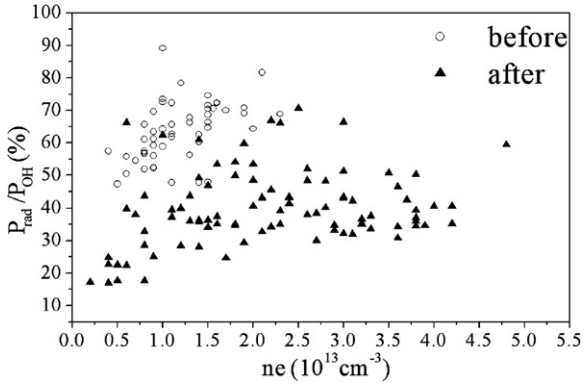

Fig. 6. Dependence of the radiated power over ohmic heating power on the line averaged electron density. Hollow circles represent the case before siliconization, the solid triangles are measured after siliconization.

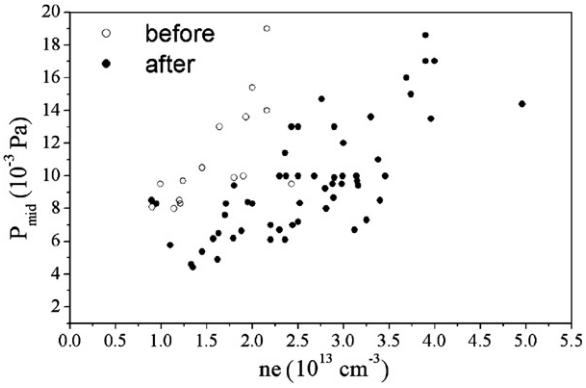

Fig. 7. Dependence of the neutral gas pressure in the main chamber on the line averaged electron density before (hollow circles) and after (solid circles) siliconization.

After wall conditioning by siliconization the density limit was also increased. Under limiter operation a density of $4.2\times10^{13}\,\mathrm{cm}^{-3}$ was achieved at the plasma current $I_p = 200$ kA, this exceeded the Greenwald limit [11] density. Besides, the confinement time after siliconization was increased by 20–40%.

6. Summary

Wall conditioning with siliconization has been performed in HL-2A tokamak. It is found that the main components of the residual gas were CO, H_2 and H_2O. The amount of H_2O was reduced from 49.5% to 24.5%, this supplied a favorable wall condition for the subsequent plasma discharges. After siliconization, the impurity fluxes released from the first wall were reduced, especially the oxygen level and high z impurities. The total radiated power was decreased from 70% to 35%. At the same time, a high density exceeding the Greenwald limit has been achieved and energy confinement improved. The repeatability of discharges and controllability on the plasma density has evidently been improved. The plasma operational region of HL-2A has been

effectively broadened. In the near future various wall conditioning such as siliconization and boronization will be studied in HL-2A.

References

[1] J. Winter, Plasma Phys. Control. Fus. 38 (1996) 1503.
[2] U. Samm, P. Bogen, G. Esser, et al., J. Nucl. Mater. 220–222 (1995) 25.
[3] T. Nakano et al., J. Nucl. Mater. 313–316 (2003) 149.
[4] H.Y. Guo, G.F. Matthews, et al., Nucl. Fus. 40 (2000) 379.
[5] G.L. Jackson et al., Phys. Rev. Lett. 67 (1991) 3098.
[6] N.M. Zhang, E.Y. Wang, M.X. Wang, et al., J. Nucl. Mater. 266–269 (1999) 747.
[7] Xiangzu Gong, Jiangang Li, Baonian Wan, et al., J. Nucl. Mater. 290–293 (2001) 1171.
[8] Y. Liu, X.T. Ding, Q.W. Yang, et al., Nucl. Fus. 45 (2005) S239.
[9] Duan Xuru, Ding Xuantong, Yang Qingwei, et al., Plasma Sci. Technol. 18 (2006) 19.
[10] K. Ensslen, S. Veprek, Plasma Chem. Plasma Process. 7 (1987) 139.
[11] M. Greenwald, Nucl. Fus. 28 (1988) 1988.