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Impurity behaviours of HL-2A divertor Tokamak during the initial operation period*

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The divertor configuration was successfully formed and the siliconization as a wall conditioning was first achieved on HL-2A tokamak experimentally in 2004. The divertor configuration is reconstructed by the use of the CFC code. Impurity as an important issue is investigated in the experiments with divertor configuration and wall conditioning. Impurities dramatically decrease after both the divertor configuration is formed and silicon is coated on the surface of the vacuum vessel.

Keywords: plasma, wall conditioning, impurity
PACC: 5255, 5225

1. Introduction

Impurity is one of the key issues in tokamak plasma research for it is closely related to plasma qualities and steady state operation. The interaction between plasma and the first wall of the tokamak device is not only the source of impurity but also a dangerous factor to possibly destroy the device chamber.[1] In order to avoid destroying the vessel wall and poisoning the plasma, at the same time to efficiently extract the waste product of the fusion process from the system, divertors were adopted in some machines just at the beginning of dealing with this problems. Up to now, the remarkable progress has been made in this respect.[2,3] However, many crucial problems related to the divertor remain to be solved such as the dissipation of plasma power extracted from the main plasma, the production of high gas pressures in the vicinity of pump ducts so that the fuel and helium gas can be pumped out of the system, the reducing or even eliminating impurity production, the screening the impurities produced at the plasma boundary or added intentionally from the plasma core.[4] There are two kinds of divertors frequently employed in the fusion devices: open divertor and closed divertor.

In order to understand the physics behind divertors, the HL-2A tokamak with two closed divertors was successfully built in 2002.[5] It is the first divertor tokamak in China. Its parameters are as follows: major radius R=1.64 m, minor radius a=0.4 m, toroidal magnetic field $B_{\rm t}$=2.8T, toroidal plasma current $I_{\rm p}$=480kA. The impurity study and control as one of the critical issues is faced during the initial operation period since the content of impurity is certainly connected with the device operation and the quality of plasma discharge. It is a new challenge to our operating of a tokamak with divertors. Moreover, the behaviour of the impurity of open divertors, which is the most common divertor configuration in laboratories, should be different from those of closed divertors, as there are differences in impurity pump efficiency, heat load on target plate, etc.

As is well known, the impurities in plasma are mainly helium, boron, carbon, oxygen, iron, copper, etc. Line emission in tokamak plasma is emitted in a very wide temperature range. The radiation at low ionization stages fall in the visible and VUV spectral ranges while H- and He-like ions offer their emission in the x-ray range of the spectrum. The main emitters in the VUV-range are the B-, Be-, and Li-like stage ions. Spatially, the ions of light elements at these ionization stages appear around and outside the

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separatrix while the ions of heavy elements at these ionization stages emerge in the confined region of the plasma. The radiation power is proportional to the electron density and impurity density, as indicated by the formula $P \sim Rn_e n_I$ under the steady state condition. R in the formula is a parameter as a function of electron temperature. When plasma temperature is lower than 1k eV the radiation loss from light elements and recombination is dominant. For the light impurities such as oxygen and carbon their radiation parameters are peaked at low temperatures in a range of about 30–50 eV. When the temperature is close to a value in that range the radiation of the element will increase rapidly with the temperature. The radiation loss is directly related with the impurity density in plasma. In the early state of discharge the electron density and temperature of plasma mostly depend on the initialization parameters of the discharge. When the initialization parameters of the discharges are similar the electron densities during the early states of the discharges are similar, especially the coefficients of the ionization and recombination are similar when the temperature is around 30–50 eV. Therefore, the radiation peak approximately expresses the impurity density. By comparing the radiation intensities of impurities at the early stage of discharge the information on impurity content in plasma and plasma quality could be obtained, as presented in this paper.

The paper is arranged as follows. After a summary of the impurity diagnostics on HL-2A in Section 2, the experimental results of impurity on divertor configuration as well as the experimental results of siliconization are described in Section 3. Section 4, the last one, is devoted to a summary.

2. Experimental set-up

A monochromator in the VUV spectral range is installed on HL-2A to survey the impurity behaviours in the main plasma region.[6] It is a Seya–Namioka vacuum monochromator with a wavelength range of 20 nm–200 nm and the surface of its detector is coated with a sensitive material. The sight line goes through the plasma centre when the main impurities such as helium, boron, carbon, oxygen, iron, copper, silicon, etc., are to be examined.

The visible spectroscopic measurement in the main plasma chamber are comprised of bremsstrahlung measurements with 6 channels for plasma effective charge, $Z_{\rm eff}$, and of H_α measurements from two-arrays each with 23 channels. There are other four channels separately for H_α measurement which are located along the toroidal direction such that the sight line of one channel goes through the plasma edge and others go through the plasma core. In the divertor chamber some optical fibres with the filters are also installed for H_α, CIII and OII measurements in a visible spectrum region. Layout of the visible spectroscopic measurements are shown in Fig.1. The detailed information is presented in Ref.[7].

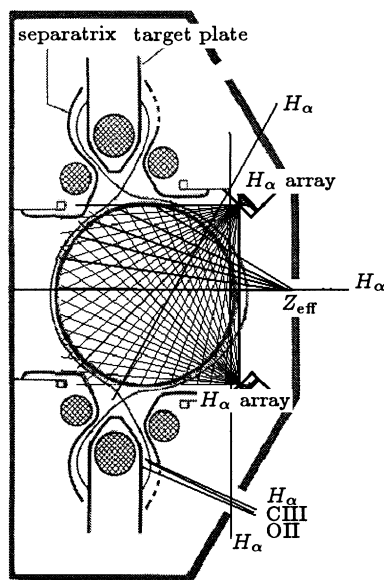


Fig.1. Layout of the visible spectroscopic measurements on HL-2A.

In the measurement for early operation stage of HL-2A there was only one array of bolometer with 16 channels. The detector is made of Absolute Extreme Ultra Violet silicon photodiodes, AXUV, which has the performances of fast response, high sensitivity and wider bandwidth. Nevertheless, it is not sensitive to the particle loss. The energy range of the detector is from 10 keV to 1 eV. The array is mounted on the horizontal port of the device with a fan-shaped line of sight.[8]

A series of plasma discharges with a single divertor was successfully carried out experimentally in 2004.[9] All of the diagnostics used on HL-2A are presented in Fig.2, covering the visible spectra for H_α and impurity, MW interferometer for electron density, fast gauge for neutral gas pressure and local probe arrays for the electron density and temperature on the target plate in the divertor chamber.

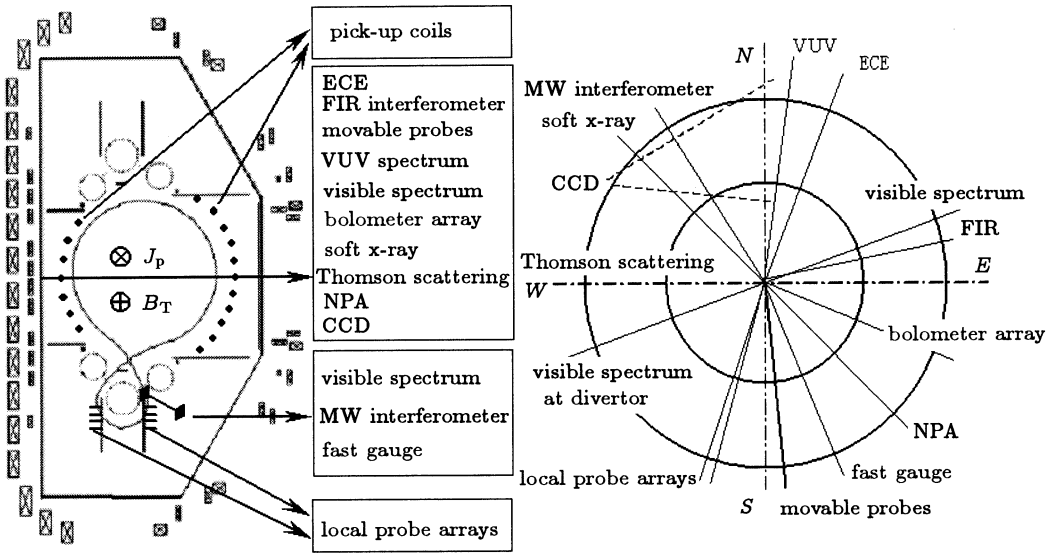


Fig.2. Single-null configuration and the arrangement of diagnostics.

A reduction in impurity is obviously observed when the divertor configuration is formed. The siliconization as a wall conditioning has been performed for the first time on HL-2A device since its operation. By using siliconization we have observed that the impurity including the line emission and the total radiation of plasma is considerably decreased. The features of the siliconization and the effect of wall condition on plasma as well as on wall recycling have been investigated.

3. Experimental results

3.1. Effect of divertor on impurity

The plasma discharge of HL-2A can typically extend to more than 1s in duration. The longest discharge duration achieved 1.58 s in 2004. A typical discharge with divertor configuration has distinct regimes: limiter phase at the early stage of discharge without X-point, and divertor phase with X-point. A typical divertor configuration is calculated by CFC code,[10,11] which is developed by SWIP, and shown in Fig.3.

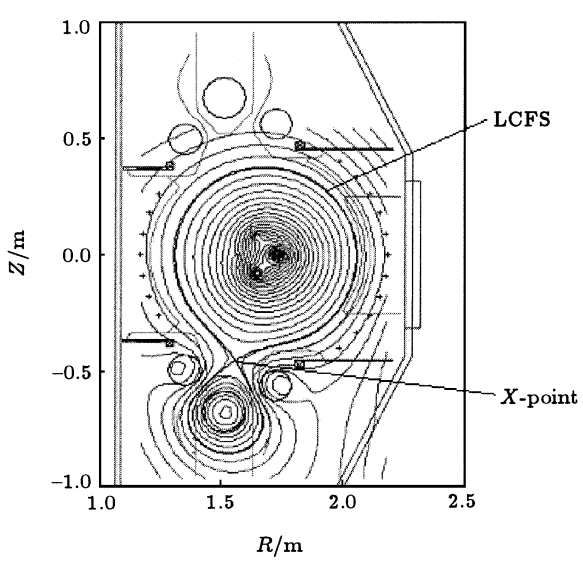


Fig.3. The magnetic field calculated by CFC code of Shot 2800.

The time is taken at 400 ms when the divertor configuration has been fully formed. The parameters of plasma are as follow, plasma current I_p=266 kA, toroidal magnetic field B_T=2.1T, line averaged electron density n_e=8×10^{12}cm^{-3}. The structure of magnetic field and the last closed magnetic flux surface are all presented in this figure. The magnetic flux surface slightly shifts outside. Therefore, the separation between the last closed magnetic flux surface and the limiter at the high field side is larger than that at the low field side. But the last closed magnetic flux surface obviously does not touch the limiter. Moreover, the last closed magnetic flux surface smoothly passes through the throat of the divertor and keeps enough space away from the wall of the throat for the particles in the scrape-off layer region to enter into the divertor chamber. X-point is really formed at the right place. It means that the divertor configuration with a single X-point is perfectly achieved at this moment when nothing is attached to the first wall of the device. The plasma lasts more than 330 ms with divertor configuration. When the divertor configuration is formed the reduction in H_α intensity and radiation from impurity is observed. Some of plasma parameters as a function

of time are shown in Fig.4.

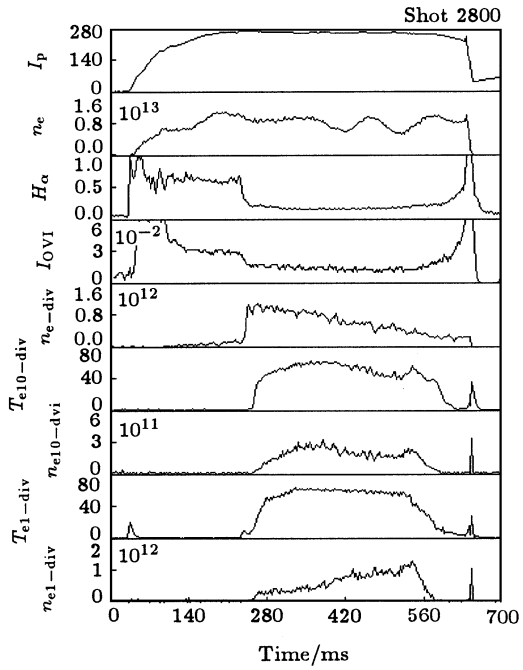


Fig.4. The typical waveforms of Shot 2800.

From top to bottom in Fig.4 the parameters are plasma current I_p (in unit of kA), line averaged electron density n_e (/cm^{-3}), H_α intensity (/arb. units), intensity (/arb. units) of OVI emission (103.2 nm), I_{OVI} measured by the VUV monochromator, electron density (/cm^{-3}) in the divertor n_{e-div} measured by the microwave interferometer, electron temperature $T_{e10-div}$ (/eV) and density (/cm^{-3}) $n_{e10-div}$ in the high field side divertor chamber measured by the probes located at the neutralized target plate, electron temperature T_{e1-div} (in eV) and density (/cm^{-3}) n_{e1-div} in the low field side divertor chamber also measured by probes. The divertor configuration is formed in the time interval from 270 ms to 600 ms. When the divertor configuration is fully formed the temperatures on the target plate both in the inner divertor and in the outer divertor increase up to about 50 eV. The electron density in the inner divertor chamber is higher than that in the outer divertor chamber; they are 9.5×10^{11} cm^{-3} and 2.7×10^{11} cm^{-3}, respectively. H_α intensity in the main plasma region dramatically decreases from 600 arb. units to 160 arb. units when the divertor is formed. The percent decrement is about 73%. During the whole discharge there is only the background gas release. Therefore, the changes of the H_α intensity and the density in divertor chamber are absolutely caused by the particle pumping capability of divertor. In the main plasma region the emission from light Z impurities such as oxygen shown in Fig.4 obviously decreases from 28 arb. units to 13 arb. units with the total percent decrement being 53%. The effect of divertor on impurity and recycling of wall can always be observed at the moment when the divertor configuration is fully formed.

By using a plasma transport code, B2, which is transferred from Germany and available only in the scrape-off layer (SOL) and divertor region,[12] the distributions of the electron density and temperature in plasma edge and divertor region are obtained.

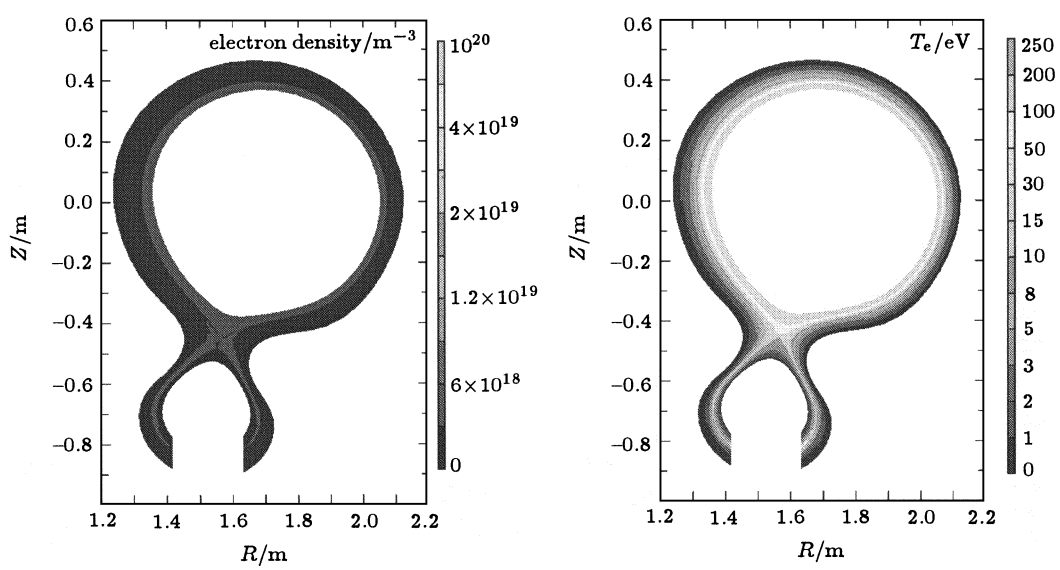


Fig.5. The results calculated by B2 code on the SOL and divertor.

The power, which goes through the separatrix from the plasma confinement region into the SOL region, is one of the important input parameters in the calculation. It is assumed to be 500 kW under the condition of ohmic heating. The results are shown in Fig.5. The distribution of electron density is on the left side and that of the temperature is on the right side. Different colors denote different values of density and temperature. The density is about $3\times10^{12} - 6\times10^{12}\,\mathrm{cm}^{-3}$ and temperature is about 30–50 eV near the last closed magnetic field surface. The calculated values of both density and temperature are very similar to their experimental ones. It means that during the first operation stage of divertor in ohmic heating case on HL-2A the typical value of plasma density is lower. Therefore, the typical temperature on the divertor target plate is slightly higher than that of the other device with additional heating power. The experimental results are confirmed by the results of B2 code.

3.2. Effect of siliconization on impurity and recycling

Inside the vacuum vessel of HL-2A there are four pairs of fixed limiters and a segment of moveable limiter. The fixed and moveable limiters are all close to the joint sections of the vacuum vessel and covered by the graphite tiles. The two domes of the divertors are also covered by the graphite tiles. The ratio of the area covered by graphite to total inner surface of the vessel is about 0.1%. Vacuum volume and inner surface of HL-2A are 26 m^3 and 76 m^2, respectively. The main pump systems are comprised of six molecular pumps: 6×3500 (ls^{-1}) and two cryogenic pumps: 2×12000 (ls^{-1}), and pre-pump systems consist of two Roots pumps: 2×600 (ls^{-1}) and two mechanical pumps: 2×70 (ls^{-1}). The total volume of two divertors is about $2\times7.2\,\mathrm{m}^3$. The total leakage rate is $9\times10^{-5}(\mathrm{Pa\cdot m^3\cdot s^{-1}})$.[13,14] The highest vacuum has reached 4.6×10^{-6}Pa. At a beginning of experiments the vacuum chamber is normally baked up to a temperature of 120°C. When the temperature of the wall is back to room temperature the glow discharge cleaning with helium gas is conducted, then the plasma discharge follows. The two big divertor chambers with the ratio of the divertor volume to the whole vacuum volume being about 55% serve the function of a huge reservoir of gas, which strongly affects the electron density in plasma. The relevant research has been published.[15] The experimental results of the siliconization are present below.

3.2.1. Effect of siliconization on impurity

By using the glow discharge cleaning (GDC) with the mixture gas of SiH_4+He the film of silicon is coated on the internal surface of the vacuum vessel. The evaporation takes about 40 minutes each time. Before and after siliconization the GDC with helium is performed, and a half-hour helium GDC is routinely carried out each day just before the plasma discharge. Comparing with boronization the siliconization can strongly absorb oxygen. Therefore, the intensity of oxygen is remarkably decreased after siliconization. Figure 6 shows the time evolutions of oxygen intensity (/arb. units) with the comparison between the discharges before and after siliconization.

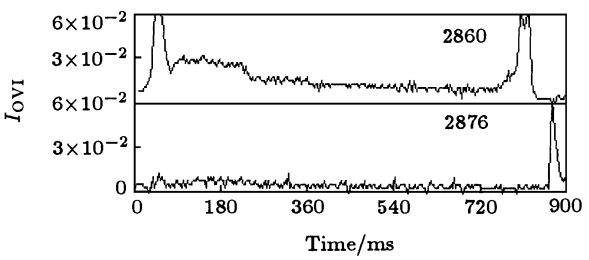


Fig.6. Comparison of oxygen between the discharges before and after siliconization.

Shot 2876 is for the discharge after siliconization and Shot 2860 is for the one before siliconization. The plasma currents for both shots are almost the same: I_p=213 kA for Shot 2860, I_p=228 kA for Shot 2876. Toroidal magnetic fields and electron densities for both shots remain unchanged: they are 2.1T and $0.9\times10^{13}\,\mathrm{cm}^{-3}$, respectively. The intensity of oxygen of fifth ionization stage after siliconization is about ten times lower than that before wall conditioning. Its intensity of radiation drops from 70 arb. units to 8 arb. units at the peak, and from 12 arb. units to 5 arb. units at the plateau. The intensity of radiation at the peak decreases nearly 14 times after the wall conditioning. It means the reduction in impurity by siliconization is significant.

We have also compared the emission of carbon between the discharges before and after siliconization. The change of intensity of carbon is similar to that of oxygen: its radiation peak decreasing about ten times and its plateau about one time after siliconization.

The effect of siliconization on the whole plasma radiation measured by bolometer array is also remarkable which is shown in Fig.7. Shot 2870 and Shot 2860 are for the discharges after siliconization and before siliconization, respectively. The radiation profiles are

directly obtained from the integral signal along the sight line of the detector. The plasma parameters are similar for both shots. The total radiation level of plasma is very high and goes up to $40\,kW/m^{-2}$ before siliconization. After siliconization the total radiation drops down to $5\,kW/m^{-2}$. The ratio of the radiation before wall coating to that after coating is about 8. The impurity radiation loss of siliconization is effectively controlled.

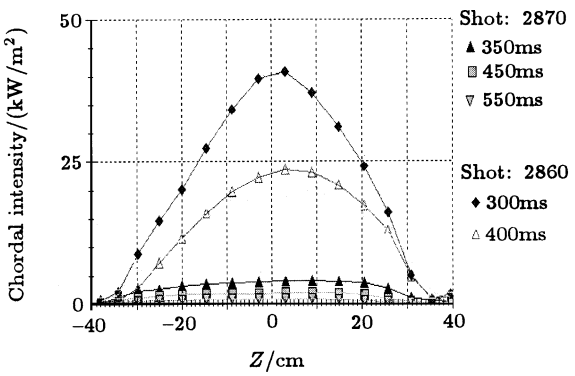


Fig.7. Plasma bolometer profile of line integration.

3.2.2. Effect of siliconization on recycling

In a normal case the procedure of siliconization is set as follows. The GDC with helium gas is carried out for about 20 minutes. And then, a gas mixture, which is comprised of SiH_4 (10%) and He (90%), is injected, and the GDC with the gas mixture is maintained for 40 minutes. Finally, the GDC with helium is conducted again for 20 minutes. The different procedures of siliconization were adopted in 2004 for investigating the effect of wall coating on impurity and wall recycling. One of the procedures included the first and second steps mentioned above. No third step was followed. The other procedures included all of three steps. Comparing with the two kinds of siliconization procedure the effects of the silicon coating on the impurity are similar except for the wall recycling. The wall recycling kept very high after the first procedure of wall conditioning had been included.

H_α intensity, the pressure of neutral gas measured by fast gauge and the emission intensity of oxygen of fifth ionization stage are shown in Figs.8(a), 8(b) and 8(c), respectively, corresponding to the two kinds of procedure of wall conditioning. Shot 2868 is for the discharge after the first procedure is settled and Shot 2877 is for the discharge with the second procedure settled. In this figure it can be clearly seen that H_α intensity in Shot 2868 is stronger than that in Shot 2877. It has a longer plateau slowly decreasing with the time in Shot 2868, whereas H_α intensity has almost no plateau and decreases very fast for Shot 2877. There is no additional gas release for both shots. It means that the hydrogen gas may be continuously released from the wall for Shot 2868. Figure 8(b) shows the time evolution of the neutral gas pressure. The starting point of time axis in Fig.8(b) is different from that in Fig.8(a) and also that of Fig.8(c). Plasma discharges start from zero on the time axis for three figures. The waveforms of the gas pressure on the minus part of time axis in Fig.8(b) express the value of background gas pressure. The value of the background gas pressure in Shot 2877 is much higher, about 1.4 times, than that in Shot 2868. However, the electron densities for both shots are comparable. It means that in order to keep the same electron density for both shots the pressure of background gas in the discharge with lower wall recycling is higher than that in discharge with the high recycling. From Fig.8(c) we can see that the intensities of oxygen are similar for both shots, and they are much lower than those in the discharges before siliconization. It is clearly shown

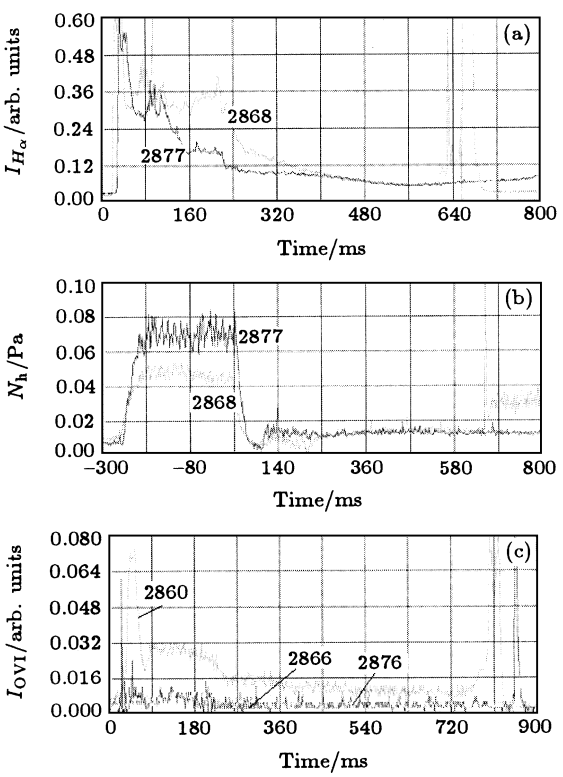


Fig.8. The comparison of H_α intensity (a), the pressure of neutral gas Ph (b) and the intensity of impurity emission (c) between two kinds of siliconization procedures.

that the third step of wall conditioning procedure plays an important role in controlling the wall recycling only, and has no influence on impurity. The coated silicon film serves the main function of absorbing impurity and controlling impurity radiation loss in plasma. The reason for the difference between two siliconization procedures can be briefly explained as follows. In the siliconization process many hydrogen atoms come from the SiH_4 gas, of which one molecule has four hydrogen atoms, and deposit on the surface of wall. The hydrogen can be released from the wall during the plasma discharge. So the recycling will be increased after the GDC with SiH_4. The third step with glow discharge cleaning in Helium can reduce sputtering of the substrates and desorbs hydrogen implanted in the wall, thus reducing recycling.

3.2.3. Lifetime of siliconization

It is hard to exactly define the lifetime of a coating. In general, the lifetime of the silicon coating is characterized by the total accumulated shot number above which the coating can no longer serve the function of preserving good performance of plasma in discharge. In the normal case, siliconization can dramatically decrease impurity radiation, thus the discharge quality is greatly improved, and the discharge performance can be well reproduced. The emission directly from the ionization stage of silicon is investigated after siliconization. Figure 9 shows the emissions of SiIV (139.4 nm) against time, measured by VUV monochromator. The intensity of silicon rapidly decreases with shot number increasing just after siliconization. Shots 2874, 2875 and 3011 are for the discharges of the first, the second and the 34th plasma discharge after siliconization, respectively. The plasma currents for these shots are similar, they are 212 kA, 219 kA and 207 kA, respectively. The toroidal magnetic field and line averaged electron density for three shots remain almost unchanged, they are 2.1T and 1×10^{13} cm^{-3}, respectively. For the first shot, i.e. Shot 2874, intensity of silicon is stronger, its value is about 20 arb. units. The intensity of silicon for the second shot, namely Shot 2875, decreases down to half the value for the first shot. And after discharges 34 times, silicon intensity almost disappears.

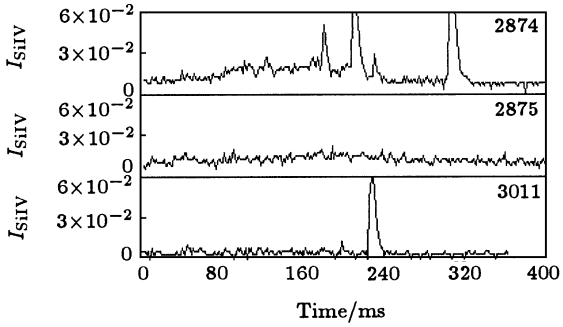


Fig.9. Time evolution of silicon intensities (/arb. units) for three shots just after siliconization.

The intensity of silicon decreases quickly with the shot number increasing. It means that the slack layer of the atomic silicon on the coating surface is losing quickly. The hard layer of compound of silicon has a strong influence on impurity. Although the line emissions of silicon decreases rapidly as a function of discharge number, even almost disappears, the effect of siliconization on the plasma properties is present but decreases gradually after a large number of discharges. Let us focus on the effect of siliconization on impurity by looking at the intensities (/arb. units) of oxygen (OIV 103.2 nm) in different discharges shown in Fig.10. Shot 2876 and Shot 2966 are for the 3rd and 92th discharge after siliconization, and Shot 2860 is for the discharge before siliconization. The plasma parameters of three shots are also similar. It is shown in Fig.8 that the intensity of oxygen increases to half the value intensity for Shot 2876. The efficacy of the siliconization can be maintained till the 160th or 180th discharge with the similar discharge parameters. In the normal case there are 30 shots a day. Therefore, the efficacy of siliconization can last 5 or 6 days. This shows that the lifetime of silicon coating is not short, and the discharge quality at the end of the lifetime is comparable with that of HL-1M at the 140th shot. We should mention that HL-2A is a new device but HL-1M is a device that has operated for 7 years. Therefore, it may be due to the divertor configuration that prevents the particles from plasma from bombarding the vessel wall. It is a role that the divertors should play in tokamak discharges. Impurities are obviously controlled by the divertor configuration and wall conditioning in HL-2A discharges.

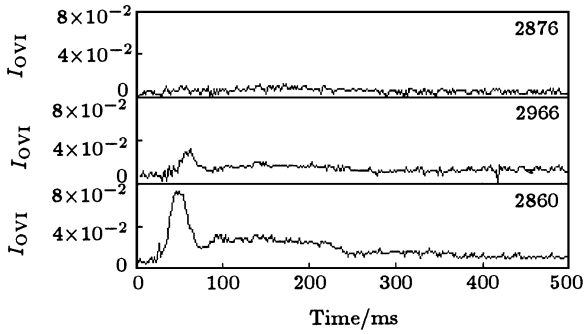


Fig.10. The intensity of oxygen vs discharge number.

4. Summary

HL-2A is the first divertor tokamak with two X-points in China. It was successfully operated under the condition of fully forming divertor configuration in 2004. The reduction in impurity is obviously observed when the divertor configuration is formed. The siliconization as a wall conditioning has been performed first on HL-2A experimentally in 2004. The radiation of impurity is greatly reduced after the wall of device vacuum vessel is coated by silicon. The recycling of the wall is also affected by the wall conditioning. Impurities are obviously controlled by divertor configuration and wall conditioning in HL-2A discharges.

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