[To be revised]

Recent Advances in the HL-2A Tokamak Experiments

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ABSTRACT

Two experiment campaigns were conducted on HL-2A tokamak in 2003 and in 2004 after the first plasma was obtained at the end of 2002. Progresses in many aspects have been made, especially in the divertor discharge and feedback control of plasma configuration. Up to now, the following operation parameters have been achieved: Ip = 320 kA, Bt = 2.2 T and discharge duration T_d = 1580 ms. With the feedback control of plasma current and horizontal position, an excellent repeatability of discharge has been achieved. The tokamak has been operated at both limitor configuration and single null (SN) divertor configuration. The HL-2A SN divertor configuration is simulated with the MHD equilibrium code SWEQU. The divertor experiment results were compared with the simulation results obtained with B2. When the divertor configuration is formed, the impurity radiation in main plasma decreases remarkably. The plasma performances are improved significantly after siliconization.

1. INTRODUCTION

HL-2A is a divertor tokamak reconstructed at the new site of SWIP in Chengdu based on original ASDEX main components (vacuum vessel and magnet coils) [1]. HL-2A project is an important part of the fusion research program of China. Mission of HL-2A Project is to explore physics issues involved in advanced tokamak. Most of the important issues of fusion physics, such as confinement improvement, divertor and scrape-off layer physics, wall conditioning, MHD instability and energetic particles, auxiliary heating and current drive, would be studied and explored on the HL-2A through the progressive improvement of the hardware [3]. For first phase, the divertor (edge plasma) and confinement research are emphasized. It is expected that the experimental results from HL-2A will make contributions to the development of worldwide fusion research. After realizing the objective for closed divertor research for a period of operation, the divertor will be modified into an open one[1].

The PF coils and vacuum vessel will be redesigned and the divertor coils will be moved out of the vessel so that larger plasma volume and more shaped configurations could be obtained.

The construction of HL-2A was started in early 1999. The civil construction was completed in 2001. The installations for the main machine structure including vacuum vessel, magnetic field coils have been accomplished in the end of 2001. The construction of power supply and control systems was finished at summer of 2002. The diagnostics and auxiliary heating systems are being developed and installed progressively. The first plasma was obtained on December of 2002 as the schedule.

After the effective wall conditioning, the device is operated with good discharge reproducibility at Ip = 168 kA, Bt = 1.4 T and discharge duration T_d = 920 ms in the first physics campaign in 2003. Up to now, the following operation parameters have been achieved: Ip = 320 kA, Bt = 2.2 T and discharge duration T_d = 1580 ms.

In this presentation, Progress in the HL-2A Tokamak Engineering is introduced in section 2. Experimental Progress is given in section 3.

2. Progress in the HL-2A Tokamak Engineering

The major parameters of HL-2A are:R=1.65m, a=0.4m, Bt=2.8T, Ip =0.48MA. The HL-2A tokamak is characterized with a large closed divertor chamber. This is unique in present tokamak experiments. This unique feature will make significant contributions to enhance understanding of complex divertor plasma physics and help validate divertor physics modeling. To utilize this unique feature completely, much more attention will be paid to the enrichment of diagnostics for divertor plasma. The machine can be operated in double null, upper single null and lower single null configurations with the same main plasma condition to study the physics of divertor operation and various improved confinements regimes.

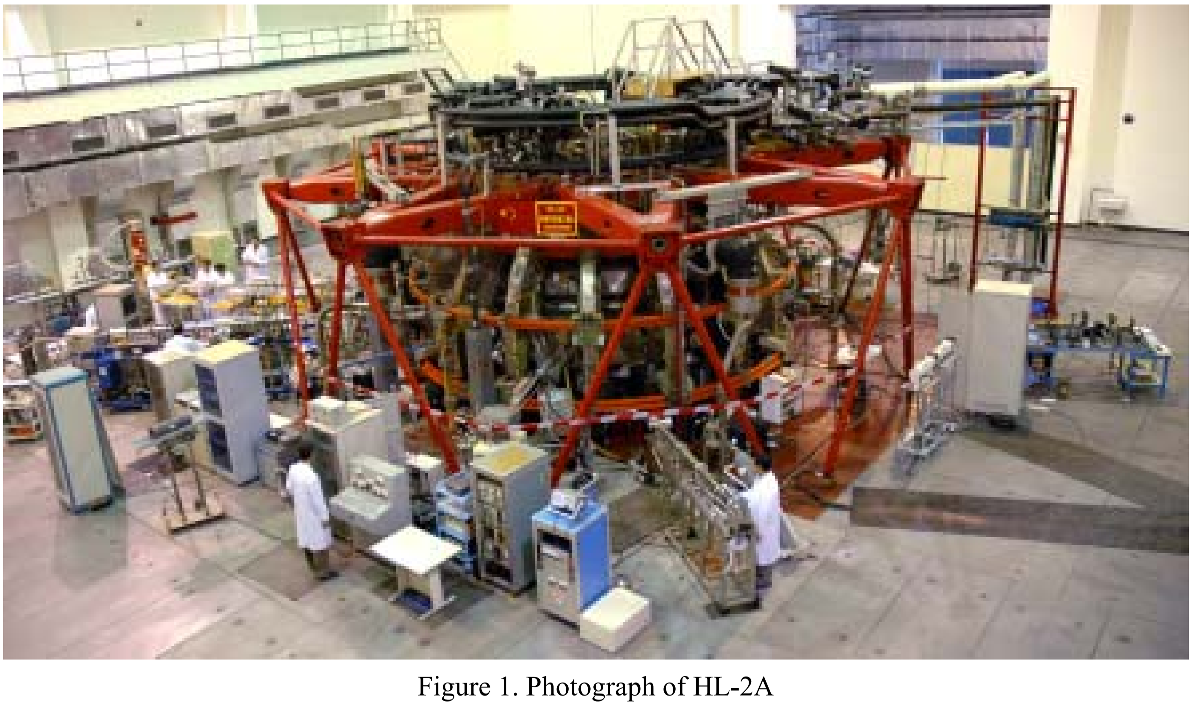

Figure 1. Photograph of HL-2A

The vacuum vessel, 16 toroidal field coils, poloidal field coil systems and supporting structure of the former ASDEX are adapted for HL-2A[2]. The other sub-systems of HL-2A, including pumping system, cooling system, power supply system, diagnostics system, auxiliary heating system, have been designed and have been or are being constructed, to meet the requirements of the experiment program of HL-2A. The photograph of the device is shown in figure 1. The main pumping system of HL-2A is composed of 8 turbo molecular pumps (3500l/s each) and two set of cryopumps with pumping speed , with 2 sets of pre-stage pumps. The divertor pumping system is composed of 18 titanium getter pumps installed in divertor chambers. The vacuum vessel can be baked up to 130°C -150°C for degasing and a glow discharge device is installed in the vessel for cleaning the inner surface of the vessel.

8 sets of DC pulse power supplies have been constructed for the coil system of the toroidal field(TF), the Ohmic heating(OH), the vertical field(VF), the radial field(RF), the multipole field(MP), the multipole compensation field(MPC) and so on. The peak power of 300MVA and the total energy release of 1200MJ per shot are required for the operation at Bt=2.8T, IP=0.48MA. Three motor generators (MG) are used for the power supply system. Two identical existing MG were modified by replacing original flywheel of 40 ton with a new one of 90 ton. After modification, the released energy will be increased to 500MJ from 100MJ. The two MG are used to power the toroidal field coils via a 12 pulses diode rectifier. Another MG with output power of 125MVA is used to power the poloidal field system with transformers and thyristor rectifiers. In order to check the system design and optimize the parameters of feedback control system, the power supply system has been simulated with EMTP code. The current in TF coils is controlled by regulating the exciting field current of MG sets. The currents in PF coils are controlled by using a feedback control system. A digital control method has been developed to adapt to the AC frequency changes from 120Hz to 96Hz corresponding to the MG shaft rotating speed slow down from 1650rpm to 1200rpm.

HL-2A control system consists of two parts, the machine control system and the discharge control system. The machine control system configures and operates all the subsystems of the tokamak. In this system, logical control and interlock protection are realized with PLC. The discharge control system is designed for controlling plasma current, plasma position and plasma shape with a real time feedback control system.

The auxiliary heating systems with total power of about 10 MW are planned, which include NBI of 4MW/60keV/2s, LHCD of 3MW/2.45GHz/1s, ICRH of 2MW/30-65MHz/2s, ECRH of 1MW/75GHz/1s. The NBI of 4MW with two beamlines will be developed with priority. According to the schedule, a NBI system with 2MW and a LHCD system with 1MW will be built up for first phase experiments. Then the auxiliary heating system will be extended to the planned parameters to realize the goals of the HL-2A tokamak. A 30 shot pellet injection system will be developed with both low field side and high field side injection. For first phase, a 8 pellet system has been moved from HL-1M to HL-2A for preliminary pellet injection experiments. The molecular beam injection, which was first proposed on HL-1M as a fueling technique, will be further developed on the HL-2A.

About 30 diagnostics have been installed in the main chamber of the device, which include the HCN interferometer, ECE, Thomson scattering, CX neutral particle analyzer, bolometer array (16 channels), VUV spectroscopy, reciprocating probes, and the visible spectrometers at the mid-plane of the device. To investigate the plasma features in divertor, 5 kinds of diagnostics have been mounted in the lower divertor. The microwave interferometer, target plate Langmuir probe arrays and visible spectrometer are used to measure the profiles of the electron density, electron temperature, Hα emission, respectively. Four target plate Langmuir probe arrays are fixed on the 4 target plates (upper and lower, inner and outer), respectively. Each array consists of 7 probes with 3 tips, and the vertical distance between two probes is 1.0 cm. The neutral gas pressure is given by the fast ionization-gauge at the divertor chamber. Especially, we used the signals detected by 18 pick-up coils which located around the plasma column and Current Filament (CF) code, a plasma boundary identification code, to reconstruct the plasma LCFS (Last Closed Flux Surface). Visible photography mounted on midplane is most direct tool to observe the plasma discharges.

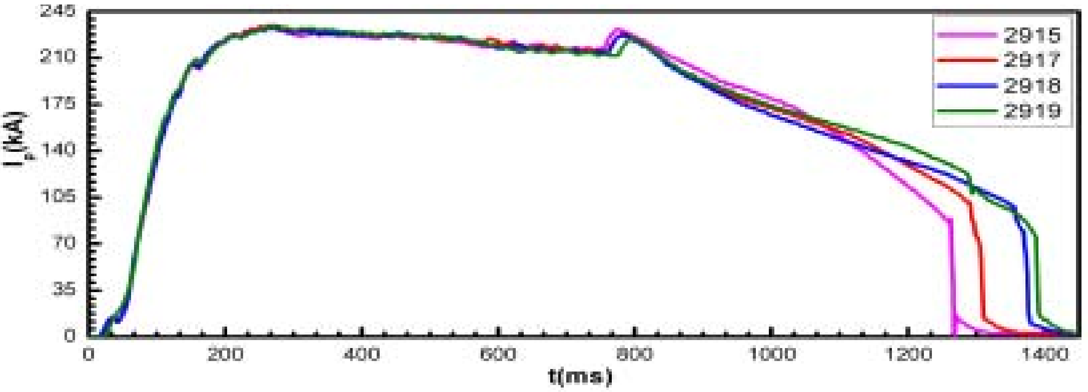

Fig.2 The repeatability of discharge in HL-2A

Since the first plasma was obtained on December of 2002 as the schedule. Performance of discharge has been improved progressively. The device was operated with good discharge reproducibility at Ip = 168 kA, Bt = 1.4 T and discharge duration T_d = 920 ms in the first physics campaign in 2003. Up to now, the following operation parameters have been achieved: Ip = 320 kA, Bt = 2.2 T , n_e=3.2*10^{13}cm^{-3} and discharge duration T_d = 1580 ms. With wall conditioning (siliconization) and feedback control of plasma current and horizontal position, an excellent repeatability of discharge has been achieved. The repeatability of discharge in HL-2A is shown in Figure 2.

3. Experimental Progress

1) Identification of divertor configuration

In the divertor experiments on HL-2A, a few kinds of ways were used to identify the formation of divertor configuration. A CCD camera is the most direct tool, which can take the images of the cross-section of plasma discharges. A typical CCD photo with divertor plasma configuration is shown in Fig. 3. Two bright legs have been observed in lower divertor throats, which indicate that the plasma has gone into the lower divertor along the magnetic field line. The magnetic surface and the position of X-point for the same discharge have been reconstructed by Current Filament (CF) code, as shown in Fig.4. The magnetic separatrix in main plasma and in divertor legs do not touch the first wall components. These results are not only in agreement with the simulation ones of plasma equilibrium, but also with the measurement results of the plasma parameters in divertor.

Fig.3 Divertor discharge photography at about 200 ms for shot 1766

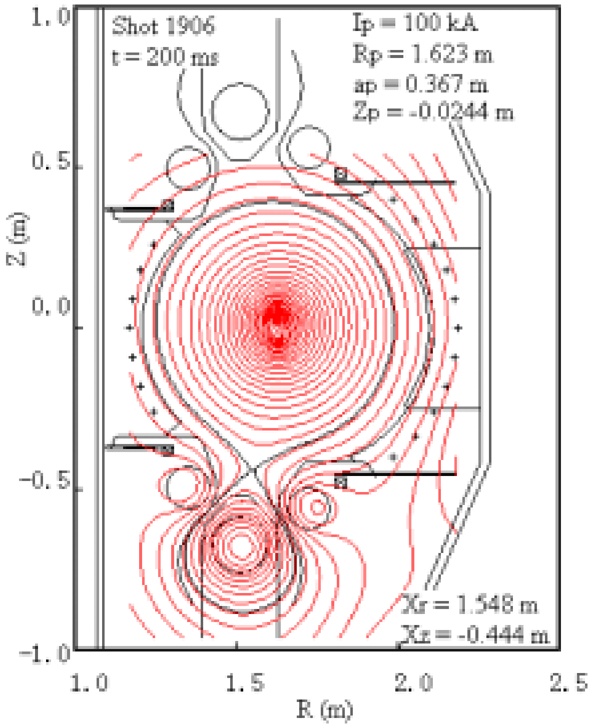

Fig.4 Reconstruction of magnetic surface using 18 Mirnov signals for shot 1906

Plasma equilibrium in HL-2A is simulated by the SWEQU code, which solves the Grad - Shafranov equation including two adjustment functions of pressure and current profiles. Double null divertor configuration can be achieved after vertical field current is optimized. Lower single null (LSN) discharges are mainly simulated. Multipole field currents of MP1, MP2, MP3, and radial field current are required to meet following equation, $I_{MP1,3}/I_{MP2} = 0.244(I_{RF}/I_{MP2}) + 0.884$. Two kinds of power supply methods are designed to realize LSN divertor discharges. A typical simulation divertor configuration is shown in Fig.5.

The parameter evolutions of a typical LSN divertor discharge are given in Fig. 6. Main parameters are plasma current (a), line –averaged density (b), Ha emission in main plasma (c), line averaged density in divertor (d), outer target plasma temperature (e) and density (f), inner target plasma temperature (g) and density (h). Divertor discharge is obtained in 250 – 600 ms. The Ha emission in main plasma abruptly drops during divertor discharge. The line-averaged density in divertor and the electron temperature/density measured by the fixed probes on target plates have been observed during the formation of the divertor configuration.

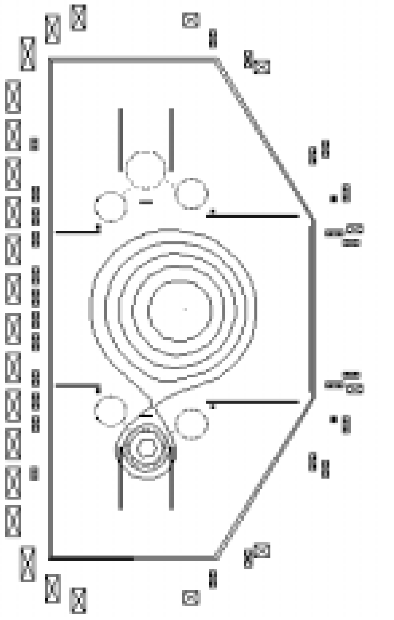

Fig.5 Single null divertor configuration simulated by SWEQU code

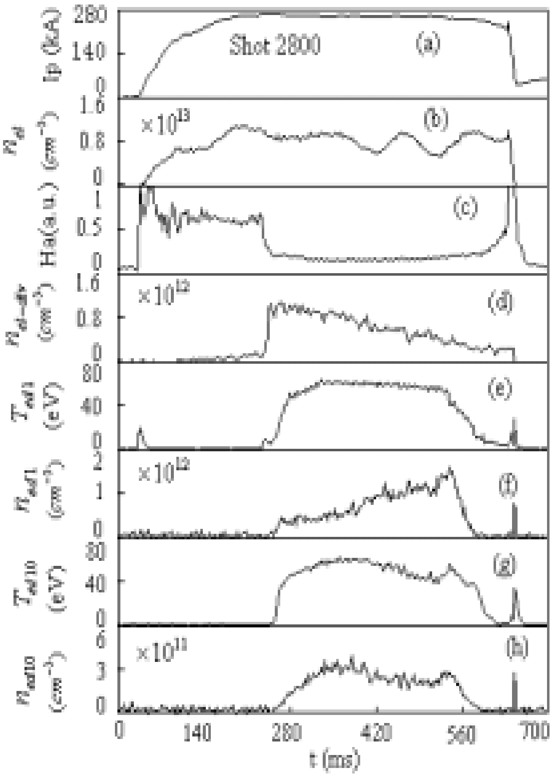

Fig.6 Parameter evolutions of divertor discharges in shot 2800

The time evolution of the target temperature distribution during the divertor configuration has been shown in Fig. 7. Main plasma parameters in this shot are current I_P = 120kA, line-averaged density n_{el} = $0.8\times10^{19}m^{-3}$, P_0 is the neutral gas pressure at divertor chamber, which is measured by FIG (Fast Ionization Gauge). In the two images (are given in the bottom), the black region presents higher electron temperature detected by local Langmuir probe arrays. Contrast to this, the white area means the lower electron temperature. I_R is the intensity of plasma radiation detected by Bolometer.

The discharge is limiter configuration during current ramp up or down. Divertor configuration is formed and sustained if the ratios of $I_{MP2}/I_P \approx$ 9~10% and $I_{MP1}/I_{MP2} \approx$ 85% are kept in 80 ~ 230ms. The magnetic field configuration of divertor plasma is very stable in about 200ms, which can be observed from the electron temperature profiles by the target plates. Meanwhile, the measurement of pressure gauge also indicates that divertor discharges can make neutral gas pressure at divertor chamber rise rapidly. The higher neutral gas pressure is because the plasma strikes the target plate and then to be neutralized. When the ratio of I_{MP2}/I_P keeps constant about 9~10%, the strike points are unchanged. In this case, the divertor legs strike at Z = -84cm on the outer plate and at Z = -81cm on the inner plate.

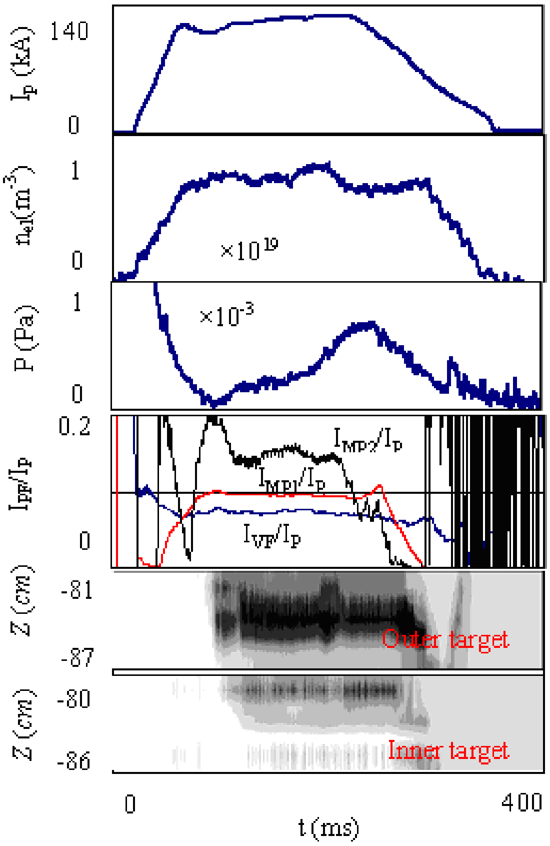

Fig.7 The plasma parameters and the images of electron temperature on strike point for shot 1766

During 225 ~ 235ms as shown in two dashed lines, the I_{MP2}/I_P increases from 10% to 12%, plasma strike point on target plate is moved downward about 2 cm. These results can be verified by simulation and reconstruction ones. The I_{MP1}/I_{MP2} can also affect the formation of divertor configuration, as shown in 90 ~ 100ms. When the ratio rises to 20%, the plasma temperature decreases.

2) Experimental results of divertor discharge

As we know, three regimes have been observed in divertor research: linear regime, high recycle regime and detached regime. For HL-2A operation region, linear recycling operation model can be obtained. The plasma with low density and higher temperature is formed near the target plate. The results of the theoretical calculation have been obtained by B2 code with typical HL-2A parameters as shown Fig.8. To compare with the results of the theoretical

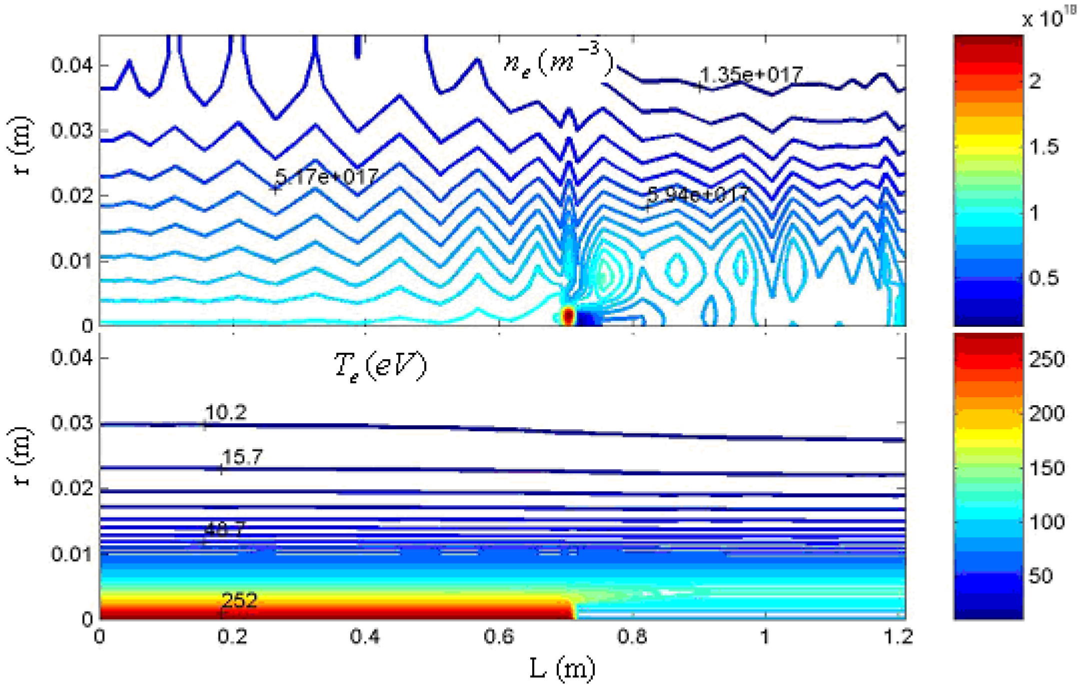

Fig.8 Electron density and temperature profile of the edge and divertor plasma calculated by B2 code with typical HL-2A parameters

calculation, in main plasma chamber, the average electron density of main plasma and edge plasma density have been measured by HCN laser interferometer and fast moveable probe respectively, in divertor chamber, the average electron density and the electron temperature/density near the target plate have been measured by microwave interferometer and the target plate probe arrays. The main parameters of the divertor discharge for shot 2800 given in Fig.6 are compared with the theoretical results. The electron temperature on the target is about 60 eV for low-density discharge. The density in divertor is 1x10^{12}cm^{-3}, which is about one fifth of line-averaged density of main plasma. The temperature asymmetry between outer target and inner one is very obvious. These results are corresponding to the prediction of theoretical models.

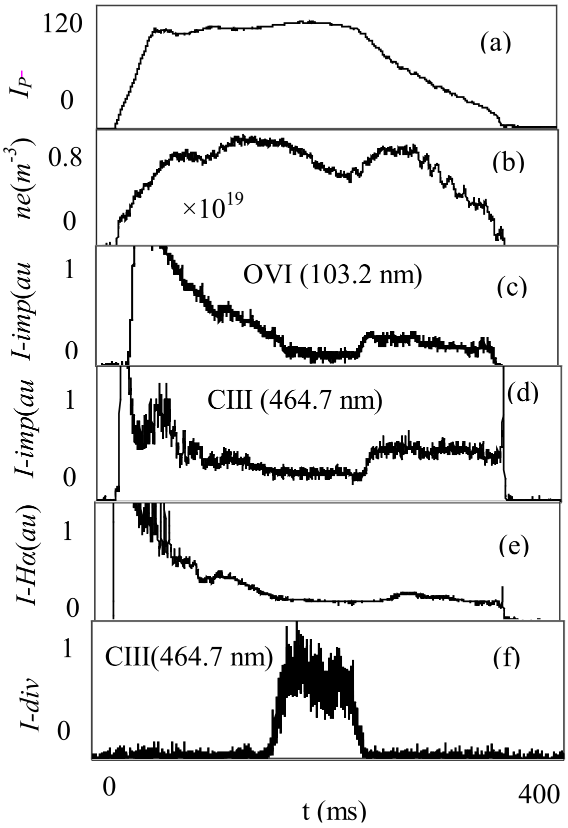

Fig.9 The typical features of divertor operation for shot 1756.

The important role of the divertor configuration, for example suppressing the impurity and decreasing the recycling, has been observed in the primary experiments on the HL-2A tokamak. The detailed description about the typical features on divertor operation is shown in Fig.9. In this shot, the plasma current is about I_P = 120kA, and horizontal displacement is about R = 168 cm by feedback control techniques. During t = 150 ~ 230ms (involved between two dashed lines), the appearance of spectrum radiation (CIII, 464.7nm) and profiles of plasma temperature (T_{ed}) which obtained from the divertor plate probes indicate that the divertor configuration is formed. In this duration, a signal dip of the impurity spectrum (OVI, 103.2nm and CIII, 464.7nm), plasma radiation and Hα emission detected in the main plasma region can be observed. After t = 230ms, the divertor structure disappears. And then the radiations of plasma in the main plasma jump up to the higher values, which imply that the divertor configuration strongly decrease the plasma radiation and impurity emission. The phenomena of impurity suppression and the plasma radiation reduction are the typical features of divertor operation. In addition, we notice that the electron density decreases gradually during the divertor configuration existence, and increases immediately after divertor configuration exhausted. Considering that the fuelling and pumping conditions are not change in this period, we could conclude that the divertor configuration can reduce the wall recycling.

4) Experimental results of the siliconization

The siliconization as a wall conditioning method has been done in HL-2A tokamak. After the siliconization both the thermal radiation and impurity radiation are suppressed obviously as shown in Fig.10 (a), (b). In Fig.10 (a), the profiles of the plasma thermal radiation measured by the bolometer array before the siliconization are compared with that after the siliconization with very similar discharge parameters. The total radiation after the siliconization has been decrease to about 10 percent. The same similar results have been also obtained with VUV measurement as shown Fig.10 (b). Discharge performances are improved significantly after siliconization. The breakdown loop voltage at the discharge decreases from 12V to 8V.

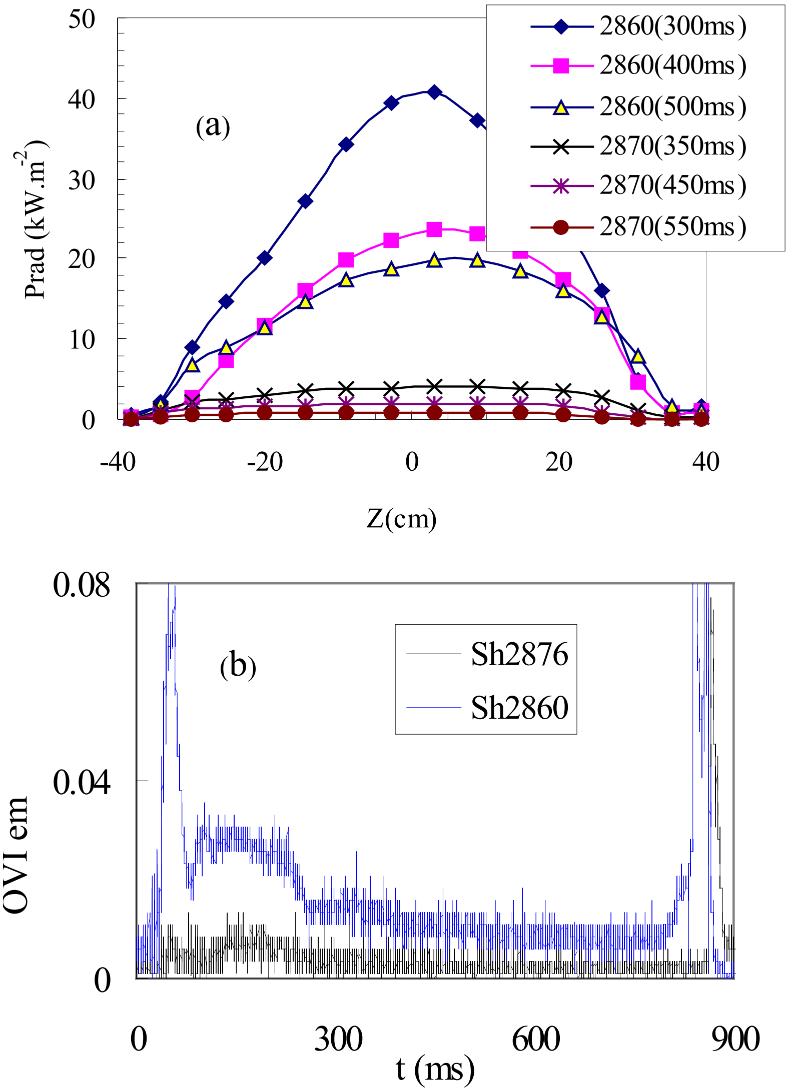

Fig.10 (a) The profiles of the plasma thermal radiation measured by the bolometer array before the siliconization and after the siliconization with very similar discharge parameters (b) The time evolutions of VUV before the siliconization and after the siliconization with very similar discharge parameters

4. Summary and future plans

The Reconstruction of HL-2A tokamak, the first divertor tokamak in China, was finished at SWIP based on original ASDEX main components. Two experiment campaigns were conducted on HL-2A tokamak in 2003 and in 2004 after the first plasma was obtained at the end of 2002. Progresses in many aspects have been made, especially in the divertor discharge and feedback control of plasma configuration. Up to now, the following operation parameters have been achieved: Ip = 320 kA, Bt = 2.2 T and discharge duration T_d = 1580 ms. With the feedback control of plasma current and horizontal position, an excellent repeatability of discharge has been achieved. The tokamak has been operated at both limitor configuration and single null (SN) divertor configuration. The HL-2A SN divertor configuration is simulated with the MHD equilibrium code SWEQU. The divertor experiment results are compared with the simulation results obtained with B2. When the divertor configuration is formed, the impurity radiation in main plasma decreases remarkably. The plasma performances are improved significantly after siliconization.

In the summer experiment campaign of 2005, the HL-2A tokamak will be operated at Ip = 450 kA, BT = 2.5 T, plasma duration t > 2 s. More experiments will be carried out with divertor discharges. 1MW LHCD and 1MW ECRH system has been installed in the device and off-axis current drive and heating will be carried out for studying the magnetic shear and the internal transport barrier. The advanced SMBI[4] fuelling will be developed with lower gas temperature and higher gas pressure than those on HL-1M and the effects of the SMBI on the plasma confinement will be investigated further. Pellet injection system and some new diagnostics are being prepared to study the pellet penetration process and ablation mechanism. After realizing the objective for closed divertor research for a period of operation, the divertor will be modified into an open one.

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