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Overview on Chinese Tokamak Experimental Progress

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Abstract. Tokamak experiment research in China has made important progress. The main efforts subjected to quasi-steady state operation, LHCD, plasma heating with ICRF, IBW, NBI, ECRH, fueling with pellet and supersonic molecular beam, first wall conditioning technique. Plasma parameters in experiments were much improved, such as $n_e=8\times10^{19}m^{-3}$, plasma pulse>10Sec. ICRF boronization and conditioning made Z_{eff} close to unit. Steady state full LH wave current drive has been achieved for more than 3 seconds. LHCD ramp up and recharge have also been demonstrated. The Best $\eta_{CD}^{exp} \approx 0.5(1+0.085\exp(4.8(B_T-1.45))n_e I_{CD} R_p / P_{LH} = 10^{19}m^{-2}$ A/W. Quasi steady state H-mode like plasma with density close to Greenwald limit was obtained by LHCD, in which energy confinement time was nearly 5 times longer than the Ohmic case. The synergy between IBW, pellet and LHCD was tested. Research on the mechanism of macro-turbulence has been extensively carried out experimentally. Ac operation of tokamak was successfully demonstrated.

1. Introduction

Steady state operation of tokamak plasma is one of the basic requirements for fusion reactor. The problems involved can be resolved by using super-conducting techniques in the tokamaks and with the developments of non-inductive current drive, plasma control, removal of particles and heat fluxes to the first wall, advanced fueling and effective heating, etc. On other hand, higher performance, such as advanced tokamak operation modes, are needed for the economic use of fusion reactors. Investigation on tokamak experiments in China are contributing to these fusion reactor relevant issues and underlying physics.

There are five tokamaks at present in China, which have different missions. HT-7 is a medium sized super-conducting tokamak in Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) in Hefei. Its main purpose is to explore high performance plasma operation under

steady-state condition. Another small tokamak HT-6M in ASIPP is used to study ICRF and transport. The South Western Institute of Physics (SWIP) in Chengdu has medium sized HL-1M tokamak, in which plasma heating and advanced fueling are investigated. Other two small tokamaks in China are KT-5 in the University of Sciences and Technology of China (USTC) in Hefei and CT-6B in the Institute of Physics, Chinese Academy of Sciences (IP/CAS). They are operated for edge turbulence/transport study and alternative concept development.
Following in this paper, main achievements from individual machine are briefly introduced in separated sections. Most of the results presented here are from the last two years.

2. HT-7 Tokamak Experiments

2.1 Outline

HT-7 is a medium sized super-conducting tokamak. Its main purpose is to explore high performance plasma operation under steady-state condition [1]. 1.2MW Lower Hybrid Wave Current (LHCD) system is tested with 10 seconds pulse length. The power for the ICRH system is 0.3MW with CW capacity. 1MW ICRF and ECRH system is still under construction. More than thirty diagnostics are equipped for the machine operation and physical investigation.
A new feedback control system was installed in the early of 1998 which gives easy control of plasma current, plasma position and density with a very fast temporal response. The machine runs normally with Ip=150KA, B_T = 2T, R = 122 cm, a = 27.5cm, with molybdenum limiter configuration. The following plasma parameters have been obtained: Ip = 250 kA, line averaged density $n_e = 6.5\times10^{13}$ cm^{-3}, B_T =2.5 T, T_e = 1.5 keV, T_i = 1.2 keV (with RF heating). The repeatable long pulse length discharges were obtained with the pulse length up to 10.7 seconds, which was nearly the limit of PF system. The LHCD experiments were successfully carried out up to 650 kW. The maximum input ICRF power into plasmas is 320 kW.
The plasma confinement was improved by LHCD. The full wave current lasting for 3 seconds was achieved [2]. Since the presence of toroidal magnetic field, ICRF conditioning has been routinely used during experiments, which has proved to be a very effective and powerful for the impurity cleaning, boronization and recycling control [3]. Very strong wall isotope exchange capability of deuterium RF conditioning was demonstrated. The MHD instability suppressed by LHCD and Ip modulation [4], the error field, lower loop voltage start-up [5], pellet injection [6], supersonic beam gas filling [7], as well as ICRF experiments [8] were carried out. The main results obtained during the last two years will be summarized in following section.

2.2 LHCD Experiments

LHCD experiments were successfully carried out in an expected manner. The system consists of twelve klystron amplifier (each can deliver 100 kW with CW capacity of 2.45 GHz), one grill coupler (an array of 2×12 sub-waveguides) and a pulse length of 10 seconds due to the present power supply. The launching spectrum $N_{||}$ can be changed from one two four within a quick 0.1 ms response time [9]. High performance of plasma discharge with an electron temperature over 1 keV was obtained and pulse length approached 4 seconds shown in fig. 1. Plasma current was fully sustained by LHCD for a time longer than 3 seconds. Further more, tokamak transformer was recharged due to the LHCD as shown in fig. 2, while magnetic flux of the transformer gradually decreased and voltage became negative. The technique could be used as one of the alternative steady state operation modes. LHCD efficiency dependence on different plasma parameters was studied. It is found that in HT-7 it is strongly depends on the toroidal magnetic field. The scaling of data showed a function: $\eta_{CD}^{exp} \approx 0.5(1+0.085\exp(4.8(B_T-1.45)))\, n_e I_{CD} R_p / P_{LH}$ [$10^{19} m^{-2}$ A/W]. A good wall condition benefits the current drive efficiency.

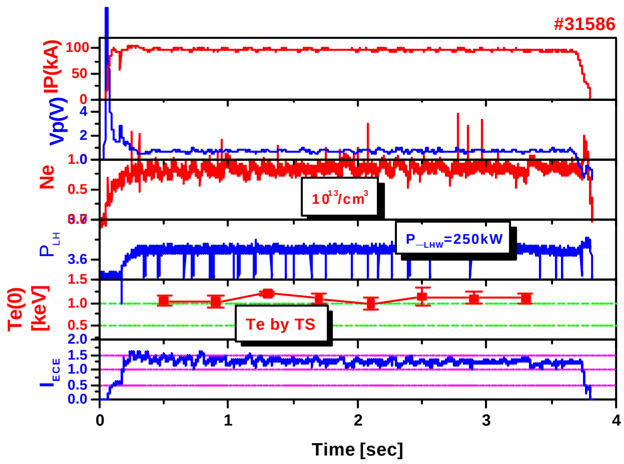

Fig. 1 Long pulse high performance plasma discharge sustained by LHCD.

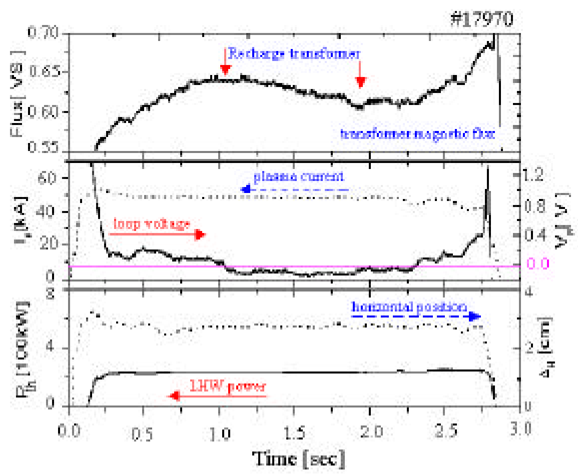

Fig. 2 Transformer recharged by LHCD

On the basis of the off-axis power deposition idea [10], high density LHCD experiments were properly arranged. By enhanced ICRF boronization and helium discharge cleaning, quasi-steady-state H-mode with a plasma density close to Greenwald density limit was obtained by LHCD. Fig. 3 shows such a typical discharge. After 20ms LHW applied, H_α line radiation suddenly dropped and confinement goes into improved phase. The energy confine time was about 1.5 times of ITER-89 L mode scaling. An extra gas puffing was applied and density increased until the plasma disruption. The H-phase, which was limiter ELM-free type, at the densities higher than 75% Greenwald density limit was normally sustained for more than 5 times τ_E^L (about 18ms). The energy confinement time during this period was nearly two time of τ_E^L. The discharge was disrupted at the density of 1.25 times of Greenwald limit during current ramp-down phase. The ray tracing simulation based on the wave diffusion/Fokker-Planck (WD/FP) modes shows that the weak absorption and multi-pass of LH waves were dominated. And the LH wave power was deposited off-axis. The off-axis non-inductive current profile by LHCD improved the confinements and sustained the reversed magnetic shear for more than 190ms which was nearly 10 times longer than τ_E^L.

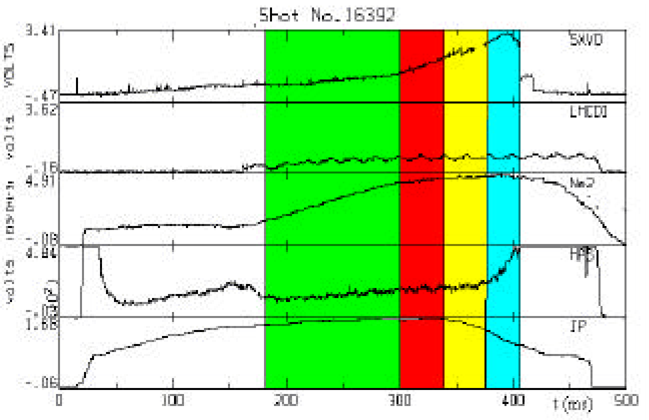

Fig.3 High density H-mode obtained by LHCD

Experiments on LHCD assisted ramp-up of plasma current on HT-7 achieved important progresses. It is of great significance for the superconducting PF magnet of a tokamak fusion reactor. The experiments showed that both the rate of the ramp-up and the saturated value of the current depended on the plasma density, temperature, toroidal magnetic field, and especially strongly depended on the wave spectrum and the wave power. At line averaged electron densities around $1\times 10^{13}cm^{-3}$, current ramp-up rates up to 0.4MA/sec have been achieved with LHW power of about 300kW, correspondingly, the conversion efficiencies up to 15% have been achieved. The observation of $\beta_p+l_i/2$ value suggested that a broad or even hollow current profile could be formed due to LHCD. Simulation using a ray tracing + 2D Fokker-Planck code shows that the change of the current profile is attributed to off-axis deposition of LHW power, which was confirmed by the measurement of hard x-ray intensity profile.

2.3. ICRF heating

Plasma heating was conducted using Both low-field-side antenna and high-field-side antenna. Three ICRF antenna configurations were installed in HT-7. Two are for fast wave heating and another is for IBW heating. ICRF was carried out in the hydrogen minority regime. The RF frequency was 30 MHz, which corresponds to an on-axis cyclotron resonant layer location with a toroidal field of 2 T. Clear ion heating was observed by NPA diagnostic measurements. The ion temperature was increased from 380 eV to 750 eV with an input power of 150 kW. An energetic ion tail was observed when the injected power was above 100 kW. Higher impurity radiation occurred and plasma performance degraded by the radiation loss.

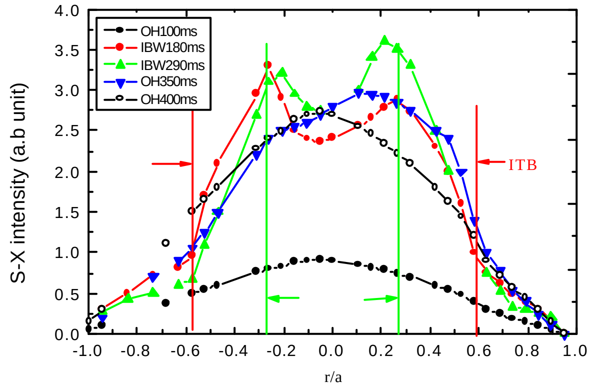

Fig.4 Plasma off-axis heating by IBW forms an ITB-like profile in SX emission

IBW heating was investigated in HT-7 super-conducting tokamak deuterium plasma with an injecting power up to 320 kW. The electron-heating mode for IBW was used in HT-7 for most case. The RF frequency was 24 ~ 30 MHz and toroidal field 1.8~2 T. Clear on-axis and also off-axis electron heating (fig.4) was observed. Maximum increment of electron temperature was about 500 eV with IBW power of 160 kW, while ion temperature less than 200 eV. The highest heating factor, $\Delta T_e \times n_e/P_{RF}$, reached 10.4 (eV 10^{13} cm^{-3}/ kW). Various evidences show that the electron heating was due to electron Landau damping. The ion heating was due to the energy transfer by electron and ion collision.

By properly choosing the heating position, both particle and energy confinement were improved. The ITB-like profile as shown in fig. 4 was observed during IBW off-axis heating and may attribute to the good confinement. Edge fluctuation was significantly suppressed when the total injected power was over a critical power threshold. The local turbulence and transport have been modified by IBW, which demonstrates that IBW could be used for poloidal velocity shear control [11].

2.4 ICRF conditioning:

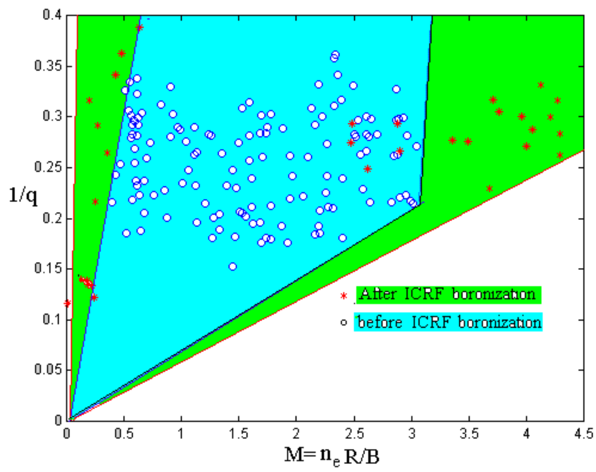

Fig. 5 Extended Hugill plot after ICRF boronization and siliconization

RF wall conditioning techniques has been developed with a permanent toroidal magnetic field and routinely used in HT-7 [3]. Comparing with GDC and TDC, the particle removing rate and cleaning efficiency is higher by a factor of three. Base plasma parameters produced by different antenna configuration and their roles to get best cleaning and coating efficiency are studied systematically. RF boronization and siliconization are carried out. The B/C:H and Si/C:H films have shown higher adhesion, uniformity and longer lifetime than those obtained by normal GDC method. This new technique shows that is very effective and powerful for the quick and real-time wall condition for future large super-conducting magnetic fusion devices. The RF discharge with deuterium was used to control the ratio of H/(H+D). After boronization, the ratio is as high as 60% since a large amount of hydrogen was absorbed in the fresh boron film. Two periods of 30 minutes of D_2 RF discharge can reduce this ratio down to 15%.

The plasma performance was significantly improved after RF boronization. The metal impurity lines were disappeared. The influxes of carbon and oxygen were reduced by a factor of three. The Z_{eff} was reduced from 4 to 2 at the density of $2\times10^{19}cm^{-3}$ and close to the unity at the density higher than $3\times10^{19}m^{-3}$. The Hugill stability operation region was extended. Better plasma performance was attitude to the large oxygen reduction. Higher LHCD efficiency and long pulse full wave current drive were obtained.

2.5 Pellet and supersonic beam injection:

Both hydrogen and deuterium pellets were fired into the plasma with the speed of 0.5~1.2 km/s. The different-sized pellets were chosen according to the different plasma conditions. Very peak density profile was obtained after the injection of the pellet under normal ohmic discharge. Up to four pellets were injected to the same shot. The results were nearly the same as other tokamaks.

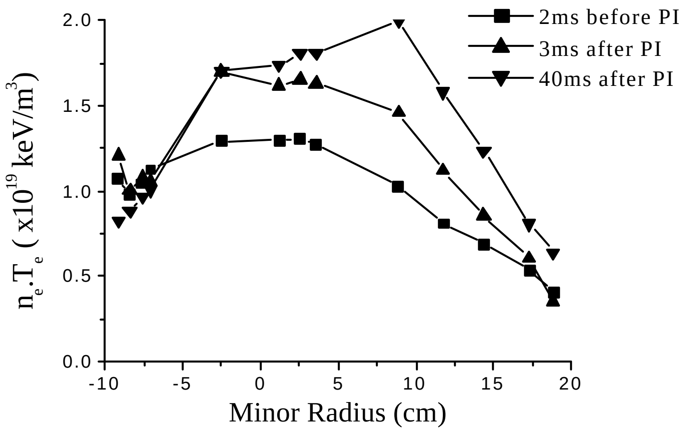

FIG. 6 Plasma parameters profile evolution of a discharge with pellet injection during RF heating (Shot 33094, I_p=140 kA, B_t=1.7 Tesla, P_{IBW}=180 kW)

Pellet injection was combined with IBW heating [12]. By properly timing the pellet and IBW, PEP like configuration was obtained. The pellets were set to deposit in the same position with the hydrogen fundamental resonant layer. It was observed that the plasma parameters were obviously enhanced by pellet injection during RF heating. Figure 6 gives the electron pressure ($n_e\cdot T_e$) profile evolution of a typical shot. The electron pressure in the plasma center increases for about 30% at 3ms later after pellet injection. The value keeps on increasing until 40 ms later, and the pressure at about a/3 outside the axis surpasses that in the plasma core, reaching about 2 times that of the pre-injection state. About 100 ms after pellet injection, the profile recovers to the pre-injection state and the electron pressure decreases to a lower value. The enhancement is attributed by two factors, the increasing of the density and the effective RF heating. The fueling efficiency is higher than the normal ohmic pellet injection.

Two Laval nozzles have been installed in the HT-7 super-conducting tokamak, with the diameter on the throat section of the Laval nozzle as 1 mm and the diameter on exit section as 10 mm. The experiments were carried out by injecting deuterium and helium into the deuterium plasmas. The density of plasma could be easily controlled by pulsed high-speed molecular beam that comes from the Laval nozzle. High plasma density could be easily maintained and controlled by modulated high-speed molecular beam, by which density exceeded Greenwald limit. With penetration depth up to 15cm, the density peaking factor was almost same with the one obtained by off-axis pellet injection.

2.6 ICRF Assistant Start-up [5]

In the super-conducting tokamak case, the character of the poloidal field coils that are made by the superconductor limits the plasma current ramp-up rate. The scenarios with low loop voltage startup are needed for the full super-conducting tokamaks. The low voltage startup plasma has been studied in HT-7 with ICRF pre-ionization and preheating. Successful ICRF (power of 130KW) assistant startup is achieved with $E \approx 0.9V/m$ (The resistance of the vacuum vessel is about $4m\Omega$) compared $E \approx 2.5V/m$ without ICRF, which matches the requirements of the HT-7U PF sysytem. With the ICRH assisted startup, it allows reliable plasma current build-up with low electric fields; lead to reduced runaway electron production during the breakdown phase. Unlike low loop voltage start-up with ECH, in the ICRF case, more careful control is generally required for gas pressure and error magnetic fields produced by OH transformer itself and by the image currents flowing through the tokamak vessel.

2.7 Summary:

Progresses in long pulse discharges related experiments have been achieved after successful installation of new feed back control system. Reproducible 10s discharges and Steady state full LHW current drive for longer than 3 s have been achieved. The quasi-steady state H-mode was obtained with very high plasma density by LHCD. The line average density range during improved confinement phase could reach 4.5~ $6.0 \times 10^{13} cm^{-3}$ which was in the range of Greenwald density limit (75~90% of Greenwald density limit). IBW heating was carried out mainly on the electron-heating mode. Very high heating factor was obtained. The good plasma condition was obtained by ICRF boronization, which makes Z_{eff} close to 1.0. High-density shots were obtained by two different fueling methods: multi-pellet injection and supersonic beam injection. The later shows a high fueling efficiency that can be used for steady-state operation. The synergy between IBW and pellet has been tested and good plasma performance has been obtained. ICRF assistant start-up was successfully carried out to a low start-up loop voltage matching the requirements for full super-conducting tokamak.

3 HL-1M Experiment [13]

3.1 Outline

HL-1M is a medium sized tokamak with R = 1.02 m, a = 0.26m and B_T = 3 T in circular limiter configuration. Its objectives are to vonduct experiments on high power auxiliary heating and current drive and to explore new fueling techniques in order to develop the physics and technology for next generation tkamak. In recent HL-1M experiments, plasma performance was greatly improved through the use of boronization, siliconization and lithiumization. The maximum parameters obtained in HL-1M ohmic heated plasmas are: I_P=320kA, n_e=$8\times10^{19}m^{-3}$, B_t=2.8T. ICRF at a power level of 0.3 MW, NBI at a power level of 0.4 MW, ECRH at a level of 0.25 MW and LHCD at a power level of 1 MW have been carried out. New fueling technique with pellet injection and supersonic molecular beam injection (SMBI) were also employed to significantly improve the energy confinement time and density limit. The main achievements are as follows.

3.2 Off Axis ECRH Experiments

With a gyrotron of 75GHz/300kW, ECRH experiments were performed successfully on HL-1M. Microwave is launched into plasma perpendicularly to toroidal field at the low field side as an ordinary mode. During ECRH the electron temperature T_e increased from 450 eV to 750 eV and the MHD activities were suppressed significantly under off axis ECRH. Furthermore, when the resonance points of the ECW are inside of the q=1 surface, the double sawtooth in soft X-ray radiation were observed, as shown in Fig.7, which implies that two q=1 surface exists and a reversed magnetic shear is formed [14].

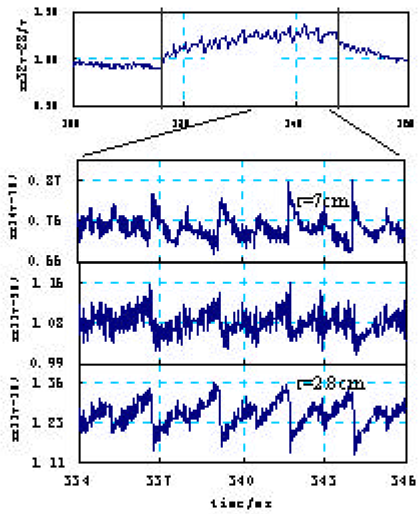

Fig.7 Double sawtooth in soft X-ray radiation during ECRH

3.3 Pellet Injection Experiments

An eight-shot pellet injector (PI) has been used in experiments. After the pellet injection, a hollow electron temperature and peaking density profile were observed, accompanied with the increase of energy confinement time.

The process of pellet ablation was investigated with CCD camera and an H_α emission detector array. The pellet penetration depth and its velocity were measured with the H_α emission detector array. The evolution of radial profile of the H_α emission is obtained with the

Abel inversion of the multi-channel signals. It is observed that the velocity of pellet is slowed down obviously after the pellet enters into the plasma.

The pellet clouds are elongated in the magnetic field direction, which can be used to estimate the current profile. By multi-exposures with CCD camera during the pellet ablation, the safety-factor q-profile was calculated with the inclination angle of ablation cloud with respect to the torus.

3.4 Supersonic molecular beam fuelling:

The fuelling of supersonic molecular beam (SMB) [15] has been improved in the HL-1M tokamak recently. A simple model of "cold injection path" during the SMB has been proposed, which is supported by measurements of edge temperature and density, H_α intensity profile, as shown in Fig.8. According to the empirical scaling law of the onset of cluster, the hydrogen cluster-like may be produced in the SMB, which is beneficial to deep injection. With SMBI the plasma energy confinement time measured by diamagnetism is 10-30% longer than that with gas puffing when other discharge conditions are kept the same. SMBI could be advanced method of gas fueling for small and medium sized tokamak. Considering the relatively high temperature of the edge plasma in large tokamaks with a divertor, such as JET or ITER, a supersonic beam with clusters, which are just like micro-pellets, will be of benefit to deeper fueling. The Cluster particles should be sufficiently fast and large in order to penetrate the separatrix and provide the necessary central particle fueling required to sustain a fusion burn.

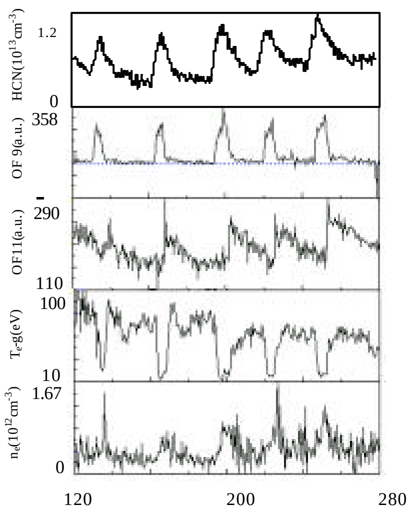

Fig.8. Edge Plasma Parameters during SMBI. HCN_average electron density, OF9, 11_Edge H_a signals far from injection port 22.5°, and 135°, T_e & n_e Plasma temperature and density at r = 23 cm (Right figure).

3.5 Density limit and wall conditioning

Density limit have been investigated on HL-1M. It was found that the SMB is much more effective than gas puffing to get higher density. A maximum line averaged density $n_e = 8.2 \times 10^{19} m^{-3}$ has been obtained in ohmic heated hydrogen plasma with Ip = 186 kA and B_T = 2.4 T, which is about 80% of the Greenwald density limit. On HL-1M, boronization, siliconization and lithiumization have been used to improve plasma performance. The siliconization is often used because of its convenience and non-toxicity. The density limit can be increased by decreasing impurity content and peaking density profile, the latter can reduce the interaction between plasma and wall. The highest density limit is a factor of 1.4 of the Greenwald's for a low plasma current Ip = 120 kA. The density limit in deuterium is somewhat higher than that in hydrogen, and the isotope effect scaling is $\bar{n}_e \propto m^{1/3}$.

3 KT-5C experiments

KT-5C is a small tokamak (R= 32.5 cm, a=12.5cm, I_p= 10-20KA) in the University of Science and Technology of China (USTC). It is aimed to fluctuation and transport investigation in the edge of plasmas.

4.1 Spatial intermittency of plasma turbulence

A sharp variation, referred to **spatial intermittency,** at some radial position superimposed on a slow change in the profiles of the fluctuation levels, fluctuation driven particle and energy fluxes, is observed in the core plasma of KT-5C tokamak [16]. The peaks in the profiles are located in the vicinity of low-q rational surfaces. The result is in consistent with the theoretical mode [17]. Such spatial structure of turbulence may help to speculate that, the transport barrier expansion could be stepwise until the local shear builds up to the point that the local instability drive can be overcome for the H or H-like mode transition [18].

4.2 Generation of E_r by electrode biasing

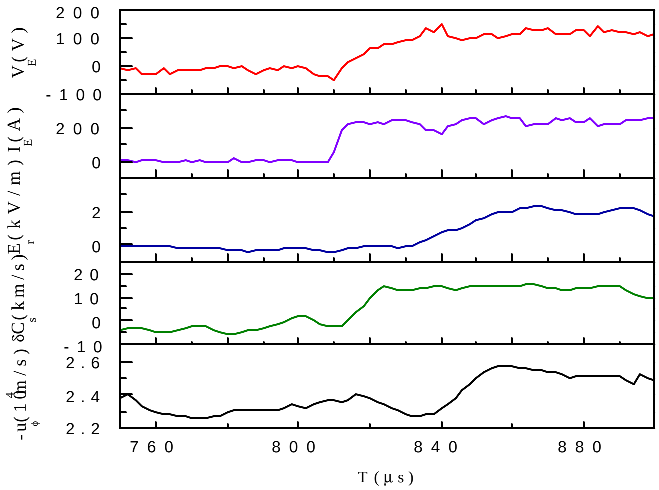

Fig. 9 Temporal evolution of the electrode voltage V_e and current I_e, radial electric field E_r, poloidal ratio ¶C_s and toroidal velocity u_f at r=7.5cm. The poloidal velocity is proportional to ¶C_s .

The suppression of the turbulent transport with the change of the radial electric field E_r induced by the biased electrode is observed. It is found that the poloidal flow contributes to the main part of the E_r. The change of the poloidal flow has a lead of about 20μs to the formation of E_r as shown in fig. 9 This fact suggests that a radial current responding to the biasing voltage drives a poloidal flow, which in turn drives the radial electric field [19].

5 CT-6B Experiments

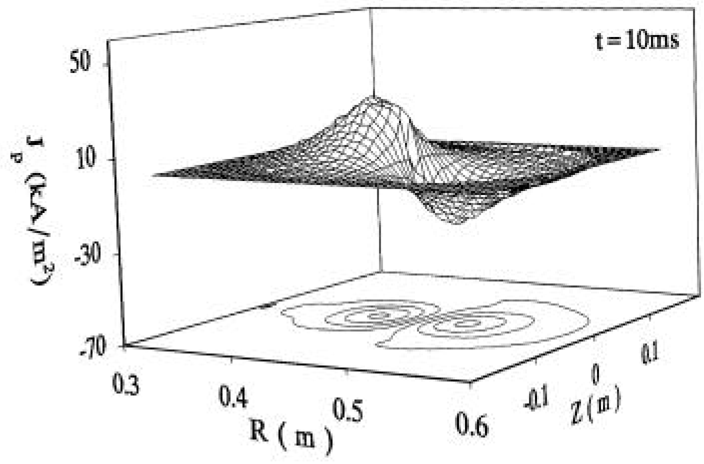

Fig.10 The plasma current distribution during the total current passes zero in CT-6B tokamak.

In the CT-6B tokamak, internal magnetic probes were used to measure the poloidal magnetic field in the plasma in an AC operation experiment, and reconstruct the plasma current profile and flux surface during the current reversal. When the first positive current pulse drops, a negative current component appears on the weak field side. When the total plasma current passes through zero, two current components flowing in opposite direction coexist as shown in fig 10. The existence of flux surface and rotation transform provides the particle confinement during the current reversal [20].

A novel method of electron cyclotron wave current startup is proposed and demonstrated in the CT-6B tokamak. A discharge between a pair of electrodes is introduced and forms a magnified toroidal current in a strong toroidal field and a weak vertical field, in which the electron cyclotron wave produces a background plasma [21].

A novel concept and data process method, wavelet correlation is used to process fluctuation data of H_α line in the CT-6B tokamak. Coherent structures are identified in radius-time plane with lifetime of 20-100 microseconds and radial length of 1-2 cm in the poloidal rotation shear region [22]. Bicoherence analyses shows strong coupling occurs between high frequencies (>50 kHz) and low frequencies (~35kHz) in the coherent structure region. The parallel flow instability is identified and its effect on transport is discussed in CT-6B tokamak [23].

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