STEADY STATE OPERATION OF THE SUPERCONDUCTING TOKAMAK TRIAM-1M

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Abstract

A 2-hour limiter discharge in circular configuration was successfully maintained using both Hall generators to be free from the drift of integrator and position control by TV image to avoid the concentration of heat load. The property of wall saturation is discussed as the serious issue for steady state operation, which strongly depends on electron density. In the high density region, the discharges sometimes terminate due to uncontrollable increase in electron density caused by wall saturation. The plasmas with high k ~1.5 can be demonstrated for longer than 1 min. The duration of discharge is limited by vertical displacement event (VDE). The avoidance of VDE is a crucial point to achieve long discharges with high k. New technique to monitor the accurate magnetic field with high time resolution for a long time is required to achieve the longer discharge with high k. A high ion temperature (HIT) discharge characterized by high ion temperature up to 5keV and by steep temperature gradient up to 85 keV/m is successfully sustained for longer than 30 sec by 2.45 GHz LHCD on single null divertor configuration. This indicates that the transport barrier of ion temperature can be maintained in steady state.

1. Introduction

The steady state operation and the achievement of high performance plasma are most important issues for tokamak fusion reactor. In these years, various improved confinement modes have been found in many devices [1-4]. As for steady state operation of tokamak discharges, although in Tore Supra, the high pressure plasma could be sustained for 2 minutes [5], the steady state discharge over 1 hour have been proceeded only in the superconducting (SC) machine TRIAM-1M [6]. The long sustainment of high pressure plasma of $\overline{n_e}$ ~1.5 × m^{-3} is also demonstrated for 1 min [6]. In this case, the abrupt uncontrollable increase in n_e sometimes occurs, which is caused by wall saturation.

The plasma shape with the high elongation, k, and the high triangularity, d, is important factor for the achievement of high performance, because the limitation of the MHD stability in the pressure gradient becomes better. However, the sustainment of high k discharge had been tried in many machine, vertical displacement event (VDE) prevents from achieving the long discharge with high k. In JET, a 1-min discharge with k~1.4 can be obtained in limiter configuration. In TRIAM-1M, the plasmas with high k ~1.5 can be demonstrated for longer than 1 min in the single null divertor configuration.

Recent progresses of high performance are supported by the transport barrier in the core and edge region [1-4]. The sustainment of the transport barrier is a key issue for the steady state high performance operation of tokamak, however the long sustainment of transport barrier is difficult, because the instability based on the high pressure gradient is excited near the transport barrier. Moreover, as the high temperature leads to long current diffusion time, the duration of plasma is not sufficient for steady state condition. Recently the steady state high performance plasma with transport barrier is also achieved on TRIAM-1M.

In this paper, a brief survey of developments to achieve the 2-hour discharge is described at first and subsequently the issues for steady state operation of tokamak are pointed out. After that, the recent progresses concerning steady state high performance plasma are described.

2. Experiments of Super Ultra Long Discharge (Suld)

2.1. Developments and issues for steady state operation

TRIAM-1M is the high-field superconducting tokamak with 16 toroidal field coils made of Nb_3Sn (R = 0.8m, a × b = 0.12m × 0.18m) [7], which can produce the steady state strong magnetic field continuously. The maximum field reaches 11 T at windings and 8 T at the plasma center. Two heating sources are installed for current drive. One is a 2.45 GHz LHCD system (1 klystron of the maximum power; 50kW, 4×1 grill) and the other is an 8.2 GHz LHCD system (8 klystrons, the total maximum power, 200 kW, 8×2 grill). The vacuum vessel is made of SS304L and the three poloidal limiters are made of Mo. The ECR discharge cleaning is carried out for wall conditioning of the plasma chamber before every experimental campaign.

In 1995, the long pulse tokamak plasma for longer than 2 hour was achieved in limiter configuration [6], based on the essential developments as the following; 1) construction of superconducting (SC) magnets made of Nb_3Sn, 2) stable operation of tokamak with SC magnet, 3) continuous wave (CW) microwave system for non-inductive current drive, 4) the plasma production by flux swing generated by the decrease in the center solenoid coil current, 5) magnetic measurement using Hall generator, 6) position control using TV image, 7) fueling control using Ha signal, and 8) data acquisition system for long operation. The progresses of steady state operation on TRIAM-1M are summarized in Fig. 1.

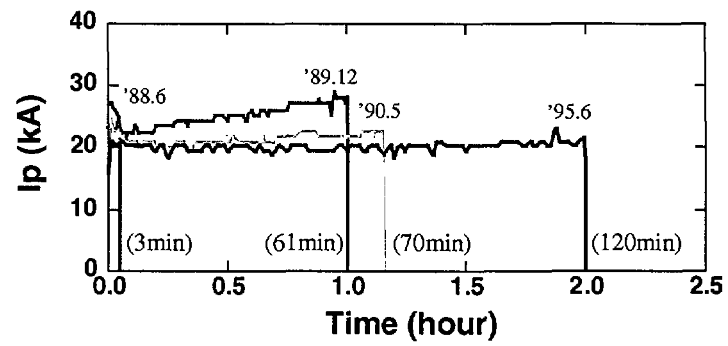

FIG.1. Progresses of steady state operation using 2.45GHz LHCD on TRIAM-1M. The main parameters are similar in all of the discharges in this Figure, I_p~20kA, $\overline{n_e}$ ~$1.5x10^{18}m^{-3}$, T_e~0.6keV, T_i~0.5keV, B_t=6T, P_{RF}~20kW.

As for the magnetic measurement, the conventional method, that is the combination of magnetic coils with integrators, is not reliable for long discharge, because of the accumulated drift of the integrators. To solve the drift problem, Hall generators are adopted to monitor the plasma position. The Hall generators can measure the local magnetic field directly, therefore they are free from the problem of the drift of integrators. However, the time response of the Hall generators is not so high for the fast change in the magnetic field as observed in the break-down and current ramp up phases. Therefore, the plasma position was controlled with the conventional magnetic coil system at the initial phase of the discharge, and the Hall generator system was used in the subsequent phase.

The heat load sometimes concentrates on a certain point of a poloidal limiter, where it becomes bright (hot spot). The hot spot is the source of impurity, and the performance of the plasma was sometimes deteriorated. The position control using the TV image of the plasma cross section and the poloidal limiter is used to avoid the appearance of the hot spot. When the hot spot appears, the bright point on the limiter is caught by the TV image and the automatic control system makes the plasma moved in the suitable direction to eliminate the hot spot.

The fueling control using Ha signal is carried out for taking the hydrogen recycling property into consideration. Temperature of wall and hydrogen recycling property changes gradually during the discharge as well as shot by shot. Moreover the amount of the fuel adsorbed on the wall varies, because it depends mainly both on the previous shots and on the present shot. Therefore, the fueling control must be adapted itself to adjust the change in the wall condition. In order to cope with it, the fueling control system has been improved by the feedback control using the Ha signal. The intensity of Ha line corresponds to the influx of the fuel to the core plasma. As the influx of the fuel is proportional to the electron density in steady state operation regime, the fueling control using the Ha intensity is also sensitive to electron density.

As for the data acquisition system, the continuous monitoring and data acquisition system, which is called "cyclic processing", was also developed [8]. On this new system, multiple lines of data processing are running simultaneously and each line of processing is switched in the regular interval. This system has been successfully applied to 2-hour discharge. Moreover event trigger method was also established to acquire the data with a high time resolution around some interesting events during long duration discharges [9]. In the case of long time or steady state operation, it is important to monitor and control the plasma condition continuously during the discharge. However, conventional systems cannot follow these operation as it shows the results after each discharge. Moreover the memory prepared in a CAMAC module is not sufficient, therefore it is impossible to store the data with high time resolution for the whole of a long discharge. These issues become more serious with the increasing of the discharge duration time.

2.2. Wall property during long-time discharge

The heat load of the 2-hour discharge on TRIAM-1M to the limiter (more than $1 GJ/m^2$) is compared to that to the divertor plate of ITER. This huge heat load generates the hot spot and intense sputtering on the limiter, which sometimes make the plasma performance deteriorated. This circumstances concerning heat load are suitable to investigate the plasma wall interaction.

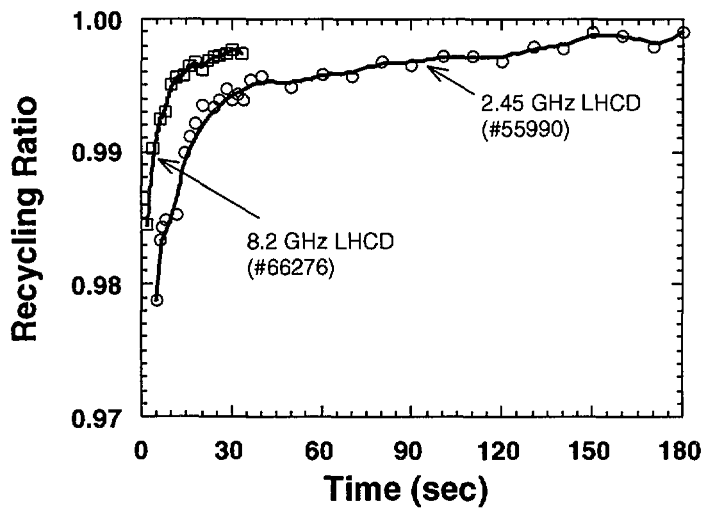

FIG. 2. Time evolutions of the recycling ratio of the low density discharge ($\overline{n}_e \sim 0.2 \times 10^{19} m^{-3}$, $I_p \sim 21 kA$, $B_t = 6T$) sustained by the 2.45GHz LHCD with ~20kW (open circles) and the high density discharge ($\overline{n}_e \sim 1 \times 10^{19} m^{-3}$, $I_p \sim 23 kA$, $B_t = 7T$) sustained by the 8.2GHz LHCD with ~100kW (open squares).

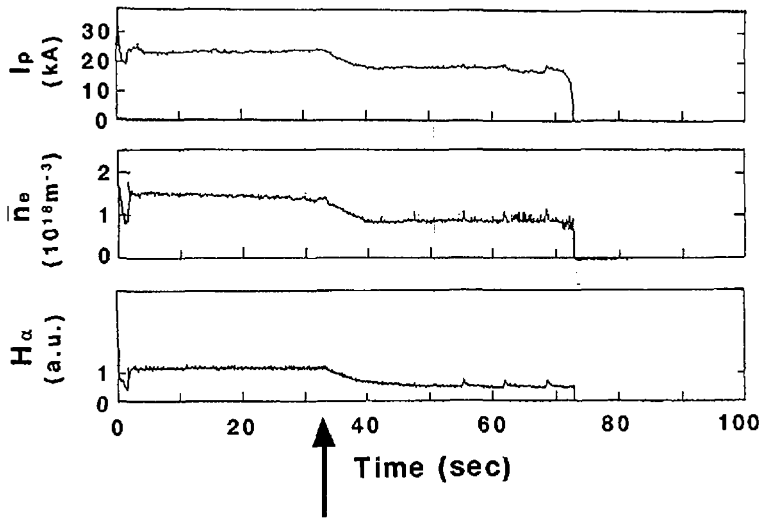

FIG.3 Time evolutions of plasma current, electron density and intensity of Ha. The arrow of the Figure shows the timing of termination of both pumping and fueling. It should be noted that the particles can be balanced well under the condition that the recycling ratio is completely unity for longer than 30 s.

The plasma was maintained in the limiter configuration by the microwave of 2.45 GHz, 20kW and the plasma current (~20kA) was driven by the energetic electrons drifting in the toroidal direction. In the limiter configuration, heat load by the plasma sometimes concentrates on the poloidal limiter. The many plasma parameters, for example density, plasma current, temperature, and so on, are kept constant. The impurities estimated by the vacuum ultra violet (VUV) become constant (O ~2%, Mo ~0.2%) [10] and they do not change significantly during discharge [11]. This is a preferable phenomenon for the steady state operation, because the contamination and concentration of impurity in the core plasma prevent from maintaining the plasma. These plasma parameters become constant in early time of the discharge, because characteristics time scale depends on the energy confinement time, t_E (~ a few ms) and current diffusion time, $t_{L/R}$ (~200ms). The recycling ratio, which significantly affects the performance of plasma, gradually increases and then reaches about unity as shown in Fig.2. It takes longer than 30 s to become constant. This characteristic time scale is one of the longest time scale required to become steady state. This shows that the duration of longer than 30 sec is necessary to obtain the steady state condition in the view of the performance of the plasma.

Steady-state operation in high density region ($\overline{n_e}$ is more than 1×10^{19} m^{-3}) has been executed. The 8.2 GHz LHCD is utilized for the sustainment of the plasma current. The line-averaged electron density reaches up to $\sim 2 \times 10^{19}$ m^{-3} and the duration of the discharge in the high density region exceeds 1 min. The termination of the discharge may be mainly caused by the wall saturation, that is the recycling ratio is excess of unity. The electron density abruptly increases without the gas feed in the end of discharge. The density control does not work well just before the termination of the discharge. The recycling ratio of high density discharge increases gradually and it approaches to unity as shown in Fig.2. It takes about 30 s to become constant in both low and high density plasma.

In the low density discharge, the recycling ratio is also close to unity after 30 s from the start of the discharge, although the absolute value of recycling ratio is slightly lower than that of high density discharge. However, the wall saturation phenomena does not take place [12]. A typical example can be shown in Fig. 3. The pumping and fueling stops at the timing of the arrow. The neutral pressure monitored by an ion gage after the stop of pumping and fueling increases up to two times and subsequently its value keeps constant. This shows that the outflux and influx of fuel particles are balanced and the recycling ratio is completely unity for 30 s. This clearly shows that the wall saturation can be avoided in low density region. From this experimental data, the abrupt wall saturation may be caused by the large outflux of the particles, because outflux of the high density plasma (~ 2×10^{20} particles/s) is about 4 times in magnitude larger than that of the low density plasma. The wall saturation may become a crucial issue for steady state operation in the high density region.

The most important and difficult problem during steady state discharge is the control of the wall condition, because temperature of the wall and the limiter increases and consequently the wall condition gradually changes during the discharge. In the 2-hour discharge, the time evolutions of the temperature of the wall and the limiter are shown in Fig. 4. The characteristic time scale is about 30 minutes. In order to investigate the performance of the steady state plasma, 1-hour discharge is necessary from the viewpoint of the wall condition.

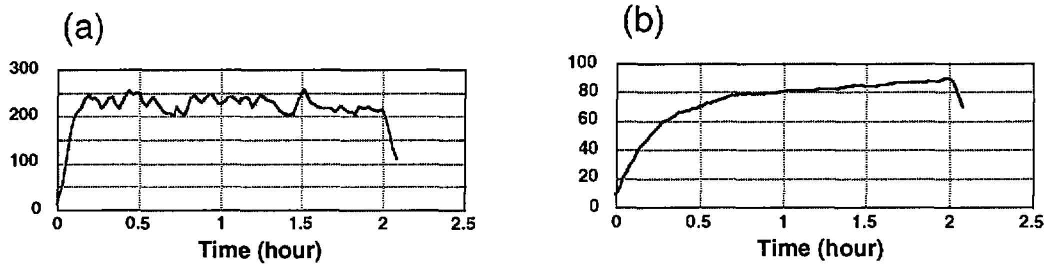

FIG. 4. Time evolutions of the temperature of (a) the limiter and (b) the wall in the case of the 2-hour discharges.

2.3. Long sustainment of high k discharge

Establishment of technique to maintain long single-null configuration with high elongation, k, has been desired for the future reactor both to remove the huge heat load and to improve the plasma performance. Figure 5 shows the summary of the achieved k plotted as a function of discharge duration in various tokamaks in the world. This figure clearly shows the difficulty of the long duration discharge with high k. Generally speaking, main reasons of the difficulty are vertical displacement event (VDE) and power handling on the divertor plate. Although discharge in circular limiter configuration was successfully maintained for longer than 2 hours using Hall generators without drift problem of integrator, VDE cannot be avoided in the single null configuration because of the slow time response of Hall generators. Vertical position control system was improved to aim at the long duration sustainment of the single null divertor configuration by LHCD and the control as fast as the skin time of the vacuum wall was tried. Although the present duration time is limited by both V^2t value of the power supply for vertical position control and the drift of the integrator, where V and t show the voltage and the duration of power supply and the value of V^2t corresponds to the calorific power of the power supply, the single null configuration with k ~1.5 for 1min by 2.45 GHz LHCD only; P_{RF} = 22 kW, B_t = 6 T, $n_e = 2 \times 10^{18}$ m^{-3}, T_e = 600 eV, I_p = 23 kA was successfully achieved. This result indicates that the steady state discharge of high k in the single null configuration is possible by developing quick-responsible and long-time-measurable magnetic sensor.

The total energy input of 200 MJ has been injected into the plasma in the limiter configuration, although the heat flux (~1MW/m^2) on the limiter is not so much. In the high density discharge, the heat flux on the limiter reaches ~5MW/m^2, if all input power is put in the limiter. The hot spot and the intense sputtering sometimes appears during the long discharge due to the huge heat load. While, the hot spot and the intense sputtering does not occur in the single null configuration. This shows the better power handling in the single null configuration can be achieved than that in the limiter configuration. The input energy to the divertor plate has been measured with the temperature rise of the cooling water of the divertor plate. At first, the plasma is produced in limiter configuration. Subsequently, the plasma configuration is drastically changed to the single null configuration by the change in the coil current. After the formation of single null configuration, the thermal input to the divertor plate increases linearly with the discharge duration. From this slope, the input power is estimated to be 10 kW, which is about 30 % of the energy lost from the plasma. This result indicates that a part of the input energy flows to the divertor plate instead of the limiter, and consequently the hot spot is difficult to be formed.

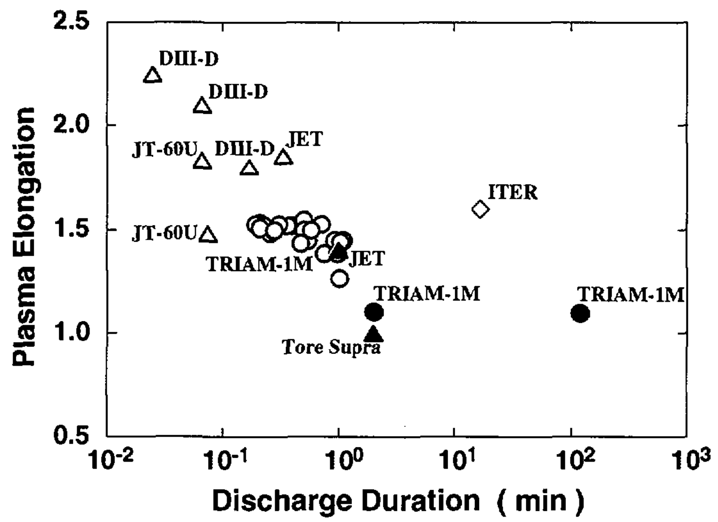

FIG. 5. Plasma elongation, k, as a function of the discharge duration in various tokamaks. The data on the single null configuration in TRIAM-1M (open circles) and in other tokamak (open triangles), on the limiter configuration in TRIAM-1M (close circles) and in other tokamak (close triangles) are plotted in the figure.

3. Achievement of high performance plasma and its long sustainment

3.1. Characteristics of high ion temperature (HIT) discharges

Recently a long duration discharge with the HIT mode has been obtained using 2.45GHz LHCD on both the limiter and the single null configuration. The ion temperatures $T_{i//}$ and T_i have been measured with two kinds of neutral particle analyzer (NEA), NEAP (q~90) and NEAT(~ 36) respectively, here q is the angle between the line of sight and toroidal direction. The HIT mode is obtained under the following conditions; 1.4×10^{18} m^{-3} $\overline{n_e}$ 2.0×10^{18} m^{-3} and -2.5cm DR(=R-R_0) - 0.5cm in the limiter configuration, where R means the horizontal plasma position. However, as the horizontal position of the plasma must be controlled tightly in the single null configuration, and the position can not be scanned. The density window is the similar both in the limiter and single null configurations. The HIT mode has been successfully maintained for 1 min by accurate control of DR and n_e as shown in Fig.6.

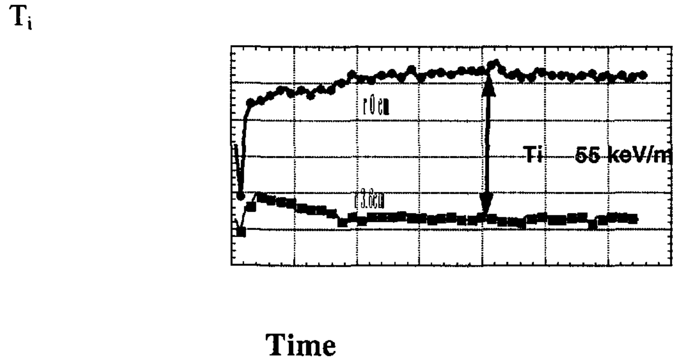

FIG. 6. Time evolutions of T_i at r~0cm (closed circles) and r ~ 3.6cm (closed squares) in long sustained HIT discharge.

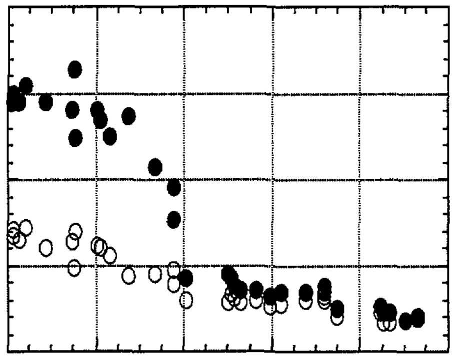

FIG. 7. Radial Profiles of T_i at r ~ 0cm in the HIT mode (closed circles) and the LIT mode (open circles).

The HIT mode is characterized by the steep temperature gradient formed around half of the minor radius as shown in Fig. 7. This suggests that a transport barrier is formed in the middle of the plasma. A transition from low ion temperature (LIT) to HIT sometimes takes place in the fast time scale (10ms). At the transition, T_i measured with NEAP sometimes changes faster than $T_{i//}$ measured with NEAT. This indicates that ions heat in the perpendicular direction and after that T_i becomes almost isotropic via pitch angle scattering process. The energetic ions with small $v_{//}$ are well confined at least during the estimated value of pitch angle scattering time (~8 ms for q = 36).

3.2. Discussion for HIT discharge

These experimental results indicate that 1) effective ion heating takes place in the pure LHCD plasma, 2) energetic ions are confined well by the weak poloidal field. In HIT region, ion heating does not occur by direct heating via linear mode conversion process of LHW. Moreover the power via the slowing down process almost flows from energetic electrons to bulk electrons. Mechanism of ion heating may be that the wave excited by the energetic electrons accelerated by LHW interacts with ions. In low density region of TRIAM-1M, the accessibility condition of LHW is significantly better than the other machine. The LHW of $N_{//}$ of 1.05 is accessible in the center of the plasma. In this situation, the energetic electrons may be produced in the core region. The HXR profile is sometimes peaked in HIT discharge, and this may support it.

The electromagnetic (EM) wave emitted from the plasma are detected by a horn antenna through a quartz vacuum window. Main part of the EM wave corresponds to the wave with the frequency of the 2.45 GHz. This is clearly originated from the injected microwave of 2.45 GHz LHW. The EM wave at the frequency of 2.450.4 GHz is sometimes observed. This sideband wave is coming from the scattering process of the waves of 2.45 GHz and 0.4 GHz, therefore, the signal of sideband wave shows that the wave with the frequency of 0.4 GHz exists in the plasma. It should be noted that the frequency of 0.4 GHz corresponds to ion plasma frequency at the core region of plasma. This wave of 0.4 GHz may have a relation to the ion heating, because the time evolution of the power of the EM wave correlates with that of the ion temperature as shown in Fig. 8. Around 6 s, T_i is clearly higher than T_e and ion heating takes place. At that time, the amplitude of the EM wave of the sideband increases and the abrupt decrease in both T_i and amplitude of EM wave occurs at 7.5 s.

As for the confinement of energetic ions, decay of energetic ions are investigated after the termination of LHW. Although the plasma current gradually decreases with the current diffusion time

(~200ms) after the termination of LHW, the decay time of energetic ions (~10keV) is about 20 ms, which is significantly longer than loss time of energetic ions due to toroidal drift (~10 ms). This clearly shows that the energetic ions are well-confined. This is a significant difference from ion heating scenario based on the linear mode conversion or the parametric decay wave. Although the mechanism of well-confinement is not made clear, the appropriate negative radial electric field shear may work effectively on the confinement of the energetic ions by weak poloidal field.

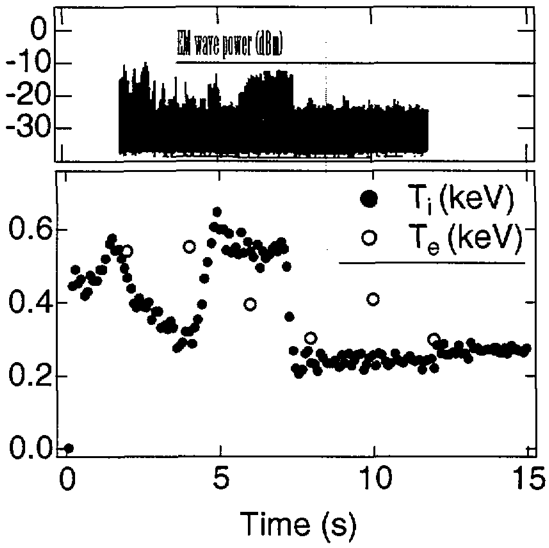

FIG. 8. Top figure shows the time evolution of the amplitude of EM wave at the frequency 2.45 GHz - 0.4 GHz measured with a spectrum analyzer. The amplitude of pump wave (2.45 GHz) is about 30 dBm. Bottom figure shows the time evolution of T_i at the plasma center.

The maximum values of T_i and T_i seem to be limited in the HIT discharge as shown in Fig. 9, although the maintenance of the HIT mode does not depend on duration of the discharge. The maximum value of T_i reaches up to 85 keV/m, which is comparable to T_i in the internal transport barrier on the large tokamaks. As the MHD instabilities are not observed just before the transition from HIT to LIT, the direct cause of the termination of the HIT mode is not made clear.

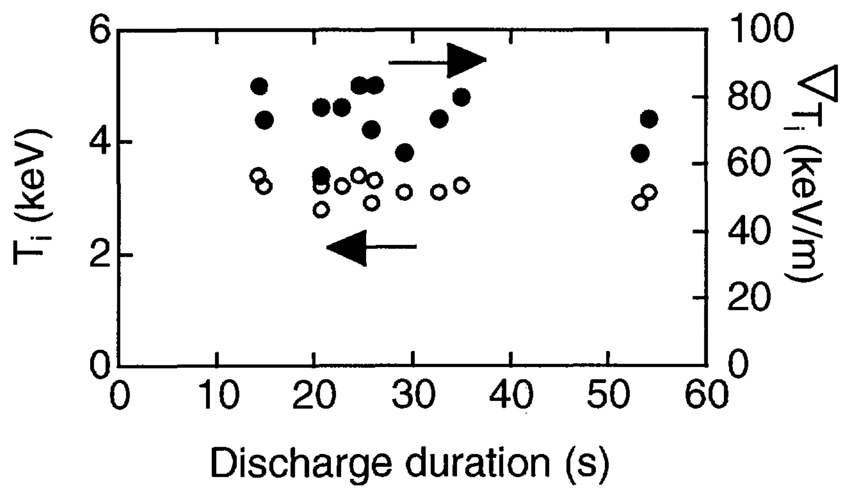

FIG. 9 The values of T_i (open circles) and T_i (solid circles) just before the transition from HIT to LIT as the function of the discharge duration.

As a part of input energy flows to the divertor plate, the heat load to limiter is reduced and consequently the hot spot and intense sputtering is difficult to take place on the single null configuration, compared with the limiter one. The improved thermal insulation between the wall and the plasma on single null configuration brings to higher performance plasma as shown in Fig. 10. The maximum ion temperature reaches at more than 5 keV.

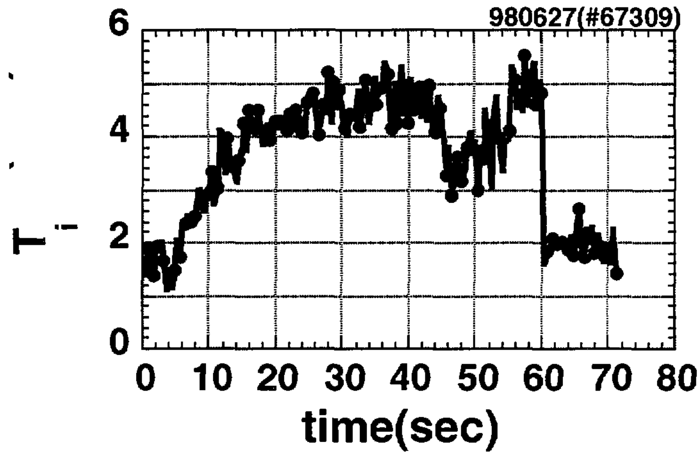

FIG. 10. Time evolution of T_i (keV). The configuration is changed gradually from 4 s to 6s and at 6 s, the single null configuration is formed completely.

4. Summary

Wall saturation and difficulty of avoidance of VDE in long tokamak discharges are pointed out as the main issues for approach to steady state fusion reactor through the experience of the achievement of super ultra long discharge (SULD).

High performance plasmas with high ion temperature up to 5keV and steep temperature gradient up to 85 keV/m can be sustained for longer than 30 sec by 2.45 GHz LHCD on single null divertor configuration. A candidate of the mechanism for ion heating and well-confinement is proposed. Energetic electrons may play an essential role in HIT discharge.

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