RECENT PROGRESSES ON HIGH PERFORMANCE STEADY-STATE PLASMAS IN THE SUPERCONDUCTING TOKAMAK TRIAM-1M

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Abstract

The overview of TRIAM-1M experiments is described. The up-to-date issues for steady-state operation are presented through the experience of the achievement of super ultra long tokamak discharges (SULD) sustained by lower hybrid current drive (LHCD) over 2 hours. The importance of the control of an initial phase of plasma, the avoidance of the concentration of huge heat load, the wall conditioning, and abrupt stop of the long discharges are proposed as the indispensable issues for the achievement of the steady-state operation of tokamak. A high ion temperature (HIT) discharge fully sustained by 2.45 GHz LHCD with both high ion temperature and steep temperature gradient is successfully demonstrated for longer than 1 min in the limiter configuration. The HIT discharges can be obtained in the narrow window of density and position. Moreover, the avoidance of the concentration of heat load on a limiter is the key point for the achievement and its long sustainment. As the effective thermal insulation between the wall and the plasma is improved on the single null configuration, HIT discharges with peak ion temperature > 5keV and steeper gradient up to 85 keV/m can be achieved by the exquisite control of density and position. The plasmas with high κ ~1.5 can be also demonstrated for longer than 1 min. The current profile is also well-controlled for about 2 orders in magnitude longer than the current diffusion time using combined LHCD. The serious damage to the material of the first wall caused by energetic neutral particles produced via charge exchange process is also described. As the neutral particles cannot be affected by magnetic field, this damage by neutral particles must be avoided by the new technique.

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. On the other hand, steady-state tokamak discharges over 1 hour have been proceeded only in the superconducting (SC) machine TRIAM-1M in the world. Recently the steady-state high performance plasma is also achieved on TRIAM-1M.

This excellent machine of foresight had been proposed to achieve the following objectives which were pointed out by one of the author a quarter century ago[1].

1) Development of the high-field superconducting magnet for fusion reactor and establishment of SC magnet technology,
2) Development of steady-state tokamak operation using non-inductive current drive,
3) Investigation of impurity dynamics and hydrogen recycling,
4) Feedback control of non-circular plasma for steady-state operation,
5) Additional heating for high performance plasma.

These objectives were considered to be fresh at that time, although the issues concerning them are well known and studied actively in many devices recently. They have been almost achieved through the progresses of TRIAM-1M project successfully. However, through the experiments of steady-state and high performance plasma, the other new issues for the fusion reactor have been made clear. These new issues may be important in order to realize the first fusion reactor in 25 years after. Before the description of recent progress, we would like to propose the new issues through the experience of TRIAM-1M experiments in order to predict for future issues in fusion research a quarter century hence.

In this paper the outline of TRIAM-1M and the survey of process of super ultra long discharge (SULD) are described in second and third chapters. The recent progress, which are the high ion temperature mode, the single null configuration, the current profile control and material studies are described from the forth to seventh chapters in order. In the last chapter this paper is summarized.

2. OUTLINE OF TRIAM-1M MACHINE AND EXPERIMENTS

TRIAM-1M is the high-field superconducting tokamak with 16 toroidal field coils made of Nb_3Sn (R = 0.8m, a x b = 0.12m x 0.18m)[2], 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. One of them was demonstrated its performance and stability in 1983[3] and the superconducting system including the TRIAM-1M machine was completed in 1986.

At the initial stage of experiment, the impurities (CO_2 and H_2O)were released from the magnets because of repetition of mechanical vibrations due to the electromagnetic force by plasma productions. They were accumulated at the refrigerator for the cryogenic system. This phenomenon obliged to turn off the refrigerator and the short runs of plasma experiment within a week were repeated. In order to eliminate the impurities, an adsorber was installed[4], and then the continuous operation of the superconducting magnets system longer than 100 days has been demonstrated successfully up to now.

The plasma chamber is made of SUS304L and the poloidal D-shape limiters and toroidal divertor plate are made of Mo. The surface of plasma chamber is cleaned effectively using electron cyclotron resonance discharge cleaning (ECR-DC) without baking the chamber[5]. In ohmic heating (OH) experiments, the maximum plasma current of 420kA was achieved and the elongation of the D-shaped cross section ($\kappa \sim 1.4$) was obtained [6].

In order to realize the continuous steady-state operation, the non-inductive current drive experiments have been carried out since 1987 using the 2.45GHz, 50kW lower hybrid current drive (LHCD) system with a klystron and a 4 x 1 grill launcher[7,8]. In 1989 the 1-hour ultra long discharge was obtained[9] and finally the 2-hour discharge was demonstrated in 1995[10]. On the other hand, aiming the operation of a high density region which is comparable to the D-T burning density in JET and TFTR, the high frequency LHCD experiments have been carried out using an 8.2GHz, 200kW LHCD system with 8 klystrons and a 8 x 2 grill launcher[11]. Then in 1995, the high density plasma was maintained for ~1 min, so the possibility of the steady-state tokamak operation with a reactor-grade plasma density sustained by non-inductive current drive could be indicated[10].

Furthermore TRIAM-1M has a unique equipment with a collector probe on which the various specimens are exposed to a plasma during the real long-time discharge, and the plasma-wall interaction have been investigated[12,13].

The problems of impurity dynamics, hydrogen recycling[14] and heat load being never experienced in pulsed plasmas have been made clear from the experiences of these long-time experiments[10].

Recently the high-performance of steady-state plasmas have been demonstrated in experiments on TRIAM-1M. The single null configuration with high elongation κ has been desired for future reactor both to remove the H_e ash and the huge heat load and to improve the plasma performance. The improved high temperature mode and the current profile control are important factors of high performance plasma for fusion reactors. These kind of experiments have been investigated in many devices, however, almost of them have been carried only in short pulses up to several sec except TRIAM-1M. From the view point of a steady-state reactor operation the control technique to maintain the high-performance plasma has to be established.

In TRIAM-1M experiments, the several world records of long sustainment for high-performance plasmas have been achieved in last two years. The single null divertor configuration with $\kappa \sim 1.5$ has been successfully maintained for 1 min by 2.45 GHz LHCD[15]. The hot ion temperature (HIT) mode ($T_i > 2$keV) has been successfully maintained for longer than 1min by exquisite control of the density and position on the limiter configuration, using only the 2.45 LHCD system without other additional heating, and especially on the divertor configuration Ti of 5 keV has been achieved[16]. Furthermore the control of the global current profile have been carried out for 50 times longer than the current diffusion time by combination of two LHW's (2.45 GHz and 8.2 GHz) with different parallel indexes spectra[17].

On the other hand, from the investigation of plasma-wall interaction in the long-time operation on TRIAM-1M, the problem is made clear that the damage against the wall due to the neutral particles should be so serious, and the new technique must be developed[18].

After the next chapter the details of the experiments on TRIAM-1M will be described.

3. EXPERIMENTS OF SUPER ULTRA LONG DISCHARGE (SULD)

3.1 Developments and issues for 3-min discharge

In 1988, the first long pulse tokamak plasma for longer than 3 min was achieved [7,8], 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, and 4) the plasma production by flux swing generated by the decrease in the center solenoid coil current. The 3-min tokamak discharge was the first step of steady state operation and some issues appeared.

The first one is the drift of the integrators for magnetic coils. The magnetic measurement plays an important role in the operation of tokamak. In fact, the 3-min discharge stopped due to the error caused by the accumulated drift of integrators. This showed clearly that the conventional method using magnetic coils was not available in the long discharges.

Second is the issue concerning the data acquisition system. 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.

3.2 Developments and issues for SULD

In 1989, the SULD for longer than one hour was demonstrated by the progresses [9], those are the adoption of the Hall generators for the measurement of the magnetic field and a new data acquisition system.

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 usual magnetic coil system at the initial phase of the discharge, and the Hall generator system was used in the subsequent phase.

As for the data acquisition system, the continuous monitoring and data acquisition system, which is called "cyclic processing", was also developed [19]. 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 SULD. Moreover event trigger method was also established to acquire the data with a high time resolution around some interesting events during long duration discharges [20].

The issue of the heat load appears in one-hour discharges. The heat load from the plasma sometimes concentrates on a certain point of a poloidal limiter, where the point becomes bright (hot spot), and it sometimes causes the intense sputtering. The hot spot is the source of impurity, and the performance of the plasma was sometimes declined by the hot spot. To avoid the appearance of the hot spot, i.e., concentration of heat load, the position control of plasma is significantly effective.

At first, the plasma position and fueling were controlled in the manual manner, because appropriate operation of the plasma position and the fueling has to be derived from many input data, for example, plasma current, position, microwave input power, coupling, density, temperature, behavior of impurity, and so on. However, the manual control strongly depends on the “know-how” of the operators. From the huge experimental data and the accumulated experiences, two important points for the steady-state operation are made clear.

One is the avoidance of the hot spot. The position control using the TV image of the plasma cross section and the poloidal limiter is suitable for this purpose. 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 inverse direction of the bright point to eliminate the hot spot. The distance and the speed of the movement of the plasma to avoid the hot spot is just "know-how" and the appropriate operation can be obtained from many experimental data.

The other is the fueling control 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 into the wall varies shot by shot, 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 Hα signal. The intensity of Hα 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, the fueling control using the Hα intensity is also sensitive to electron density.

Based on the two improvements, a longer discharge than 2-hour could be achieved by the automatic control in 1995 [10]. This is a milestone of the steady-state operation of tokamak. The progresses of steady-state operation on TRIAM-1M are summarized in Fig. 1.

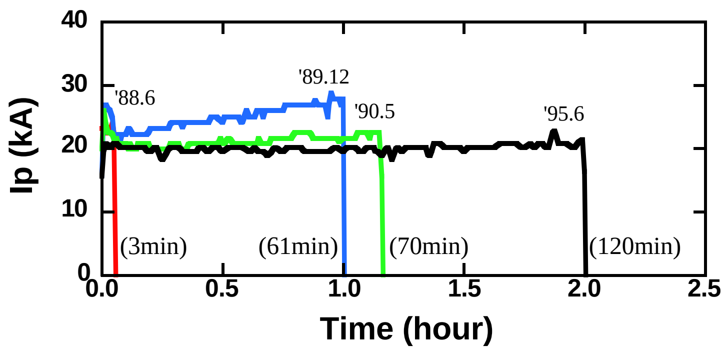

Fig.1. Progresses of steady-state operation using 2.45GHz LHCD on TRIAM-1M. The main parameters is similar in all of the discharges in this figure, I_p~20kA, $\overline{n_e}$ ~$1.5x10^{18}m^{-3}$, T_e~0.6keV, T_i~0.5keV, B_t=6T, P_{RF}~20kW.

3.3 Time scale for steady state during SULD

The characteristics time scale for steady-state should be investigated in the SULD. 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 concentrates on the poloidal limiter. The many plasma parameters, for example density, plasma current, temperature, and so on, are kept constant during the discharge. The impurities estimated by the vacuum ultra violet (VUV) become constant (O ~2%, Mo ~0.2%) [21] and they do not change significantly during discharge [9]. 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, τ_E (~10ms) and current diffusion time, $\tau_{L/R}$ (~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 sec 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.

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. 3. 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 view point of the wall condition.

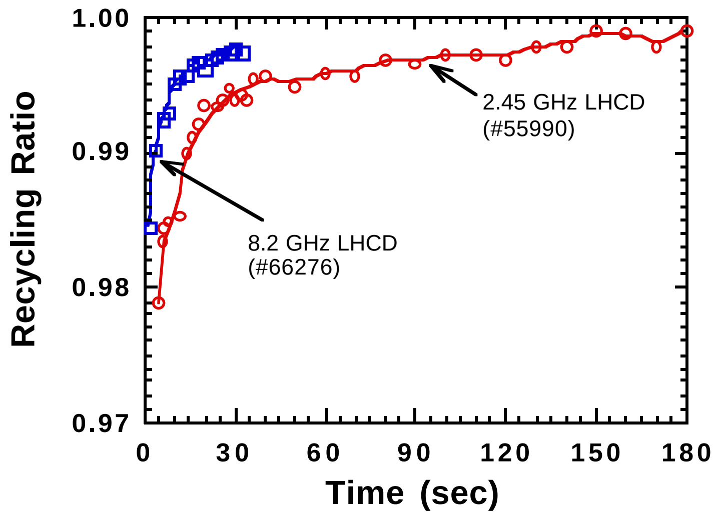

Fig. 2. Time evolutions of the recycling ratio of the low density discharge ($\overline{n_e}$ ~0.2x$10^{19}$$m^{-3}$, I_p~21kA, B_t=6T) sustained by the 2.45GHz LHCD with ~20kW (open circles) and the high density discharge ($\overline{n_e}$ ~1x$10^{19}$$m^{-3}$, I_p~23kA, B_t=7T) sustained by the 8.2GHz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

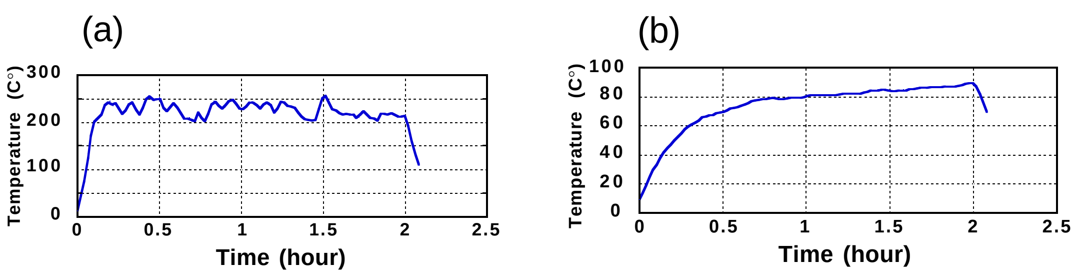

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Fig. 3. Time evolutions of the temperature of (a) the limiter and (b) the wall in the case of the 2-hour discharges.

3.4 Long duration discharge in the high density region

Steady-state operation in high density region ($\overline{n_e}$ is more than 1x10^{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 ~2 x10^{19} m^{-3} and the duration of the discharge in the high density region exceeds 1 min. Two important points are made clear from the high density discharge. One is the recycling property. The recycling ratio also increases gradually and it approaches to unity. It takes about 20 sec to become constant as shown in Fig. 2. It is found that the time scale for the saturation of the recycling ratio corresponds to a few 10 sec even in the high density plasma.

The other is that the termination of the discharge is 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 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 larger than that of the low density plasma. The wall saturation may become a large issue for steady-state operation in the high density region.

3.5 Heat load issue for future fusion reactor

Heat load issue is also important in steady-state operation. Heat load levels in many devices are summarized in Fig.4.

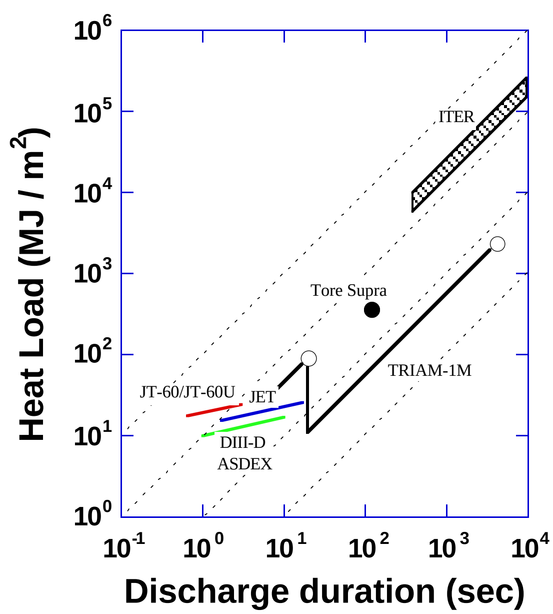

Fig. 4. Heat load as the function of the duration of the discharge. The data of TRIAM-1M were estimated as the heat load at the limiter and the others were estimated as the heat load at the divertor plate. The dotted lines in the figure show that the heat flux is constant. In high density discharge in TRIAM-1M, heat flux is comparable to large tokamaks.

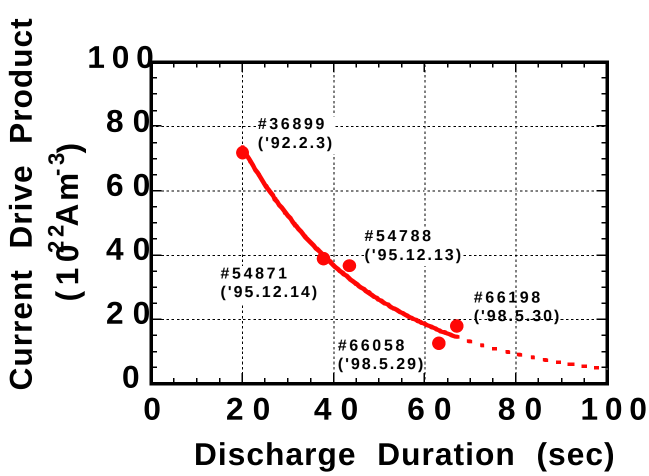

Fig. 5. Current drive products ($\overline{n_e}\ EI_p$) in 8.2GHz LHCD plasma as the function of the duration of the discharges. The current drive product is proportional to the input power, if the current drive efficiency is constant.

The heat load of the 2-hour discharge on TRIAM-1M at the limiter (more than 1GJ/m^2) is compared 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 declined. Figure 4 shows that the hot spot and intense sputtering may occur in the divertor plate on ITER and this huge heat load has been realized on only TRIAM-1M in the world. This circumstances concerning heat load are suitable to investigate the characteristics of the material for the fusion reactor. The issue of the heat load has appeared already in TRIAM-1M as shown in Fig.5. It shows that the duration of the discharge is limited by the heat load. The steady-state operation in low current and density can be realized by the capacity of a cooling system of TRIAM-1M, however, it is impossible to obtain the SULD in high density region without the improvement of cooling system.

3.6 Issue for current drive efficiency of non-inductive current drive

Current drive efficiency is the important index for the steady-state cost-effective tokamak reactor, and required efficiency corresponds to 0.2-0.3x10^{20} A/Wm^{-2}. The current drive efficiency OF LHCD is sufficient for the requirement of tokamak reactor in many tokamak devices. However, these current drive efficiency have been estimated not in full current drive discharge but in the partial current drive discharge assisted with the OH electric field. It should be noted that the current drive efficiency of LHCD estimated in the OH plasma does not follow the synergetic effect between OH electric field and LHW. In TRIAM-1M, the investigation of the effect of OH electric field for the current drive efficiency is carried out and the result is summarized in Fig. 6. The current drive efficiency is significantly enhanced by the OH electric field. The enhancement factor strongly depends on the value of the OH electric field and it reaches over 3. This indicates that the non-inductive current drive efficiency in the plasma assisted with the OH electric field is over-estimated [22].

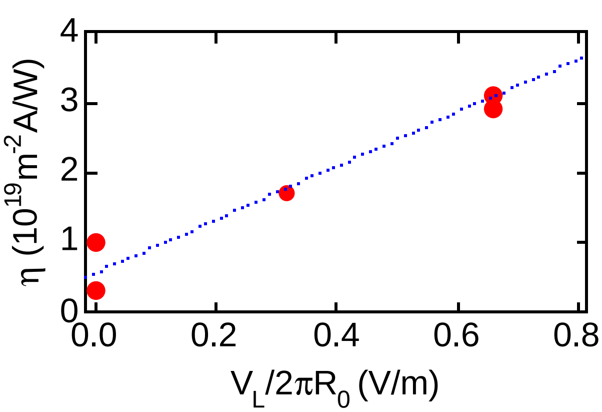

Fig. 6. Current drive efficiency as the function of loop voltage. The zero loop voltage cases corresponds to the full current drive plasma sustained by LHCD for longer than the current diffusion time.

3.7 Other issues for steady-state operation

Two large issues are made clear through the real experiments of steady-state operation. One is that the discharges sometimes stop abruptly, although the automatic control is active. The cause of this abrupt stop of the discharge is not clear. One possibility is that large Mo grains generated by the sputtering from the limiter may plunge into the plasma. If this hypothesis is true, it may be difficult to avoid the abrupt termination of long discharges. The solution will be the avoidance of the concentration of heat load by the plasma as possible.

The other is the difficulty of the plasma control at the very early phase, especially break-down phase as shown in Fig.7. The difference between these two discharges is only in the horizontal plasma position of about 20 mm. In the case of short discharge due to the plasma disruption, the interaction of plasma with the limiter at the break-down phase may have sputtered the impurity from the limiter. As the result, the plasma current is not sustained by LHCD in spite of the effort of the control system. This indicates that the control in the very early phase of plasma is one of key points for the steady-state operation of tokamak.

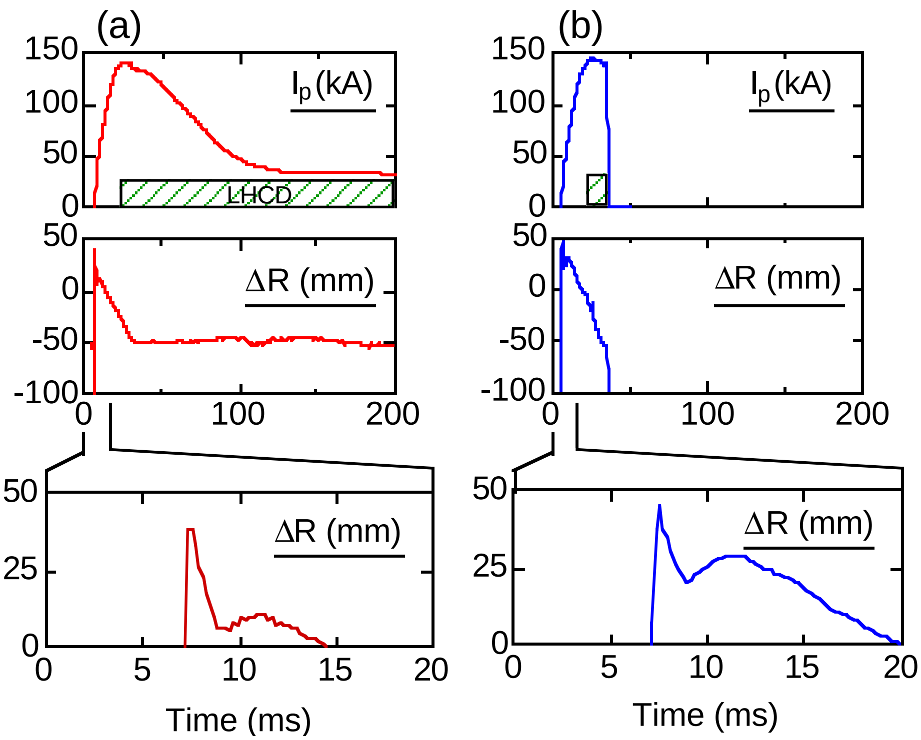

Fig. 7. Typical examples of the discharge (a) operated well and (b) operated bad in very early phase. It should be noted that the small difference of the horizontal plasma position in the early phase causes large effects.

4. ACHIEVEMENT OF HIGH PERFORMANCE PLASMA AND ITS LONG SUSTAINMENT

Recently a long duration discharge with the high ion temperature (HIT) mode has been obtained using 2.45GHz LHCD on both the limiter and the single null configuration[16]. The ion temperatures $T_{i//}$ and $T_{i\perp}$ have been measured with two kinds of neutral particle analyzer (NEA), NEAP (θ~90 K) and NEAT(θ~36 K) respectively, here θ 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 ΔR(=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 scan can not be carried out in the single null configuration. 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 exquisite control of ΔR and n_e as shown in Fig.8.

The HIT mode is characterized by the steep temperature gradient formed around half of the minor radius as shown in Fig.9. 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, both $T_{i//}$ and $T_{i\perp}$ measured with NEAT and NEAP change simultaneously within the sampling time of 10ms. This indicates that T_i becomes almost isotropic at any time and the energetic ions with small $v_{//}$ are well confined at least during the estimated value of pitch angle scattering time (~8 ms for θ=36 K).

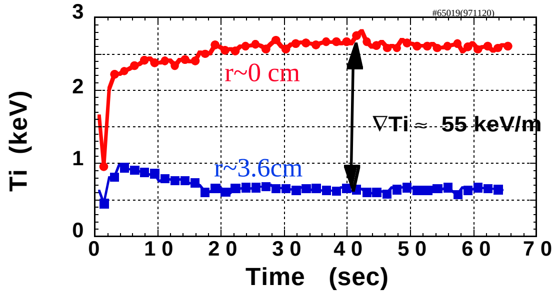

Fig. 8. Time evolutions of T_i at r~0cm (closed circles) and r~3.6cm (closed squares) in long sustained HIT discharge.

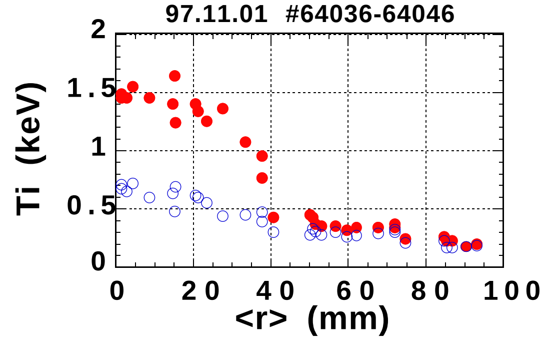

Fig. 9. Radial Profiles of T_i at r~0cm in the HIT mode (closed circles) and the LIT mode (open circles).

These experimental results indicate that 1) effective ion heating takes place in the full 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. 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 LHCD. The EM wave at the frequency of the 2.45 } 0.4 GHz is sometimes observed. This sideband wave is originated by 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. 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. 10. 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 of both T_i and amplitude of EM wave occurs at 7.5 s.

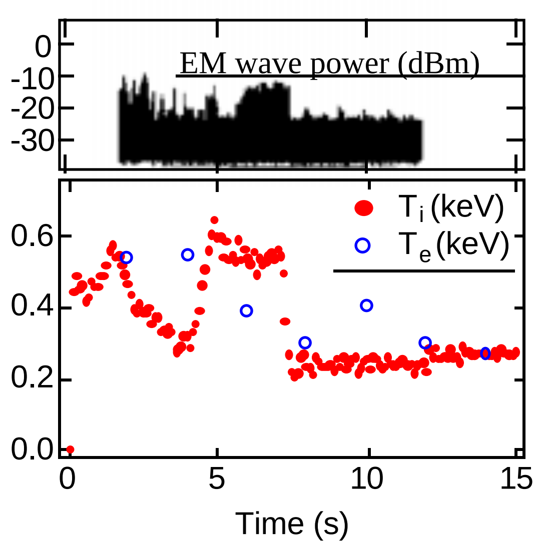

Fig. 10. Top figure shows the time evolution of the amplitude of EM wave at the frequency 2.45 GHz - 0.4 GHz measured with a spectrum analyzer. The amplitude of pump wave (2.45GHz) is about 30 dBm. Bottom figure shows the time evolution of T_i at the plasma center.

As for the confinement of energetic ions, although the mechanism is not made clear, the energetic ions by weak poloidal field may be confined well by the presence of appropriate negative radial electric field shear. The study for the confinement of energetic ions in the weak poloidal field must be continued further, because the same situation is considered in the field of α particle physics in a reactor plasma.

The optimum window for HIT may be qualitatively explained as the following. For the density window, the coupling of LHW to the plasma and the slowing down process of energetic electrons play an essential role. In low density side of the window, electrons are easily accelerated, but the coupling between the plasma and LHW become worse. On the contrary, the improvement of the coupling are competed with the enhancement of the slowing down process in high density side of the window. As the results, the number of energetic electrons has an optimum value at the appropriate density. For the position window, the coupling and the loss of energetic electrons are essential. An outward shift of plasma improves the coupling. However, as the orbits of energetic electrons shift outward, the energetic electrons frequently hit the limiter and the launcher of LHW . On the contrary, inward shift of plasma reduces the loss of energetic electrons, but it makes the coupling of the LHW with plasma worse. Therefore, the number of energetic electrons has an optimum value at the appropriate position.

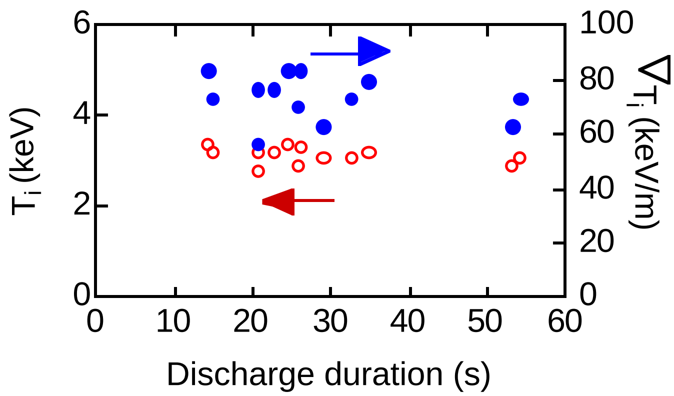

Fig. 11 The values of T_i (open circles) and ∕ T_i (solid circles) just before the transition from HIT to LIT as the function of the discharge duration.

The maximum values of T_i and ∕ T_i seem to be limited in the HIT discharge as shown in Fig. 11, 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.

When the hot spot sometimes appears in the very early phase of the discharge on the limiter configuration, the HIT mode can not be obtained for the whole of the discharge. This suggests that the impurity generated by the hot spot plunges into the core plasma and it prevents from achieving the HIT mode. It should be noted that the performance of the plasma is not recovered after the extinction of the hot spot appeared in the very early phase. This indicates again that the position control in the break-down phase is very important to achieve the high performance plasma.

Generally speaking, the HIT experiments on TRIAM-1M is the good news of steady state operation of tokamak, because the high performance plasma can be maintained by exquisite control for the longer time than the required time for steady recycling ratio. While, the high performance results in the large tokamaks may not reach the steady state condition, but remain transient phenomena in the view point of the recycling. This result of TRIAM-1M indicates that the steady-state high performance plasma with ∕ T_i ~ 60 keV/m can be obtained by the exquisite control for the whole of discharges including the very early phase.

5. @RECENT PROGRESSES OF THE PLASMA ON THE SINGLE NULL CONFIGURATION

Establishment of technique to maintain long single-null configuration with high elongation, κ, has been desired for the future reactor both to remove the huge heat load and to improve the plasma performance [15]. Figure 12 shows the summary of the achieved κ 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 κ. 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 κ ~ 1.5 for 1min by 2.45 GHz LHCD only; P_{RF} = 22 kW, B_t = 6 T, n_e = 1 x 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 κ in the single null configuration. is possible by developing quick-responsible and long-time-measureable magnetic sensor.

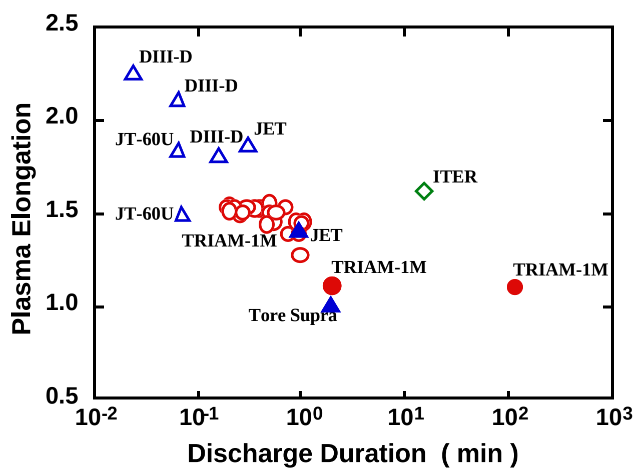

Fig. 12. Plasma elongation, κ, as a function of the discharge duration in various tokamaks. The data on the single null configuration in TRIAM-1M (open circles) and in other tokamak (open triangles), on the limiter configuration in TRIAM-1M (close circles) and in other tokamak (close triangles) are plotted in the figure.

The energy of 200 MJ has been injected into the plasma in the limiter configuration. 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 cooling water of the divertor plate. The thermal input calculated by integrating the temperature rise multiplied by the water flow is plotted as a function of discharge duration in Fig. 13. At first, the plasma is produced in limiter configuration from 0 to 4 s. During this phase, the thermal input to the divertor plate is not detected as shown in Fig. 13. From 4 s to 6 s, the plasma configuration is drastically changed and the single null configuration is formed at 6 s. After 6 s the thermal input to the divertor plate increases linearly with the discharge duration. From the 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.

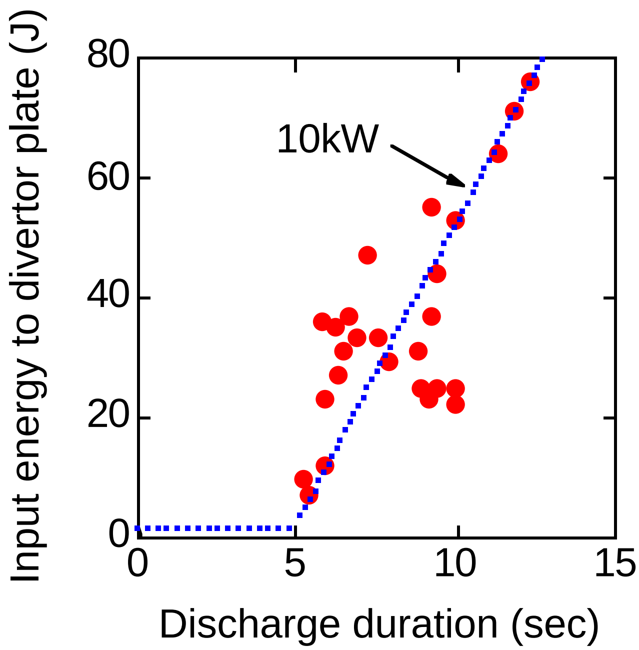

Fig. 13. Input energy to the divertor plate as the function of the discharge duration in 8.2GHz LHCD plasma. The single null configuration is formed completely at 6 s.

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. 14. The maximum ion temperature reaches at more than 5 keV.

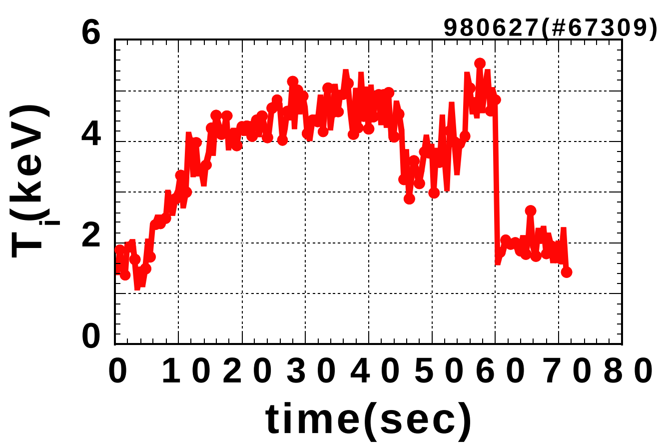

Fig. 14 Time evolution of T_i (closed circles). The configuration is changed gradually from 4 s to 6s and at 6 s, the single null configuration is formed completely.

6. CURRENT PROFILE CONTROL USING COMBINED LHCD

Recently the controllability of the magnetic shear (i.e., current profile) has been investigated from a viewpoint of correlation with the various improved confinement modes. In the present method, the negative shear is formed by increasing the current diffusion time using the neutral beam heating at the current ramp-up phase. However, this method is not available for the steady-state plasma. As for the method of the current profile control using LHCD in many devices, the discharge duration is not enough because it is shorter than the current diffusion time. The development of the non-inductive current drive method is indispensable to sustaining the current profile in the steady state. As for the current drive efficiency, in many devices it is estimated under such a best condition as the electric field exists in the plasma as described in the section 3.5. It is an important issue whether the improvement of the current drive efficiency can consist with the control of the current profile in steady state.

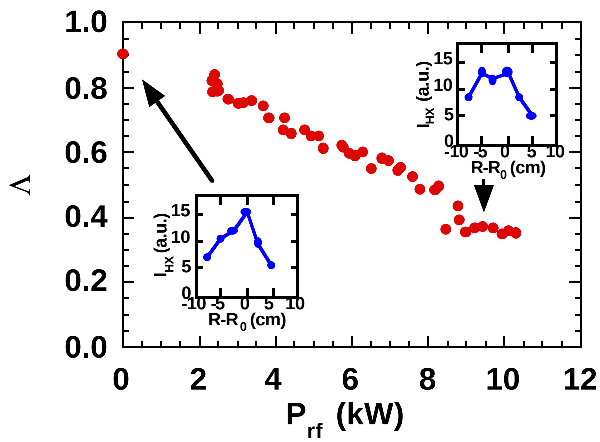

Fig. 15 Demonstration of the controllability of current profile using combined with 8.2GHz and 2.45 GHz LHCD. Insets show the radial profile of hard X-ray of 80 keV emitted from energetic electrons driving plasma current.

The controllability of the current profile has been investigated by the combination of 2.45GHz and 8.2GHz LHCD with different spectra of parallel refractive index ($N_{//}$) [17]. The 2.45GHz LHW is superimposed on the high density plasma sustained by 8.2GHz LHCD (8.2GHz + 2.45GHz LHCD). The controllability of the current profile in 8.2GHz + 2.45GHz LHCD is shown in Fig.15. Shafranov Λ ($=\beta_p + l_i/2 - 1$) remarkably reduces depending on the power of 2.45GHz LHW, P_{rf}(2.45GHz). The internal inductance l_i is estimated using Λ and β_p , which is obtained in a kinetic manner. From this estimation, the value l_i decreases with P_{rf}(2.45GHz) and the change in l_i is up to about -0.4. It suggests that the current profile becomes broad with P_{rf}(2.45GHz), which is supported by the measurement of hard X-ray emission profile viewing vertically as shown in the insets of Fig.15.

In the combination of two LHW's, the current drive efficiency is improved by a factor of about 1.5 times (~0.4×10^{19}Am^{-2}W^{-1}). The effective temperature of the high energy electrons estimated from the slope in the spectrum of hard X-ray emission increases by a factor of 1.2 times by superimposing the 2.45GHz LHW, although it does not change by increasing only P_{rf}(8.2GHz). This suggests that the higher energy electrons are accelerated by superimposing the 2.45GHz LHW and therefore the local current density may be changed.

The well-controlled current profile can be successfully sustained for about 2 orders in magnitude longer than the current diffusion time ($\tau_{L/R}$~200ms) and moreover and the current drive efficiency is improved by the combined LHCD. This indicates that the compatibility of the profile control and sufficient current drive efficiency is achieved by the combined LHCD.

7. PLASMA-WALL INTERACTION AND INTERACTION AND MATERIAL STUDIES USING LONG DISCHARGES

High energy charge exchange (CX) particles emitted from the core plasma bombard the plasma facing wall and result in the sputtering and formation of lattice defects in the materials. The defects may affect material properties such as thermal conductivity and mechanical strength. The behavior of CX-particles and their effects on materials have been studied by exposing the material specimens to the long duration discharge plasma of the TRIAM-1M by using a collector probe system [18].

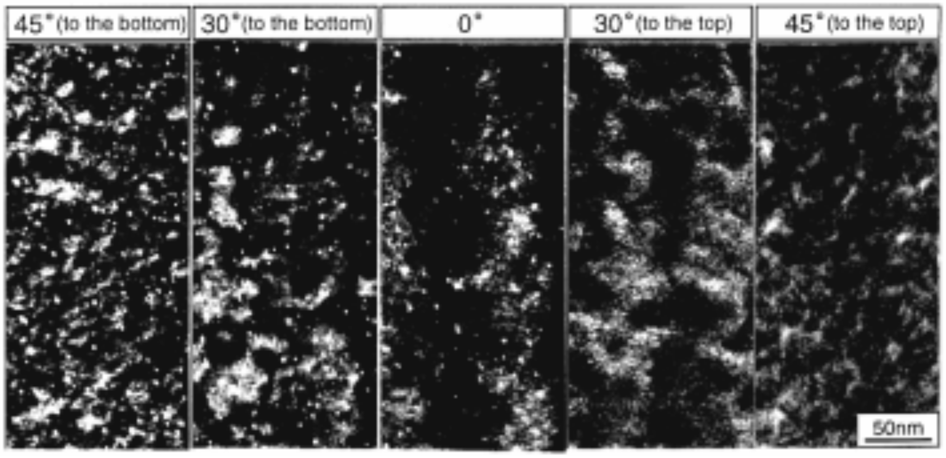

Fig. 16. TEM dark field images showing radiation damage in molybdenum placed at plasma facing side by exposing to the high ion temperature discharges.

The transmission electron micrographs (dark field images) in Fig. 16 show typical damage in molybdenum specimens exposed to plasma by inserting in the scrape-off layer through a horizontal port; 6mm behind the poloidal limiter surface. In order to eliminate the effects of the charged particles and to collimate the incident directions of the neutral particles, the specimens were mounted in the holes (2 mm in diameter and 4 mm in depth) at the plasma facing side. The holes direct to the five different directions from the bottom to the top of the plasma with semiangle of 14 degrees. They were exposed to successive high ion temperature discharge (hydrogen plasma, limiter configuration) sustained by lower hybrid current drive (2.45GHz). Typical plasma parameters were as follows; T_i=1.5~2.5keV, $\overline{n_e}$ =1.5x10^{18}/m^3, I_p=20~25kA. The duration time of each discharge was about 1 min and the total duration time reached 31.5 min. The temperature of the specimen holder during exposure was almost constant at about 23ºC. Such type of material irradiation experiment, which requires large accumulation of particle load, cannot be performed so easy except TRIAM-1M. As shown in the figure, dislocation loops (aggregates of radiation induced interstitials, small white dot images) were formed with strong specimen direction dependence. Namely, considerable amount of damage (defect density: 3-4x10^{15}/m^2) was observed in the specimens directing to the lower side (-45, -30 degrees) and the plasma center (0 degree), while almost no damage for those directing to the upper side (30, 45 degrees). These results imply that CX-neutrals with enough energy to cause radiation damage in metals were mainly formed in the lower half of the plasma. According to the stereo-observation, the defects distribute up to 40-50nm in depth, which corresponds to those for the damage production by hydrogen particles ranging from 3 to 6 keV. This fact means that some part of CX-particles have energy of several keV, which is enough for radiation damage in molybdenum, and is correspond well with the result of energy spectrum measurement of neutral particles with NEA. By comparing quantitatively with hydrogen ion irradiation experiments carried out before, the flux of the hydrogen neutrals responsible for the damage was estimated to be about 1.5x10^{18}/m^2/s. It must be pointed out that this flux is not low from the stand point of material damage. As demonstrated in Fig.17, which shows the evolution of radiation damage in molybdenum under 2 keV hydrogen ion irradiation, the amount of the defect reaches saturated level by the irradiation about 10^{22}ions/m^2 [23] and results in strong surface hardening [24]. Due to strong interaction between hydrogen and the radiation induced interstitial atoms, formation of the dislocation loops is enhanced very much under hydrogen irradiation [25]. Figure 18 shows macroscopic damage of a pre-thinned tungsten foil, which was located at 6mm behind the poloidal limiter surface for one experimental campaign. The specimen was cracked along grain boundaries. It seems that the energetic hydrogen atoms, which can penetrate into the subsurface region through the surface, diffused into the bulk and brought the hydrogen embrittlement. These experimental results indicated the influences of the energetic hydrogen influx are not restricted in the surface and shallow subsurface range but may change even the properties of bulk materials [26].

The localized formation of energetic CX-neutrals at the lower half of the plasma indicates stronger sputtering and radiation damage at the bottom of the torus. The present results are also important for understanding and assessment of erosion and damage of PFC and also for impurity behavior.

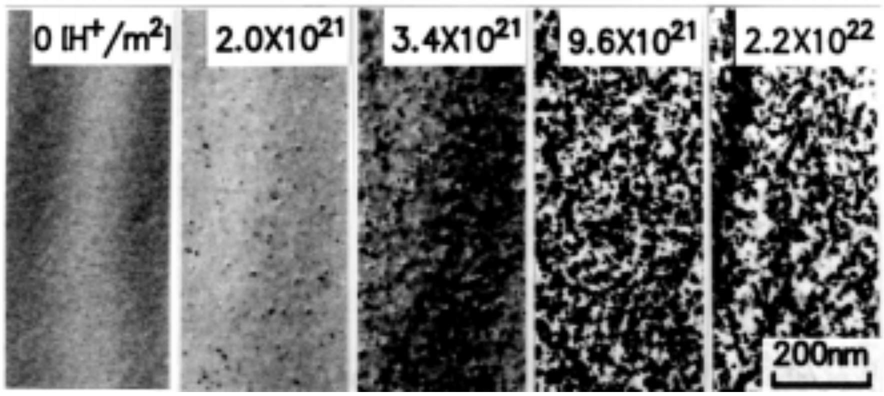

Fig. 17. TEM bright field images showing radiation damage in molybdenum under 2 keV hydrogen ion irradiation at room temperature.

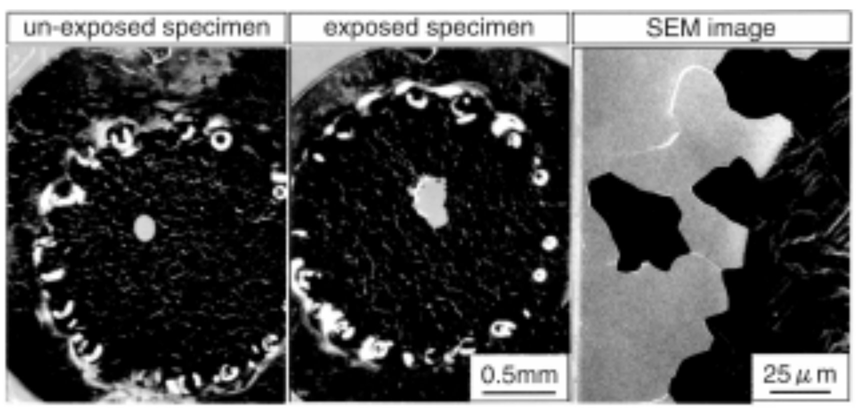

Fig. 18. Macroscopic damage of pre-thinned tungsten specimens placed on the inner wall of the vacuum vessel for one experimental campaign (about 3 months).

8. SUMMARY AND CONCLUSION

The up-to-date issues and demonstrations for approach to future fusion reactor are proposed as the following through the experience of the achievement of super ultra long tokamak discharges (SULD) sustained by lower hybrid current drive (LHCD) over 2 hours.

1) Issue of the control of initial phase of plasma.
2) Issue of the avoidance of the hot spot.
3) Demonstration of the recycling property.
4) Issue of the abrupt stop of the long discharges.
5) Demonstration of steady-state high performance plasma.
6) Issue of the development of new control to maintain the plasma with high κ.
7) Demonstration of the long discharge with the favorable current profile.
8) Issue of the serious damage to the material caused by energetic neutral particles.

These issues and demonstrations may become guide for future fusion reactor.

The position control is very important to avoid the hot spot, especially in the initial phase of plasma the bad control sometimes causes the plasma disruption. The time scale required to reach the steady recycling ratio is about a few tens seconds, which does not depend on the electron density so much. This time scale is the standard for steady-state operation. The transport barrier could be maintained for longer than 1 min and this indicates that the high performance plasma with transport barrier can be maintained in steady state. In TRIAM-1M, the steady-state plasma both with high κ on the single null configuration and with controlled current profile using the combination of LHW's. are successfully demonstrated. These efforts for the steady-state operations has been carried out to obtain the steady-state higher performance plasma.

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