HIGH ION TEMPERATURE DISCHARGE AND ITS LONG SUSTAINMENT IN THE SINGLE-NULL CONFIGURATION ON TRIAM-1M

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Abstract

A high ion temperature discharge in the lower hybrid (LH) current drive scheme has been first obtained in the world in the superconducting tokamak TRIAM-1M. The high ion temperature mode is triggered by a transition which occurs within an operation window for the density, horizontal plasma position and antenna phasing. A steep ion temperature gradient (> 80 keV/m) is formed near the core region at the transition. Long duration operation of this discharge is successfully demonstrated also in the single-null (SN) configuration by the several control technique.

1. INTRODUCTION

In these years various modes for improved confinement and performance have been investigated in many devices. However, in order to apply each mode to a future reactor effectively, it is indispensable to examine each steady state characteristics in detail. In ITER the steady state operation has been designed, however, experiences of this operation are quite few in tokamaks[1,2]. One of the key issues to guarantee the ITER mission is to investigate the steady state operation of the high temperature plasma with high performance in the present devices. Recently, two subjects concerning the realization of high ion temperature and its long sustainment have been performed in full current drive plasmas on TRIAM-1M[3].

2. HIT DISCHARGE

The HIT(Hot Ion Temperature) discharge has been studied under the following experimental conditions; B_0 = 5-7 T, I_{LHCD} 30 kA, P_{rf} 25 kW, 1×10^{18} m^{-3} n_e 6×10^{18} m^{-3}, R_0=0.84 m. In the limiter configuration the minor radius a is ~ 0.12 m and in the SN configuration a ~ 0.11 m and b ~ 0.16 m. The working gas is hydrogen. Plasma positions (vertical Δz and horizontal $\Delta R = R-R_0$) are feedback controlled. In order to control the total influx including recycled and gas puffed particles a feedback system using the H_α emission is also developed [4]. Thus the density is scanned by a piezo valve feedback controlled under the constant influx. Lower hybrid waves (LHWs) are launched at a frequency of 2.45 GHz via a four waveguides grill located in the low field side. The head of the antenna is behind the ring limiter (made of Mo) by 5 mm. Although the antenna phasing, $\Delta\phi$, between waveguides is scanned from 70° to 130°, most data are taken at 110°, at which the peak parallel refractive index of LHWs is around 1.5. The energy of the resonant electrons via Landau damping is above 100 keV. Since there is no linear mode conversion point (corresponding to n_{LMC}~1.8×10^{20} m^{-3} at B_0 = 6 T) in the plasma due to the low density, the direct ion heating due to LHWs cannot be expected [5]. The ion temperature T_i has been measured by neutral particle energy analyzers (NEAs). The density n_e is measured by a microwave interferometer at 140 GHz, the electron temperature T_e, measured by a Si(Li) detector, and the perpendicular hard X-ray temperature profile, T_{HX}(R), is measured by a NaI scintillator array viewing vertically.

Typical HIT discharges in both limiter and SN configurations are shown in Fig. 1. The HIT mode appears at a transition (typical transition time scale ~ 10 ms) and in some cases HIT to LIT (Low Ion Temperature) back-transition occurs. In the HIT discharge T_i increases ~ 2.8 keV in the limiter configuration and ~ 3.8 keV in the SN one, but T_e is 0.3-0.7 keV. The density and driven current is only slightly affected or not changed.

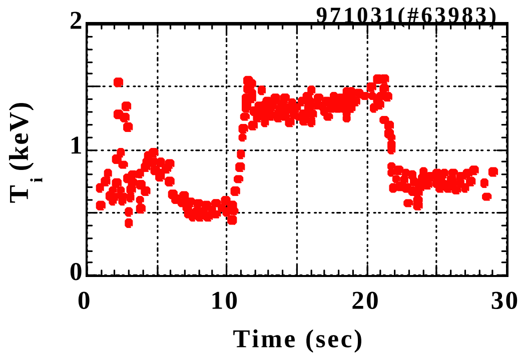

Fig.1(a). Typical HIT discharge in the limiter configuration. A transition to the HIT mode occurs at t ~ 11 sec, the mode is sustained for 10 sec, and finally a back-transition to the LIT mode occurs at t ~ 22 sec.

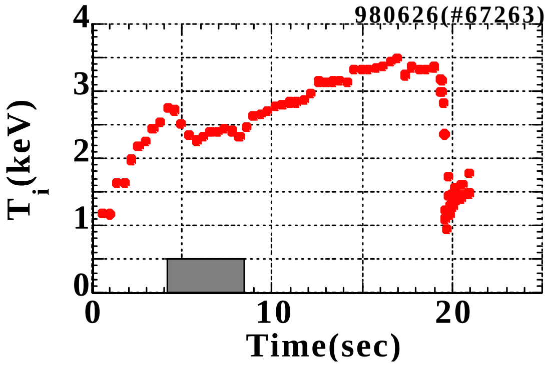

Fig.1(b). Time evolution of $T_i(t)$ in the SN configuration. A transition to the HIT mode occurs in the earlier phase (t< 4 s) and high T_i is sustained until a HIT-LIT transition occurs at t=19.5 sec. During the hatching area the SN is formed.

2.1. Onset conditions

In order to identify the onset conditions various parameters (n_e, Δz, ΔR, $\Delta\phi$, P_{rf}) are surveyed mainly in the limiter configuration. First n_e is scanned in time during a single discharge by varying a reference level for feedback controlled gas puffing at the fixed ΔR and Δz. Second, the reference level for a feedback controlled vertical coil system is varied smoothly during the discharge at the fixed H_α reference level and Δz. Thus it is found that the HIT discharge is realized at $n_e l$ ~ 3.5 ± 0.4×10^{17} m^{-2}, (n_e ~ 1.6×10^{18} m^{-3} in the limiter configuration) and for -2.5 cm ΔR -0.5 cm, as shown in Fig.2. These $n_e l$ and ΔR windows are similar to those in the SN one. It is observed that the HIT mode is insensitive to Δz within~ ±3 cm and P_{rf} from 15 kW to 35 kW. Within these density and ΔR windows the sensitivity of $\Delta\phi$ was studied. It is found that the HIT transition occurs from 90° to 120°corresponding to the region in which the current drive efficiency is high [6].

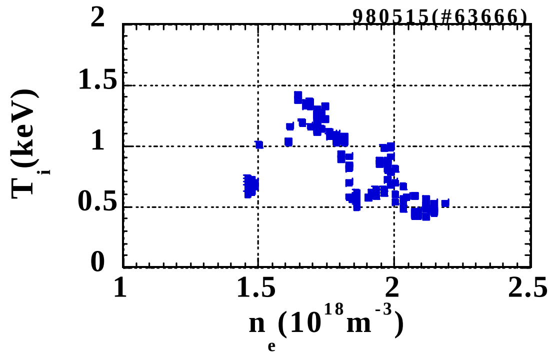

Fig.2(a). The n_e window in the limiter HIT discharge. The main n_e peak is ~ 1.6´10^{18} m^{-3}. The 2nd sub-peak also exists ~ 2´10^{18} m^{-3}.

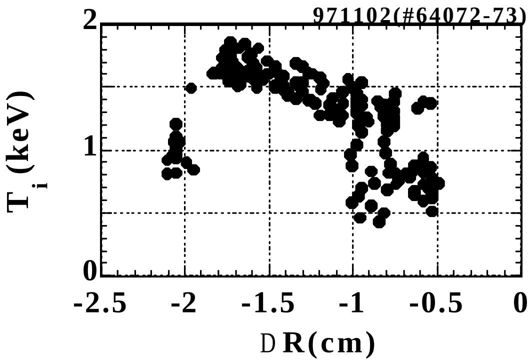

Fig.2(b). The DR window in the limiter HIT discharges. The DR is scanned sinusoidally during the shot.

The optimum windows of n_e and ΔR are qualitatively explained as follows. For the density window, the coupling of LHWs to the plasma and the slowing down process of energetic electrons play an essential role. Since these two factors compete each other, in lower n_e energetic electrons can be easily created, but the coupling becomes worse, and vice versa in higher n_e. As the results, the number of energetic electrons has an optimum value at the appropriate density. For the position window, if the wave-plasma coupling and the loss of energetic electrons are assumed to be essential, the same scenario is possible from an electron orbit point of view.

In the $\Delta\phi$ window T_i is raised or the HIT transition occurs, but both T_e and T_{HX} are lower than those outside of the window. Therefore it is considered that the ion heating in the HIT mode is related to the change in the electron energy spectrum in the relatively wide range (~1 keV to 200 keV). If the ion heating is ascribed to the waves excited by the energetic electrons [7], these operational windows of the HIT mode may be explained by this behavior of energetic electrons, which will be discussed later.

2.2. Transport barrier formation

An ion temperature profile $T_i(z)$ at eight spatial points along the vertical direction is measured by NEAP whose lines of sight are perpendicular to the toroidal magnetic axis. Since NEAP detects ripple trapped ions with $v_\parallel \sim 0$ in collisionless plasmas, the measurement of $T_i(z)$ in low n_e LIT discharges shows that $T_{i,\text{ ion-drift-side}} / T_{i,\text{ electron-drift-side}} \sim 3$ at the plasma boundary, as shown in Fig. 3. This up-down asymmetry is reversed when the direction of the toroidal magnetic field is reversed. In the HIT mode, $T_i(z \sim 0)$ shows rapid changes corresponding to LIT-HIT and HIT-LIT transitions, however, $T_i(z \sim -a)$ in the ion drift side does not change in time. Some barrier formed around r~ a/2 prevents ripple trapped ions from drifting down. In order to clarify this barrier, the measurement of $T_i(z)$ has been done in great detail in good reproducible discharges by shifting Δz by ±2.5 cm on the shot-to-shot basis. As shown in Fig. 4, the steep temperature gradient ∇T_i formed at ~ 4 cm is clearly observed, which is considered to be the transport barrier. The obtained ∇T_i reaches ~ 55 keV/m in the limiter configuration and ~ 80 keV/m in the SN configuration.

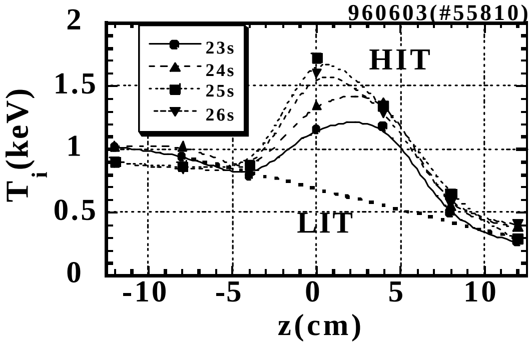

Fig.3. The time evolution of $T_i(z)$ after the HIT mode is triggered. The ion drift side is the negative z direction (downward). The steep gradient is formed in both direction.

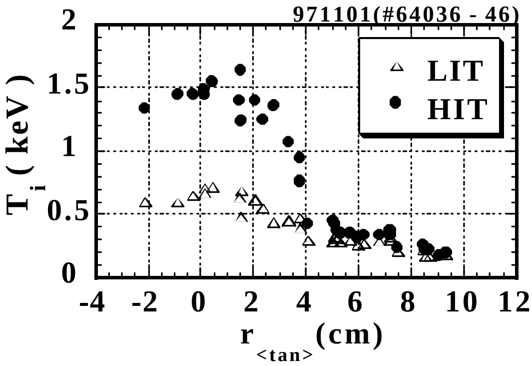

Fig.4. Both ion temperature profiles(HIT and LIT) are shown as a function of the tangent radius. The steep temperature gradient is formed at around 4 cm

2.3. Confinement of energetic ions

The role of the transport barrier is also experimentally confirmed by investigating the decay process of the charge exchange fluxes $\Phi_{CX}(E,t)$ in the HIT mode after the RF is turned off. Although the driven current starts to decay a few ms after the RF turn-off and is terminated at ~ 50 - 80 ms by a rapid vertical displacement event in the SN configuration, the decay time $\tau_{decay}(E)$ of $\Phi_{CX}(E,t)$ at the energy of ~5 keV is found to be about 20 ms, which is much longer than the drift loss time of < 1 ms, and as expected $\tau_{decay}(E)$ increases with decreasing energy, which means that high energy ions are well confined, as shown in Fig.5. In the limiter configuration, since the driven current lasts for ~0.25-0.3 sec after the RF turn-off, $\tau_{decay}(E)$ becomes longer.

Indirect validation for improved confinement of the energetic ions with $v_\parallel \sim 0$ is done by comparing energy spectrum of NEAP (ripple trapped ions) with that of NEAT (toroidally co-moving ions). Here the angle θ_{chord} between the sight line of NEAT and the toroidal direction is ~36°. The result is shown in Fig.6. The pitch angle scattering time for ions to be scattered by 36° is evaluated to be ~ 50 ms at E ~ 5 keV, $n_e \sim 1.5\times10^{18}$ m^{-3} and $Z_{eff} = 1$. If ions with $v_\parallel \sim 0$ are assumed to be first heated and then thermalization occurs between ions via collisions, T_i of NEAT cannot increase without better confinement of ions with $v_\parallel \sim 0$. Therefore, the observed spectra and the scattering time estimation suggest that ripple trapped ions are well confined in the HIT mode.

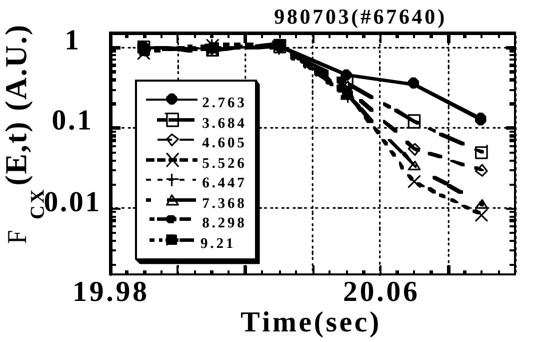

Fig.5. The decay process of F_{CX}(2.8 < E <9.2 keV) normalized at the value before the RF is turned off. The sampling time for the flux is 20 ms. and the RF is turned off at 20.04 sec.

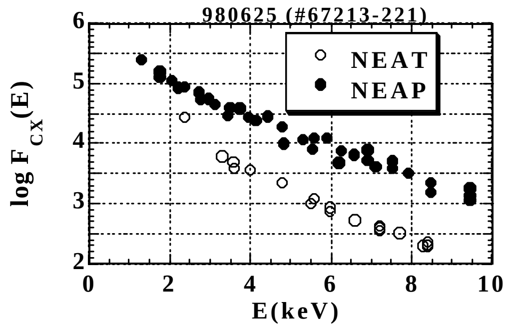

Fig.6. The typical energy spectra (NEAP and NEAT) in the HIT mode. The data are taken in several shots by changing the analyzer energy.

2.4. Ion heating and transport improvement

The HIT discharge is characterized by simultaneous achievement of ion heating and transport improvement. Although such mechanisms are not yet completely clear, related phenomena will be discussed in this subsection.

Since our experimental conditions are far from the mode conversion heating scenario and no edge ion heating due to parametric instabilities is observed, another heating mechanisms are examined. In slide-away and runaway regimes of the low density Ohmic plasma, perpendicular ion heating has been observed [8,9]. In Ref.[7,8] it has been pointed out that the energetic electrons drifting along the magnetic field lines can excite waves which can heat ions perpendicularly when the drift parameter $\xi = u_{drift}/v_{the}$ exceeds ξ_{crit}.(~ 0.2-0.4). In TRIAM-1M the mean value of ξ is evaluated to be 0.1-0.3 with assumptions of $u_{drift} \propto j / n_e$ and a parabolic current profile j(r). Thus it is qualitatively considered that the upper limit of the n_e window corresponds to a condition $\xi > \xi_c$. The electromagnetic wave emission at around 2.45 GHz is measured by a horn antenna and spectrum analyzer [10]. Particularly, it is observed that the amplitude of waves at ~ 2 GHz, which is considered to be the scattered waves by waves at ~ 400 MHz (~ a few times the ion plasma frequency), well correlates with T_i(t). As n_e is increased these waves disappear, which is consistent with the upper limit of the n_e window. We consider that one of the candidates for ion heating is due to waves excited by a distorted electron distribution function in full current drive plasma.

Two possibilities (j(r) and electric field effects) for improved ion transport are also examined. The horizontal hard X-ray profile measurement (T_{HX} and the number of photons N_{ph}) is used to deduce a change in j(r). It is observed that under some condition the peaking of N_{ph} occurs in the HIT mode in both configurations. Since I_{LHCD} is low, however, a simple estimation of the collisionless orbit shows that energetic ions with $v_{||}$ ~ 0 cannot be confined even when j(r) is peaked. In the limiter configuration it is also observed that the potential behind the limiter correlates well with the time variation of T_i(0). Thus we expect that one of candidates of mechanism for improved ripple ion confinement is an orbit squeezing effect due to the electric shear [11]. Preliminary orbit calculations show that protons with E=10 keV and $v_{||}$~0 can be confined using a model of a potential profile whose peak value is ~ -1keV and strong electric shear near the edge.

3. LONG SUSTAINMENT OF HIT DISCHARGE IN THE SN CONFIGURATION

As mentioned before, it is very important to demonstrate the sustainment of the HIT discharge in a steady state. Three kinds of control technique, controlling the desired configuration, minimizing the 'plasma-PFC (Plasma facing component) interaction', and keeping the HIT windows must be successfully operated for a long time.

3.1 Long duration discharge with high elongation factor k

Although it is well known that the plasma performance enhances with κ [12], such long duration discharges with higher κ have not yet been achieved (see Fig. 12 in Ref. [10]). One of the reasons is a difficulty in high-speed control against vertical position instabilities. In TRIAM-1M, although a discharge in the limiter configuration has been successfully sustained for more than 2 hours using hall effect sensors without drift problems of integrators [1], this control system is not enough in the SN configuration because the time response is too slow to suppress fast growing instabilities. The vertical position control system has been improved to aim at the long duration sustainment of the SN configuration. The magnetic coupling between the vertical and horizontal coils has been eliminated, high frequency noise from the Pulse Width Modulated invertor power supply for the horizontal field coils has been reduced with RC filters and the feedback parameters have been optimized by taking into account the delay due to the filter. As a result, the SN configuration with κ ~1.5 is achieved for 60 sec by 2.45 GHz LHCD only.

3.2. Minimizing the 'plasma - PFC' interaction

Through experiments for long sustainment of limiter HIT discharges it has become clear that minimizing 'plasma - limiter' interaction is also important in addition to adjusting ΔR within the HIT window. Since high energy electrons can still hit the limiter even in the SN configuration, this is important. A TV image processing circuit is developed to control the plasma - limiter interaction [1]. In Fig. 7 well controlled and failure cases are shown. In addition to the spectroscopic evaluation of Mo I (a measure of the Mo atom influx from the limiter), the energy loaded on each component(launcher, limiter, divertor plate, vacuum chamber) has been estimated by the temperature rise of cooling water [10]. The histogram of energy distribution is shown in Fig. 8. Thus it can be expected that the SN configuration is suitable to minimize the 'plasma - PFC' interaction for long HIT sustainment.

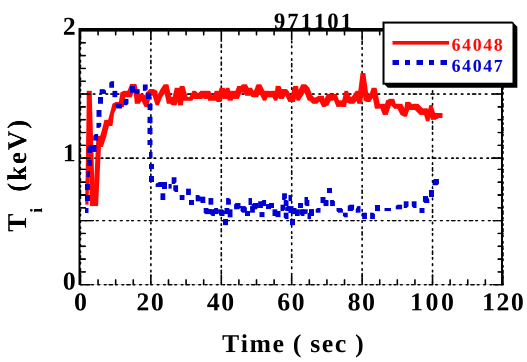

Fig.7. Example of well controlled HIT discharge (#64048) and failure case(#64047). The limiter temperature reaches ~ 54 °C in the latter case, but ~ 21 °C in the former case.

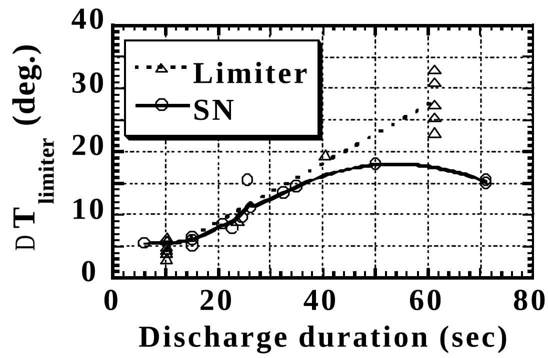

Fig.8. The fraction of energy loaded on launcher, limiter, divertor plate, and vacuum chamber. Both configurations are compared. The increase in the launcher is due to an increase of the reflected power.

3.3. Steady operation of the SN HIT discharge

In the SN long duration experiments, various controls have been applied; that is, particle influx control to keep the n_e HIT window, shaping control to maintain the high κ, horizontal control to adjust ΔR within the HIT window, TV image method to minimize the limiter heat load are used in whole discharge duration. Figure 9 shows a typical discharge demonstrating that the SN HIT discharge can be successfully maintained for a long time. The first transition occurs in the limiter configuration (t < 5 sec) and then after mild transition at t~ 15 sec, T_i gradually increases for ~ 40 sec. Although the higher T_i is achieved in SN HIT discharges compared with the limiter HIT discharge, the HIT-LIT transition cannot be avoided. The reason why this transition occurs is not clear, but, the fastest event compared with the transition is the sudden n_e change (reduction or increase). Enhancement of Mo influx and current reduction delay by > 0.3 sec. Furthermore, once the plasma current started to decay after the transition, final ' current disruption' could not to be avoided. Thus the solution of mechanisms for HIT-LIT transition and establishment of a method to avoid it are left in the future.

Different ramp-up schemes of T_i with various time scales are tried to find out the best way for the SN HIT discharge. Within conditions of these experiments it is also found that there seems to be a limit for ∇T_i. That is, the total HIT mode duration seems to depend on ∇T_i. This aspect is demonstrated in Fig. 10, in which the attainable ∇T_i in several discharges is plotted as a function of the sustained duration. In conclusion the duration at high ∇T_i is independent of the ramp-up scheme of T_i evolution.

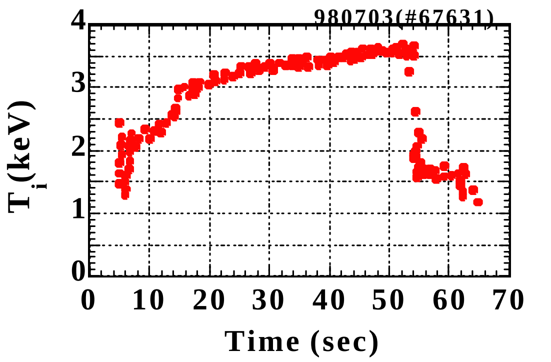

Fig.9.A typical discharge demonstrating that the SN HIT discharge can be successfully sustained for a long time.

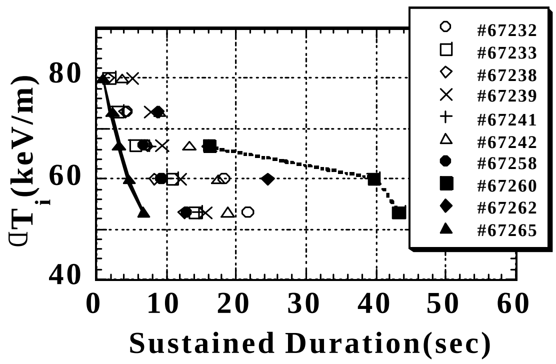

Fig.10. A relation between attainable ∇T_i and its sustained duration. Solid line denotes the case of rapid ramp-up, and dotted the case of slow ramp-up.

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