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Density Limit in Discharges with High Internal Inductance on JT-60U

H. Yamada et al.

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H.Yamada 1,2), H.Takenaga 3), T.Suzuki 3), T.Fujita 3), T.Takizuka 3), Y.Kamada 3), N.Asakura 3), T.Tuda 3), M.Takechi 3), G.Matsunaga 3), Y.Miura 3)

1) National Institute for Fusion Science, Toki, Gifu-ken, 509-5292 Japan
2) The Graduate University for Advanced Studies, SOKENDAI, Kanagawa-ken 240-0193, Japan
3) Japan Atomic Energy Agency, Naka, Ibaraki-ken, 311-0193 Japan

email address of main author: hyamada@LHD.nifs.ac.jp

Abstract. High densities exceeding the Greenwald limit by a factor of 1.7 have been obtained in discharges with high internal inductances of ℓ_i as high as 2.8 in JT-60U. The internal inductance is controlled by ramping down the plasma current. In addition to the extension of the operational regime limited by disruptions, confinement performance remains as good as an H89PL factor of 1.5 beyond the Greenwald limit. While the earlier work of a high ℓ_i study has indicated that core confinement improvement due to enhancement of the poloidal field, the additional improvement of the tolerance against the high density is turned out to be correlated with high edge temperature. The normalized density when the detachment characterized by the decrease in a Dα signal at the divertor occurs is even higher in the case with no disruption compared with the case with a disruption. These comparisons have indicated that the improvement in thermal and particle transport does exist in the periphery and the edge in the high ℓ_i plasmas, and mitigation of the density limit is observed coincidently. Although the high ℓ_i discharge studied here lies outside of the usual parameter space for a steady-state operation of tokamak, demonstration of a stable discharge with good confinement beyond the Greenwald limit suggest the magnetic shear at the edge is one key parameter to uncover its physical element.

1. Introduction

Density limit of magnetically confined plasmas is a critical issue from the aspect of development of a scenario towards attractive reactors as well as the aspect of equilibrium limit of a dynamical system. Many experimental works have been dedicated to this issue and consequently empirical understandings have progressed [1]. In particular, Greenwald limit which scales only with the product of plasma current density and elongation [2] has been widely accepted as a reference of operational density limit in tokamaks. Nonetheless, this phenomenological characteristic is quite empirical and underlying physics of Greenwald limit remains an open question. In addition to the operational density limit determined by occurrence of disruptions or MARFE [3,4], it has been widely recognized that the performance of plasma confinement degrades below the operational density limit. Physics models to describe the core plasma have progressed and simulations based on these advanced models are becoming sufficiently reliable to predict the future device like ITER. However, the modeling of edge plasma which provides the boundary condition in the above mentioned simulations is behind with accountability. It is an acceptable argument that the edge density rather than the core density plays a deterministic role in the density limit. For example, many reports have shown that the peaked density profile in discharges with pellet injection or efficient edge pumping allow the higher averaged density operation. Mechanisms leading to edge cooling are often discussed in theoretical approaches to clarify the density limit

In contrast to tokamaks, the operational density regime in helical systems is not limited by disruption but radiation collapse [5-7]. Therefore power balance and transport play more essential role in the density limit than in tokamaks. However, tokamak and helical systems have a wide range of commonality as the same toroidal system and also the role of plasma currents is supposed to be of much less importance in the edge region because the current itself as well as current gradient is tiny there. A recent study in LHD suggests that the density where the electron temperature falls down to 100 eV is an index of the density limit [8]. Therefore, if the confinement (or stability) improvement leading to the higher temperature is realized, the density limit in tokamak may be improved as well, in particular, in L mode where the MHD stability limit is less deterministic role to characterize the edge plasma parameter than in H mode.

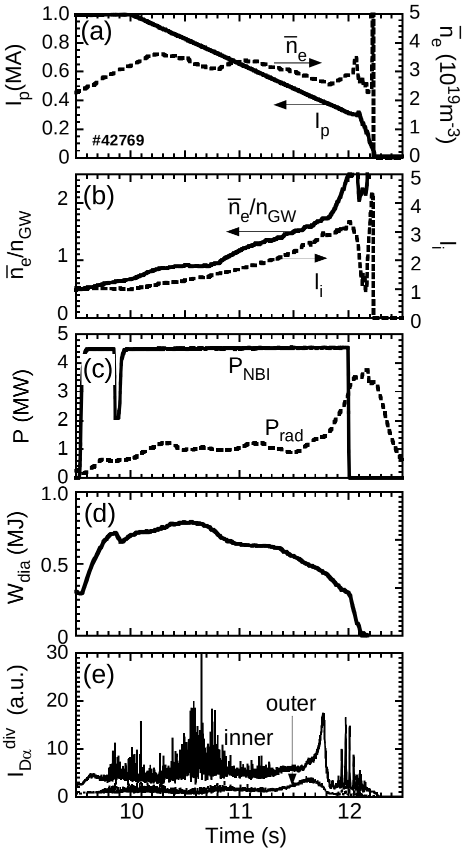

FIG.1 Discharge with monotonic current ramp down. (a) Plasma current and density. (b) normalized density and internal inductance ℓ_i. (c) Heating and core radiation power. (d) Stored energy. (e) $D\alpha$ signal at divertor.

In this study, we pay attention to the high ℓ_i discharges. An earlier work has indicated confinement is improved by increase in ℓ_i [9] and its mechanism is attributed to the large poloidal flux or field in the core region. These studies, however, have not explored the density limit and the effect on edge plasmas. The high ℓ_i plasmas are generated transiently by the current ramp down and the magnetic shear at the edge region is strengthened simultaneously.

The magnetic shear can stabilized pressure driven modes both in tokamaks and helical systems and also consequent confinement improvement is anticipated. Since it can be postulated that density limit is attributed to the stability itself or instabilities driving transport in the peripheral region, magnetic shear is supposed to be another potential parameter for density limit.

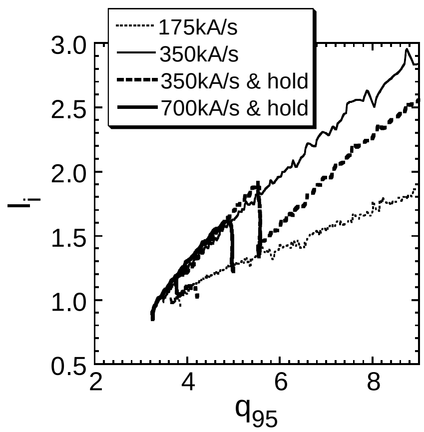

FIG.2 Discharge trajectories on q_{95} and ℓ_i

2. Current Ramp-down Experiment in JT-60U

With making use of the later phase of discharges in JT-60U, ℓ_i and the magnetic shear have been controlled by changing the current ramp down rate (0.175MA/s - 0.75MA/s) from the flat top (I_p=1MA). Region of incidence of disruption have been surveyed together with simultaneous density control. The major and minor radii are 3.4 m and 0.85 m, respectively. The magnetic field ranges between 1.7 and 3.6 T. The change of magnetic field is supposed not to make a difference since the Greenwald density does not depend on the magnetic field. It should be noted that the plasmas studied here is L mode.

Figure 1 shows waveforms of a typical discharge (E042769). Plasma current has been ramped down from 1MA with the rate of 0.35MA/s. Magnetic field and deposited NBI heating power are 2.1 T and 3.5 MW, respectively. During the ramp down phase, the density has been controlled by feedback control. Plasma discharge has been declined to disruption from 11.8 s. In this study, the time of disruption is defined as the start of thermal quench. Nonetheless the plasma does not disrupt even in $n_e > n_{GW}$, where $n_{GW} = I_p / \pi a^2$, and the density measured by tangential CO_2 laser interferometer has reached 1.73 times Greenwald density at t = 11.75 s. At this time confinement performance is as good as H_{89PL} and HH_{y2} factors of 1.5 and 0.99, respectively. These parameters have never been obtained in flat top phase in JT-60U. Internal inductance ℓ_i has reached 2.84, which suggests peaked current profile with enhanced magnetic shear. The plasma eventually disrupts at I_p of 380 kA. Prior to thermal quench, contrasting behavior is observed in the outer and inner divertor Dα signals. Before the drop of the Dα signal on the both side which indicates the detachment in the edge region, the outer signal starts to increase while the inner signal starts to decrease.

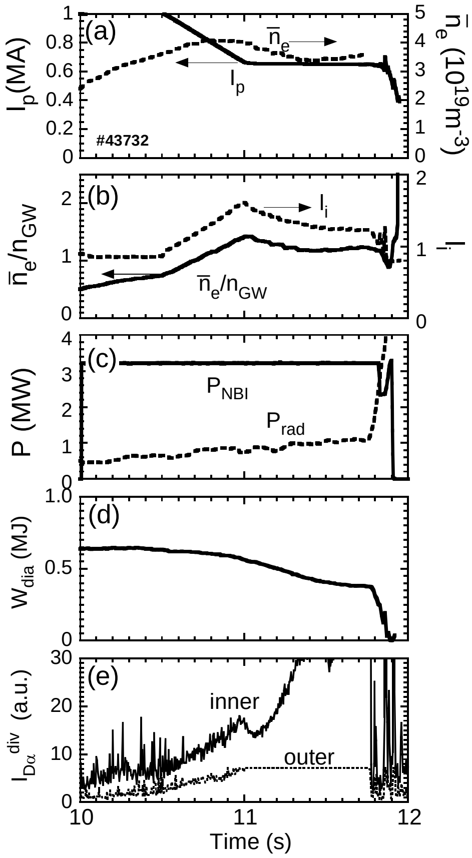

FIG.3 Discharge with current ramp down and subsequent pose. (a) Plasma current and density. (b) normalized density and internal inductance ℓ_i. (c) Heating and core radiation power. (d) Stored energy. (e) Dα signal at divertor. Outer signal is saturated from t=11 s.

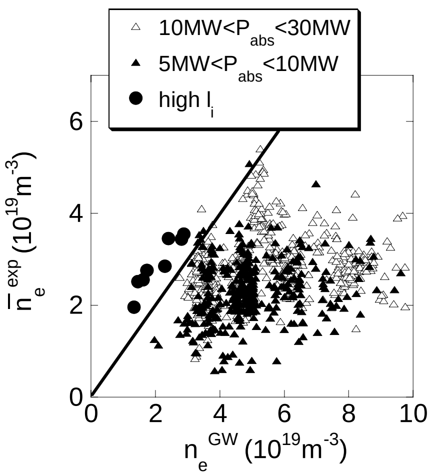

FIG.4 Comparison of experimental density and prediction from scaling of the Greenwald density.

In a scheme of monotonic current ramp down, magnetic shear and q have colinearity as shown in Fig.2. In order to separate these two factors, the current ramp down has been posed at I_p = 0.65 MA and the phase with decreasing magnetic shear at the constant q has been investigated. Figure 3 shows waveforms of a typical discharge of this operation (E043732). The ℓ_i increases in the current ramp down phase and the density exceeds the Greenwald density. Then the ℓ_i starts to decrease in the constant current phase. During the current sustainment at I_p=0.65 MA, disruption has occurred at the even lower normalized density (t=11.8 s). At the pose of the current t=11.0 s, normalized density and ℓ_i are 1.41

and 1.60 while they are 1.23 and 1.22 at t=11.75 s; 0.05s before the disruption, respectively.

Discharges with different ramp down rate and with/without pose have been devoted to this kind of experimental sequence. Figure 4 shows the operational density as a function of the Greenwald density. The envelope of the operational density can be described by the Greenwald density for regular discharges in JT-60U and does not depend on heating power. However, the high ℓ_i discharges studied here clearly exceed the Greenwald density and provide a new operational regime. The single point well beyond the Greenwald density shown by triangle is the reversed shear discharge with the density ITB. The edge density is suppressed to 40 % of the Greenwald density in this case [11].

As seen in two discharges illustrated in Fig.1 and 3, the plasma with high ℓ_i does not exhibit disruption in the high density regime which is not accessible in a regular operation. Figure 5 shows the discharge trajectory on the plane of the internal inductance ℓ_i which is a reference of strength of magnetic shear as well and the density normalized by Greenwald density. Circles indicate occurrence of disruption. The trend that higher density can be obtained with larger ℓ_i, i.e., stronger magnetic shear can be seen. It is important that this extension of operational density is accompanied by the confinement improvement. Figure 6 shows confinement enhancement factor on the L mode scaling as a function of ℓ_i. This observation is consistent with the earlier study on high ℓ_i discharges [8] even though the density regime is extended even beyond the Greenwald limit.

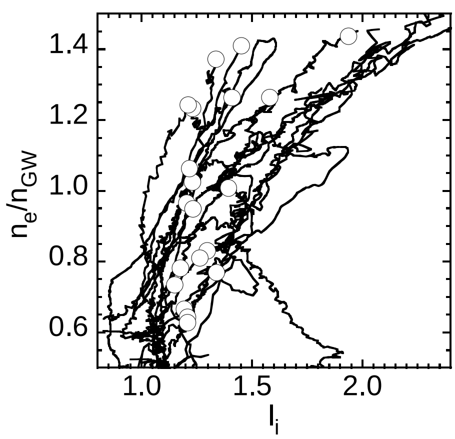

FIG.5 Discharge trajectories on ℓ_i and normalized density. Solid circles represent occurrence of disruption.

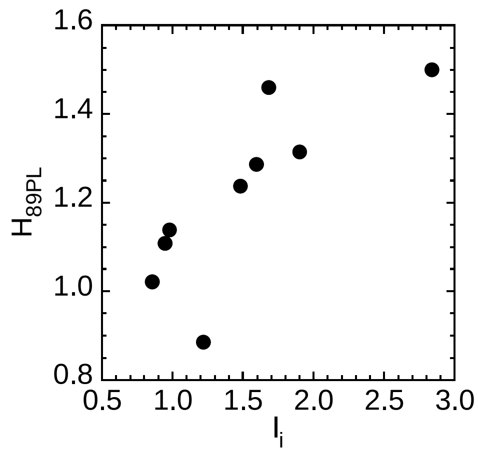

FIG.6 Enhancement factor of energy confinement on the L-mode scaling as function of ℓ_i.

3. Characterization of High Internal Inductance Discharges

A slight increase of density with similar condition (except for magnetic field, B=2.5T) to the discharge (E042769) illustrated in Fig.1 has resulted in disruption at I_p of 530 kA in the earlier phase of current ramp down (E042780). Figure 7 (a) and (b) show the electron density and temperature profiles in these two discharges. The time slice in the case with earlier disruption is 0.1 s before the start of the thermal quench, when the plasma current is 553 kA. The compared profile in the discharge with later disruption (E042769) is taken at the time with the same the surface q as in E042780. Since the magnetic field is different (2.1T), the plasma current is 483 kA. Also q profile derived from the MSE measurement 0.1 s before the disruption of the discharge with the higher density (E042780) and at the time with the same surface q value in the discharge shown in Fig.1 ; t =11.5s (E042769). The derived magnetic shear $r/q \cdot dq/dr$ is also plotted. Normalized density of the case with later disruption is even higher than the case with earlier disruption. It should be also noted that the case of earlier disruption reaches the density limit while the case of later disruption could have still margin to the density limit. The temperature is higher in the case with later disruption than the case with earlier disruption. The case with earlier disruption has lower ℓ_i (1.94 from the equilibrium calculation and 1.81 from the MSE measurement) than the case with later disruption (2.28 and 1.99 from each evaluation). Although the surface q values are the same, the q profile in the case with later disruption is located below that in the case with earlier disruption, which leads to enhanced magnetic shear in the edge. This comparison suggests the enhanced magnetic shear is effect on confinement improvement and that consequent higher temperature mitigates density limit. The density normalized the Greenwald density when the detachment characterized by the decrease in Dα signal at the divertor occurs is higher in the case with later disruption compared with the case with earlier disruption.

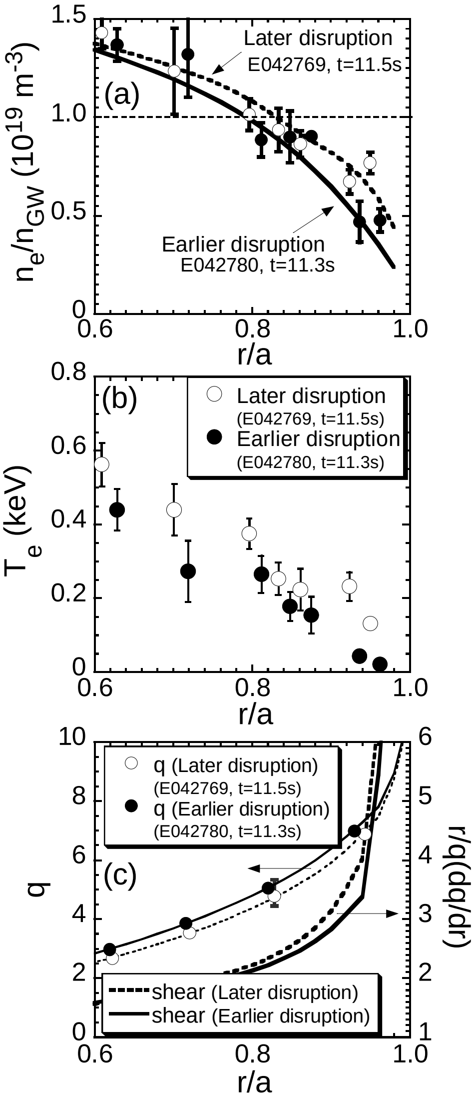

FIG.7 (a) Normalized density profiles and (b) q and magnetic shear profile derived from MSE measurement in current ramp-down phase of two discharges earlier/later disruptions.

In the discharge with a disruption, the m/n=2/1 mode with a frequency of 2 kHz was observed in the magnetic probe signals during the thermal quench phase. This frequency is consistent with the toroidal rotation velocity near the q=2 surface. This result indicates that the disruption was triggered by a tearing mode and thus the plasma current profile can affect the density limit. The stability analysis of a tearing mode suggests that the observed difference in q profile does not make a significant difference. These MHD modes do not appear before the thermal quench, therefore, they are not the cause but the consequence of the present density limit.

The next is the comparison of the different time slices in the discharge illustrated in Fig.3. This comparison pronounces the effect of the magnetic shear since the plasma current is kept constant. Figure 8 shows the electron density, electron temperature, q and the magnetic shear profiles at the end of current ramp down (t=11.0 s) which gives the maximum ℓ_i and at the time 0.05 s prior to the thermal quench (t=11.75 s). The normalized density by the Greenwald density at each time slice is 1.41 at t=11.0 s and 1.23 at t=11.75s, respectively. During this time frame, ℓ_i decreases from 1.60 to 1.22, which are evaluated by the equilibrium. The estimate from the MSE measurement also indicates the decrease from 1.80 to 1.56. At t=11.0 s, even the density in the peripheral region is even higher than at t=11.75 (see Fig.8(a)). The temperature decrease is pronounced in the edge region (see Fig.8(b)). The radiation power increases from 0.75 MW to 1.05 MW, however, this increase is not significant compared with the NBI heating power of 3.2 MW. Corresponding to the difference in ℓ_i, the MSE measurement indicates that the magnetic shear is stronger at t = 11.0 s than at t = 11.75 s while the surface q is the same because of the same plasma current.

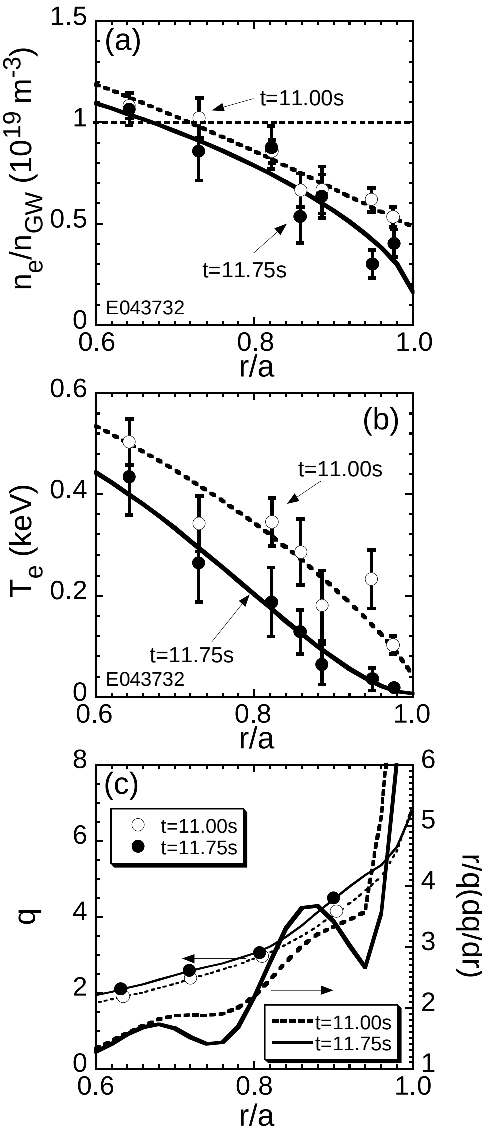

FIG.8 (a) Normalized density profiles and (b) q and magnetic shear profile derived from MSE measurement in current constant phase after the current ramp down shown in FIG.3.

4. Effect of Heating Power on Density Limit

Major parametric studies on the effect of heating power on the density limit suggest that the density limit does not depend on or is not sensitive to the heating power [10]. Nonetheless, the present study suggests the improvement of the edge electron temperature in high ℓ_i discharges and motivates the effect of heating power on the edge temperature in these discharges. Two discharges with the different heating power are compared. In both discharges, the plasma current was ramped down from 1 MA to 0.65 MA with the rate of 0.7 MA/s. Waveforms are illustrated in Fig.9 (a) and (b). In the case of lower heating power (P_{NBI}=4 MW, E046767), disruption occurred at the density of 0.77n_{GW} with ℓ_i of 1.3 just before the end of I_p ramp down. In contrast, the discharge with larger heating power (P_{NBI}=10MW, E046768) survived for about 1 s after the end of I_p ramp down and disrupted at 1.0 n_{GW} with ℓ_i of 1.4 during the constant I_p phase of 0.65 MA. The reason why the disruption occurred in relatively low density regime can be attributed to unfavorable wall condition in these experimental sequences.

Although main plasma radiation is larger for the case with higher heating power that the case with lower heating power, the edge electron temperature at r/a =0.94 is kept higher in the case with higher heating power. It is pointed out that the edge electron temperature at the disruption is the same as in both discharges. It should be noted that ℓ_i is almost the same for these two discharges. This suggests the important element of the density limit is the edge temperature rather than ℓ_i itself. These results support the hypothesis that large magnetic shear due to high ℓ_i provides confinement improvement and consequent high edge temperature mitigates the density limit.

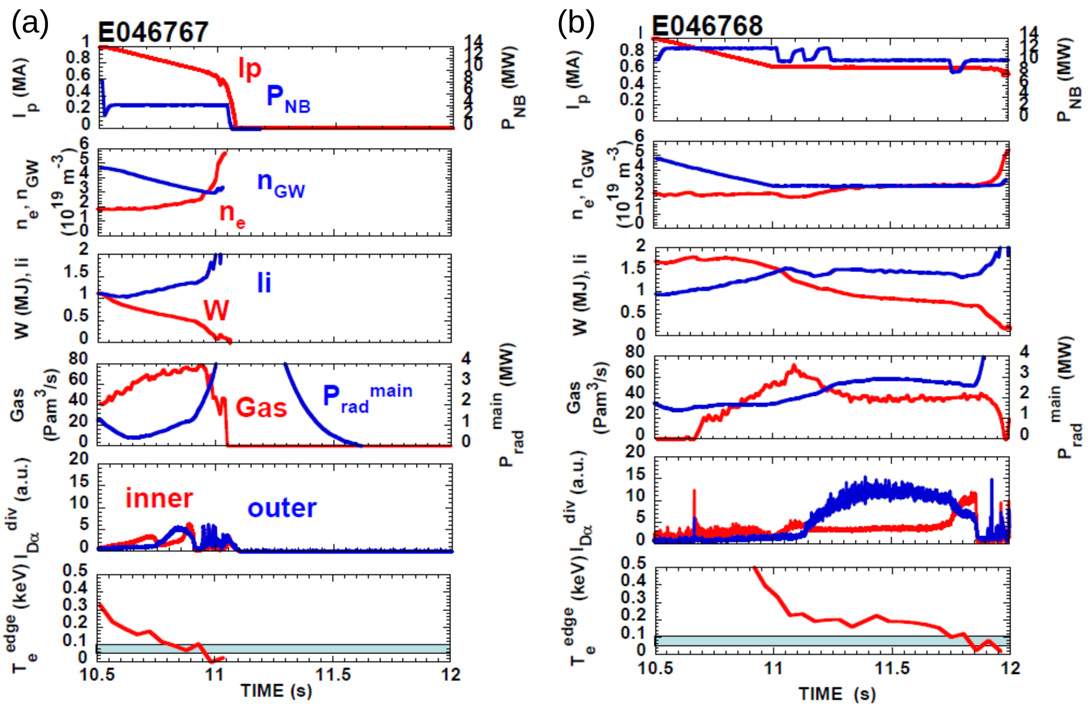

Fig.9 Waveforms of current ramp down discharge with the lower NBI heating power of (a) 4MW (E046767) and (b) 10 MW (E046768). From the top tot the bottom, plasma current and NBI heating power, line averaged density and the Greenwald density, stored energy and internal inductance, gas flow rate and radiation power in the main chamber, divertor Da signal, and the edge electron temperature are illustrated.

5. Summary

Plasmas with high internal inductance ℓ_i have been investigated in terms of the density limit on JT-60U. During the current ramp down, it has been found that the density limit with respect the Greenwald limit is significantly mitigated. In addition to the extension of the operational regime limited by disruptions, confinement performance remains as good as an H89PL factor of 1.5 beyond the Greenwald limit. While the earlier work of a high study has indicated that core confinement improvement due to enhancement of the poloidal field, the additional improvement of the tolerance against the high density is turned out to be correlated with high edge temperature. Although the high discharge studied here lies outside of the usual parameter space for a steady-state operation of tokamak, demonstration of a stable discharge with good confinement beyond the Greenwald limit suggest the magnetic shear at the edge is one key parameter to uncover its physical element.

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