FORMATION CONDITION OF INTERNAL TRANSPORT BARRIER IN JT-60U PLASMAS

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Abstract

Onset condition of Internal Transport Barrier (ITB) in reversed shear discharges was investigated. Local values of electron density, electron temperature, and ion temperature seem not to be essential for the ITB onset. Remarkable correlation between electron temperature gradient and magnetic shear was observed at the onset. In addition, ITB well outside the q-minimum position was found. Its onset condition seems to be continuous with that observed in negative shear region.

1. INTRODUCTION

Background and purpose of this study are as follows. Internal Transport Barrier (ITB) in reversed shear discharges in JT-60U has the following features. First, thermal diffusivities of electrons and ions (χ_e and χ_i, respectively) are reduced at ITB [1], which appears as steep gradients of ion and electron temperature profiles ($T_i(r)$ and $T_e(r)$, respectively). Second, the radius of ITB (r_{ITB}) reached 70% of minor radius (i.e. normalized radius ρ_{ITB}=0.7) [2]. The wide improved confinement region leads to good confinement. These characteristics are useful in burning plasmas. However, in most cases, ITB radius is limited by a radius where local safety factor q takes its minimum (ρ_{min}) [2]. The reason for this is not elucidated yet.

The final goal of this study is to develop method of active ITB position control. As a first step, condition of ITB onset in reversed shear discharges was investigated and the results are discussed in section 2.

The limitation mechanism of ρ_{ITB} by ρ_{min} should be made clear from the viewpoint of further improved confinement and MHD stability. In relation to this subject, we found a phenomena where ITB suddenly appears in the outside of ρ_{min}. This phenomena is dealt with in section 3 and its onset condition is compared with that obtained for reversed shear case in section 4.

2. ONSET CONDITION OF ITB FORMATION IN REVERSED SHEAR DISCHARGES

The ITB onset was analyzed as in the following. Reversed shear configuration was produced using early neutral beam injection in the initial current ramp (Fig. 1(c)). Discharge parameters are : hydrogen plasma, plasma current of I_p=1.2 MA, toroidal magnetic field of B_t=3.5 T, major and minor radii of R=3.4 m and a=0.8 m, respectively, safety factor at 95% of the enclosed poloidal flux of q_{95}=4.9 and plasma volume of V_p=62 m^3. Figure 1(b) shows an evolution of T_e at normalized minor radius of ρ=0.1 to 0.45 and profiles at t=6.4 s and 5.98 s are shown in Fig. 1(a). Structure of steep ∇T_e is recognized at ρ=0.4-0.45. The steep ∇T_e corresponds to the shaded region in Fig. 1(b) and it started to increase at t=5.98 s. So we define ITB onset at ρ=0.4 at t=5.98 s. In the analyzed data set, similar evolutions are observed in T_i and electron density (n_e) as well.

We carried out systematic scans of beam power (P_{NB}) and n_e. Plasma configuration was fixed (Fig. 2). Lines in the figure are trajectories of perpendicular beams (Perp.) and parallel beams (Para.). Parallel beams of 5.1 MW was injected with balanced momentum input to all discharges.

Figure 3 shows n_e-scan case. Density was controlled by changing the gas fueling rate before the main heating ($t \leq 5$ s shown with a shaded region in Fig. 3(c)). Figure 3(b) shows traces of line-averaged electron density ($\bar{n}_e$) . According to the different target density ($\bar{n}_e$ at t=5 s), ITB onset time changed (Fig. 3(a)) Shown in Fig. 4 is power-scan case. Beam power was scanned during current flattop phase with $\bar{n}_e$ fixed. Changes in plasma parameters at the onset were investigated using these systematic scans and results are discussed in the followings.

In Fig. 5(a), T_e at the ITB onset is plotted with closed circles as a function of local n_e at the onset. Crosses are data taken at 0.3 to 0.5 s before the onset. T_e varies from 1.4 keV to 2.4 keV and n_e varies in a range of $1.5\text{-}3.8 \times 10^{19}\,\mathrm{m}^{-3}$. However, there seems to be no sign of critical values on n_e nor T_e. Similar result is obtained on T_i as well (Fig. 5(b)). From these results, onset condition seems not to be a strong function of local n_e, T_e and T_i.

Next we investigated the correlation between ∇T_e and magnetic shear s ($\equiv$ (r/q)dq/dr). This is motivated by an observation of the following two discharges. Figure 6 shows T_e(r) and s(r) at the onset time (t=6.37 s), where onset position ρ=0.39 is characterized by small s and high ∇T_e (-7.2 keV/m). By contrast, the onset of the discharge at ρ=0.24 (Fig. 7) is characterized by high s (-0.7) and substantially lower ∇T_e than that in Fig. 6.

Based on this observation, we define ∇T_e just inside the region of ITB onset ($\equiv \nabla T_e^{in}$) as shown in Fig. 8(d) and investigated its correlation with s.

The ∇T_e^{in} is plotted as a function of s in Fig. 8(a). Closed circles are data of ITB onset, showing a remarkable correlation between them. It should be noted that this data set has various ITB radius from r_{ITB}=0.25 to 0.44 m (i.e. ρ=0.26-0.45) (Fig. 8(b)) and that no evident tendency of T_e on s is visible (Fig. 8(c)).

Based on this result, we made a working hypothesis that "∇T_e^{in} - s" relation triggers ITB formation. We speculate that outward moving ITB [3] is interpreted that the region which satisfies the condition moves outwards.

However there still remain some unclear points on this hypothesis. Crosses in Fig. 8(a) are data before the onset, and most of them move upwards in this diagram and then reach transition. However there are some exceptions. For example, a cross point at s~-0.55 stays above this line. This may be due to some missing factors to be included in this hypothesis.

3. ITB WELL OUTSIDE THE ρ_{min} REGION

In this section, sudden appearance of ITB well outside the ρ_{min} region is discussed. Figure 9 shows evolution of a discharge with $\rho_{ITB} > \rho_{min}$. Discharge parameters are : deuterium plasma, I_p =1.5 MA, B_t=3.8 T, R=3.3 m, a=0.8 m, q_{95}=4.6 and V_p=66 m^3. Plasma shape was almost the same as that shown in Fig. 2. Reversed shear configuration was produced in the same technique mentioned before (Fig. 9(a)). Electron temperature traces in the current flattop phase are shown in Fig. 9(b), the radial position of which is from ρ=0.35 to ρ=0.65. T_e profiles at t=5.8, 6.1 and 6.5 s are shown in Fig. 9(c). At t=5.8 s , a steep ∇T_e due to ITB formation was observed, the position of which was in the inside of ρ_{min}. After that T_e(r) was relaxing in time (Fig. 9(c)). ITB outside ρ_{min} suddenly appeared after that (a period with a shaded region in Fig. 9(b)). Evolution across the transition is shown in Fig. 10. Figure 10(a) shows an evolution of electron temperature at ρ=0.5 to ρ =0.65. A sudden increase in ∇T_e was produced first at t=6.55 s and it moved outwards in time. Similar change was observed as well as in T_i (Fig. 10(b)) and n_e (Fig. 10(c)). Please note that the increase of beam power was after the transition and it was constant across the transition (Fig. 10(d)).

Figure 11(a) shows evolution of T_e(r) across the onset. Open circles show T_e(r) just before the transition. Later a region of increased ∇T_e was produced around ρ~0.6 and moved outwards in time (see T_e(r) at t=6.66 and 6.75 s) . q profile was measured at t=6.72 s as shown in Fig. 11(b). It should be noted that the region of increased ∇T_e was well outside the ρ_{min}. Relationship between ITB region and q profile is shown using 2-dimensional plot (Fig. 11(c)). In this figure, evolution of inverse scale length of $T_e(r)$ ($1/L_{T_e} \equiv \nabla T_e/T_e$) is shown with gradation. The steeper gradient is shown with the much more white tone. The horizontal axis is radial direction based on the channel position of T_e measurement (tilted as guide by two lines, which is due to the change of MHD equilibrium inside the last closed flux surface) and time goes vertically downwards. The time window of Fig. 10(a) (t=6.5-6.75 s) is shown with a vertical arrow in this figure. ρ_{min} is shown with a broken line, which was interpolated from measurements at the beginning of current flattop (t=5.55 s) and just before the minor collapse (t=6.72 s) (Fig. 11(b)). From this figure, we conclude that ITB was produced at $\sim \rho_{min}$ and expanded outwards.

4. COMPARISON OF ONSET CONDITION OF $\rho_{ITB} > \rho_{min}$ WITH $\rho_{ITB} < \rho_{min}$ CASE

In section 2, condition of ITB onset for reversed shear discharges are investigated and a remarkable correlation between ∇T_e^{in} and s are found. In this section, condition of ITB onset in positive s region described in section 3 is compared with it from the viewpoint of extension of the criterion to s>0 region.

In Fig. 12, two data points (squares) from the discharge with $\rho_{ITB} > \rho_{min}$ are plotted on the " ∇T_e^{in} - s" diagram. These two data are from two different radial positions, ρ=0.52 and 0.6 : the data at s~0 is from the first transition at t=6.55 s and the other is from the later transition at t=6.61s.

As for the point near s=0, its direction of motion before the onset seems to be downward in the diagram and the reason for it should be examined later. However the tendency seems to be continuous with that for negative shear data.

This result shows that higher ∇T_e^{in} is required to trigger ITB in positive s region. This may be a hint to understand the observation that positive s throughout the plasma often leads to no clear χ_e reduction [4]. Furthermore, this result suggests that local electron heating by ECH is effective to trigger ITB.

5. SUMMARY

Onset condition of ITB in reversed shear discharges was investigated using systematic scans of n_e and P_{NB} .

Local n_e, T_e and T_i seem not to be essential for ITB onset. We found a remarkable correlation between ∇T_e^{in} and s. Based on the correlation, we made a working hypothesis that their combination gives onset condition of ITB.

ITB in the outside of ρ_{min} was observed. It first appeared near ρ_{min} and moved outwards. The onset condition is continuous with that obtained for negative shear region, suggesting that higher ∇T_e^{in} is required for ITB onset in s>0 region.

To date, the criterion is not a sufficient condition because direction of motion of some data is not regular. This may be due to some missing factors which are not fully addressed yet. Other parameter dependences such as I_p (or local poloidal magnetic field), ∇T_i and velocity shear should be investigated to obtain better onset criterion.

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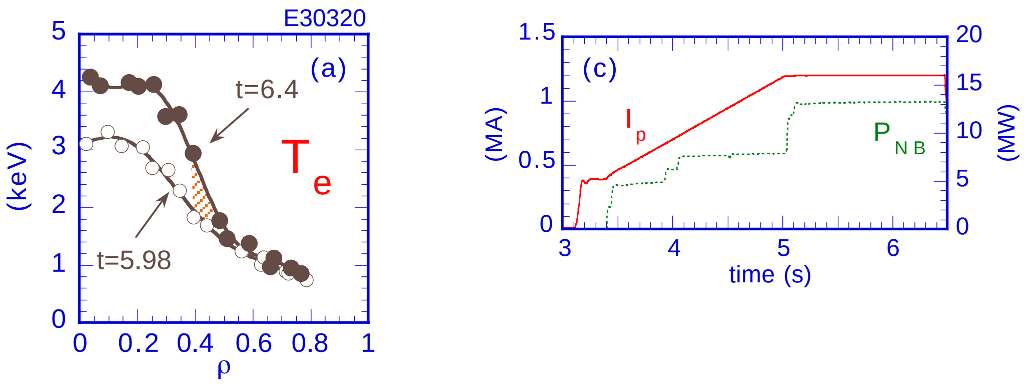


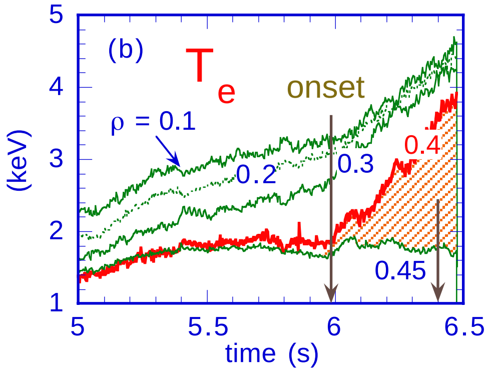


Fig. 1. Definition of ITB onset. In this figure, onset at $\rho=0.4$ is considered. (a) Electron temperature profile at the onset (t=5.98 s) and 0.4 s after the onset (t= 6.4 s). (b) Traces of electron temperature at $\rho=0.1$-0.45. (c) Waveform of plasma current and heating power of neutral beams.

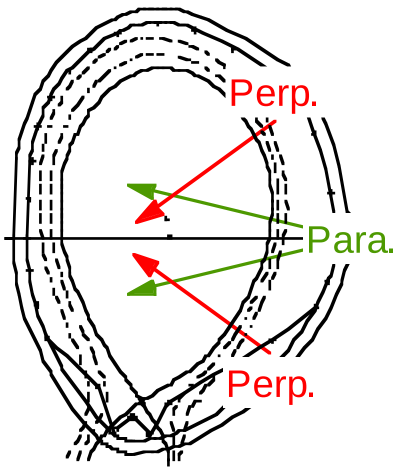
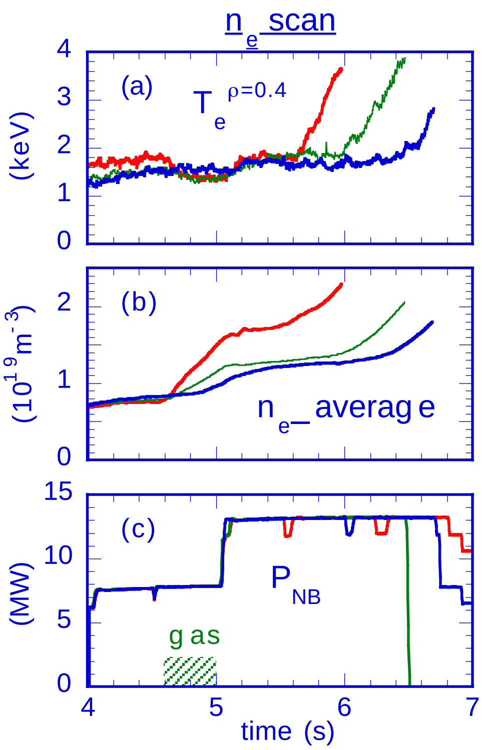


Fig. 2. Plasma shape used for the onset experiment. Arrows show trajectories of neutral beams (Perp. : perpendicular beams, Para. : parallel beams).



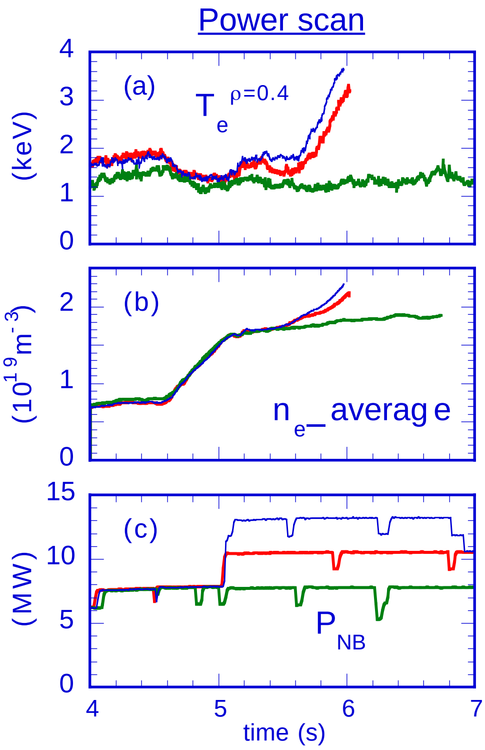


Fig. 3. Method of density scan. *Fig. 4. Method of power scan.*
(a) Response of electron temperature at $\rho = 0.4$*. (b) Line-averaged electron density. (c) Beam power.*

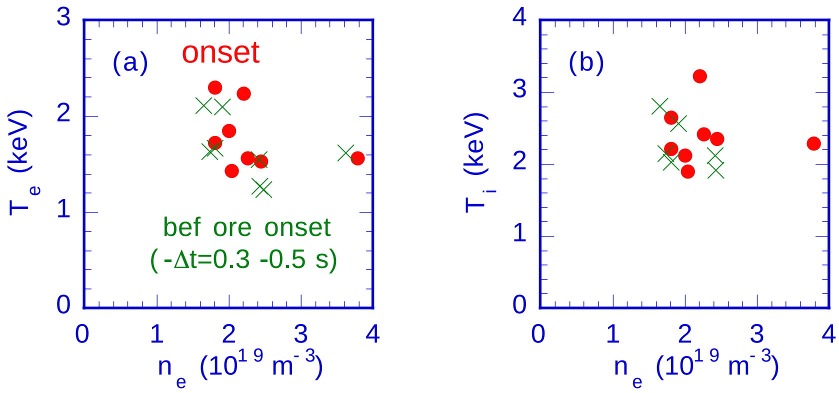


Fig. 5. Relationship between onset parameters. (a) Electron temperature vs electron density (b) Ion temperature vs electron density.

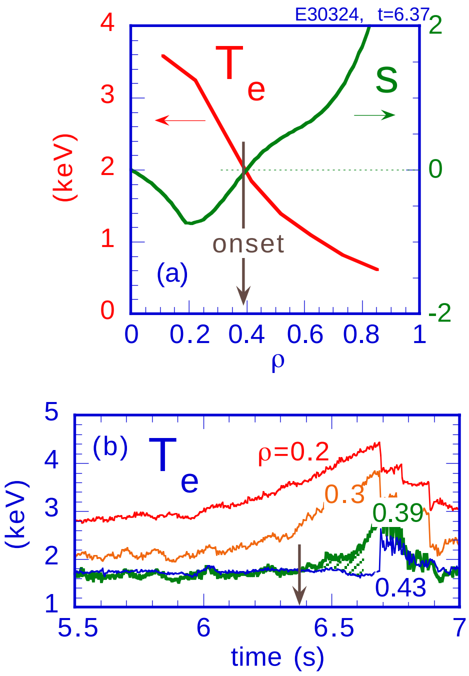


Fig. 6. Example of ITB onset , the region of which is characterized by low magnetic shear and high ∇T_e.

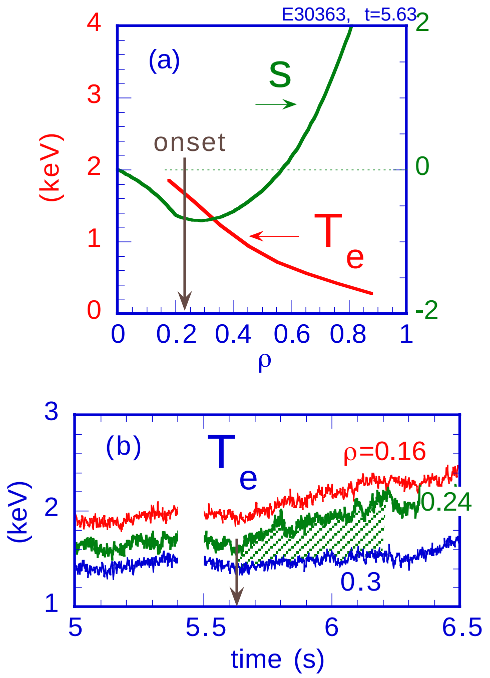
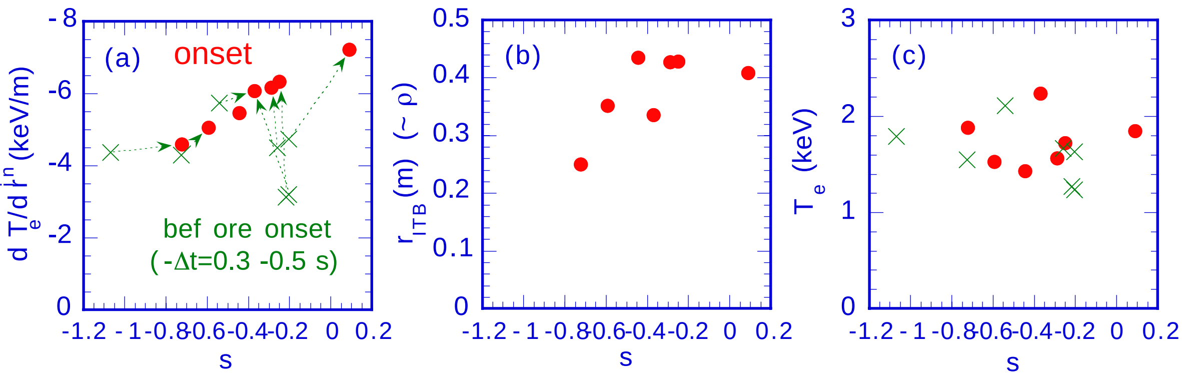


Fig. 7. Example of ITB onset , the region of which is characterized by high magnetic shear and low ∇T_e. Missing data during t=5.4-5.5 in (b) is due to calibration of ECE diagnostic .



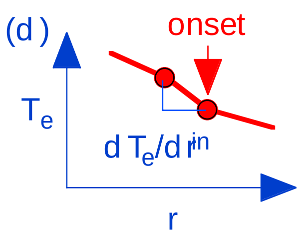


Fig. 8. (a) Correlation between ∇T_e^{in} and s at the onset (closed circles). Crosses are data 0.3-0.5 s before the onset. (b) r_{ITB} vs s. (c) T_e vs s. (d) Definition of ∇T_e^{in}.

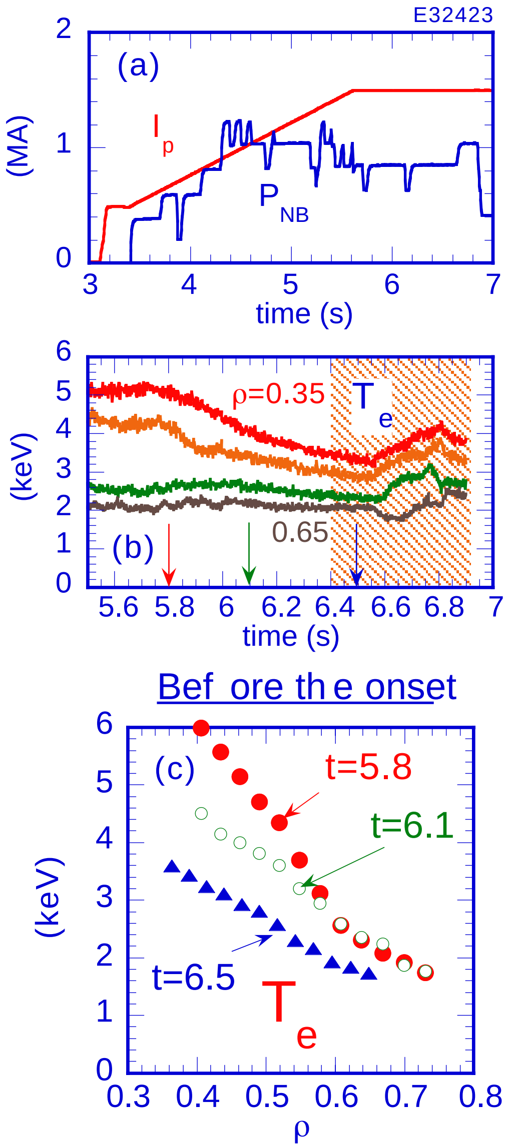


Fig. 9. Evolution of discharge with $\rho_{ITB} > \rho_{min}$. (a) Waveform of plasma current and beam power. (b) Traces of T_e at ρ =0.35-0.65. (c) $T_e(r)$ before the onset of $\rho_{ITB} > \rho_{min}$.

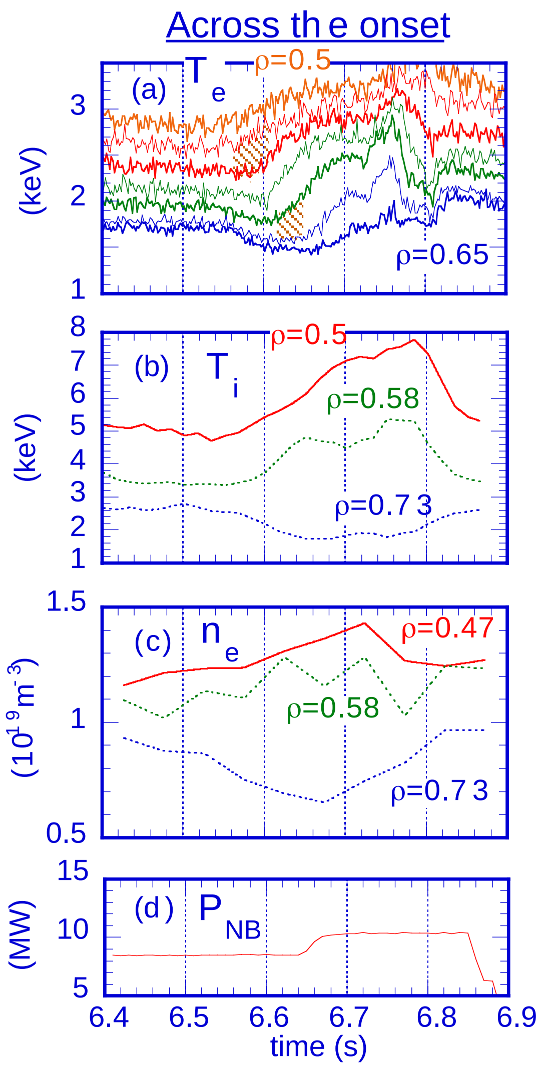


Fig. 10. Evolution across the ITB onset with $\rho_{ITB} > \rho_{min}$. (a) Evolution of T_e (b) Evolution of T_i. (c) Evolution of n_e. (d) Waveform of beam power.

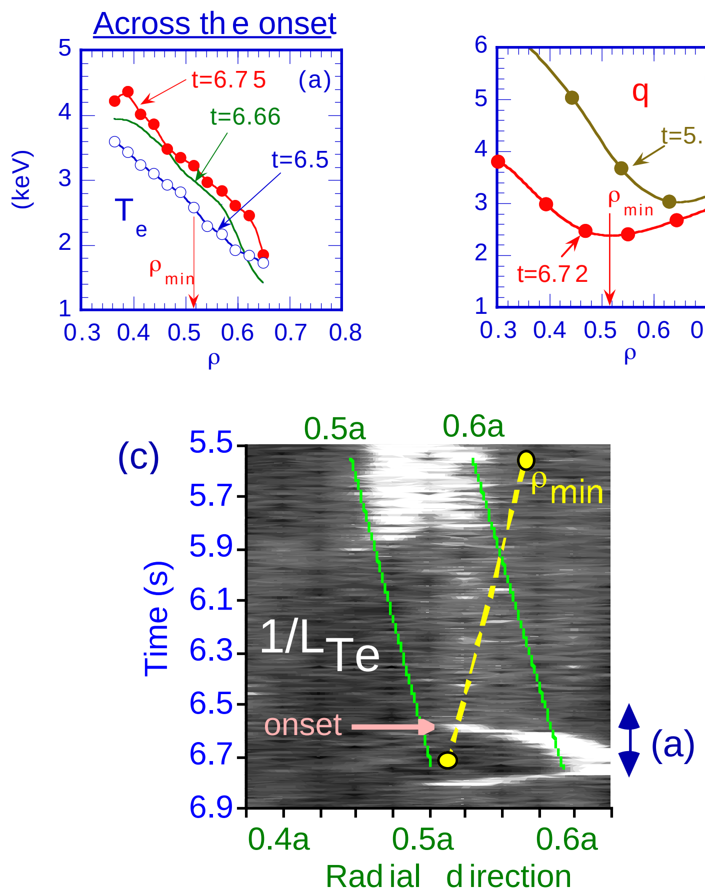


Fig. 11. Relationship between steep ∇T_e region and q profile. (a) $T_e(r)$ across the ITB onset with $\rho_{ITB} > \rho_{min}$. (b) Measured q(r). (c) Evolution of region with high $1/L_{T_e}$.

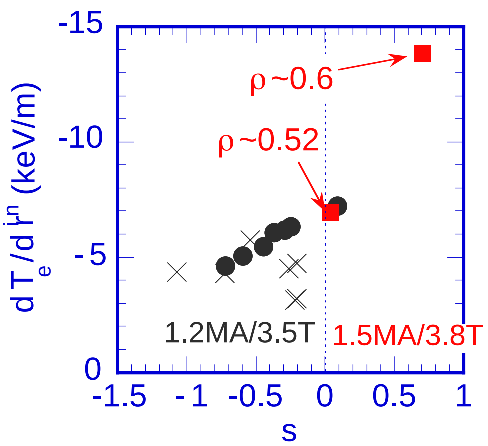


Fig. 12. Plot of onset condition of ITB with $\rho_{ITB} > \rho_{min}$ on "∇T_e^{in} - s" diagram (squares).