

Prediction of the Major Disruption in JT-60U Reversed Shear Plasmas

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1. Introduction

High performance has been obtained for reversed shear plasmas with Internal Transport Barrier, ITB, in many tokamaks[1-4]. However the intensively improved plasma performance is transient. When the minimum safety factor, q_{\min} , closely approached 2, the reversed shear discharges with L-mode confinement in the plasma peripheral region terminated with a fast beta collapse at $\beta_N \sim 2$ [5], where slow (~ 10 ms) and fast (~ 10 μ s) precursor oscillations were found for the electron temperature (measured by ECE grating polychromator) in the ITB region at the low field side. These observations were estimated from ERATO-J code as the β_N limit phenomena owing to low-n kink-ballooning modes[6]. Since discharge scenarios were optimized to raise the plasma stability (e.g. the feedback control of neutron emission rate), the highest plasma performance with the record of equivalent fusion multiplication factor $Q_{DT}^{eq} = 1.25$ was obtained[7]. Furthermore β_N of 2.3 was achieved with $q_{\min} = 1.5$ with generating H-mode in the plasma peripheral region [7].

In JT-60U the quasi-steady state with high plasma performance has been obtained with $q_{\min} \sim 2$ for reversed shear plasmas. The improvement of the plasma stability at $q_{\min} \sim 2$ is essential, which will be the same situation for reactor core plasmas. However hard disruptions frequently occur even for lower β_N than the ideal limit (see Fig.12 in ref.[8]). This paper investigates methods to reduce the possibility of disruptions at $q_{\min} \sim 2$, which is also beneficial to create algorithms for predicting major disruption for reversed shear plasmas.

2. Disruptions for Reversed Shear Plasmas

Reversed shear plasmas are generated by fast plasma current ramp-up with early NB injection. Disruptions are observed at the transient phase with the decrease in q_{eff} (effective safety factor at the divertor plasma surface) and q_{\min} . Here q_{95} is $\sim 0.72 \times q_{\text{eff}}$. In JT-60U $q_{\min} \sim 2$ can be assumed for plasmas obtained at $t \geq 3.5$ sec (a discharge starts from $t=0$ sec) with $q_{\text{eff}} < 6$.

The maximum of the local gradient of ion temperature in ITB, dT_i/dr , increases with the decrease in q_{eff} as shown in Fig.1(a), where -182 keV/m has been obtained for $q_{\text{eff}} = 4.4$ ($q_{95} = 3.2$, $q_{\min} \sim 2.0$). The ion temperature gradient is measured by CXRS just before the major disruption for NB heated plasmas with NB injection power of 5~25 MW. Since q_{\min} roughly has a linear relation with q_{eff} , Fig.1(a) suggests that dT_i/dr increases with the decrease in q_{\min} . For limited case of stable and disrupted discharges, where the current profile has

been estimated, the minimum dT_i/dr increases with the decrease in q_{min} . A typical case of ion temperature profile is shown in Fig.2 (a), with a definition of dT_i/dr . Figure 1 suggests the improvement of ITB with the increase in dT_i/dr , is obtained with the decrease in q_{min} .

The radial profile of the toroidal rotation, v_t , is complicated in JT-60U as shown in Fig.2 for a typical case, because counter rotation is generated in the plasma peripheral region due to the loss of high energy ions caused by the toroidal field ripple and the rotation profile can be modified by co/counter and on/off axis NB injectors[9]. Here the direction of rotation is compared with that of plasma current. The pressure gradient at ITB does the effect on the toroidal rotation through the diamagnetic effect, so the toroidal rotation shear is compared with dT_i/dr in the ITB with defining three regions as shown in Fig.2(b): #1 and #2 are inside and outside of the location of the minimum v_t , and #3 is in the plasma peripheral region (just outside of ITB). As shown in Fig.3, the v_t shear in region #1 has a linear relation with the amplitude of dT_i/dr , but that in #2 regions has no clear relation with dT_i/dr , which may be due to the momentum input from NBI and the formation of the radial electric field. The v_t shear in region #3 is nearly zero.

2. Toroidal rotation shear at $q_{min} \sim 2$

The toroidal rotation shear has a stabilizing effect for the tearing mode, so the toroidal rotation shear at $q_{min} \sim 2$ has been investigated. In the v_t profile, the radial location of a connection point from #2 to #3 (see Fig.2) is defined as r_x . The location of q_{min} , $\rho_{q_{min}}$, is compared with ρ_x (normalized r_x by the minor radius) as shown in Fig.4 for discharges with $q_{min} \sim 2$ and β_N lower than 1.9. For open circles, q_{min} decreases lower than 2 without hard disruptions. Closed circles show disrupted discharges when q_{min} approaches to 2. When ρ_x is larger than $\rho_{q_{min}}$ by 0.1 (or q_{min} locates in region #2 with a shear of $2 \sim 5 \times 10^5/s$), all discharges are stable. Hard disruptions are observed at $\rho_x - \rho_{q_{min}} = 0 \sim 0.05$, but this is within the error bar of the location of ρ_x and $\rho_{q_{min}}$.

A growth of electron temperature fluctuation with a time constant of ~ 1 ms is observed for disrupted discharges at $q_{min} \sim 2$ even for β_N lower than 2. The toroidal rotation shear with $2 \sim 5 \times 10^5/s$ and the poloidal rotation shear that can be assumed for region #2 may does the stabilize effect on some resistive MHD modes.

The v_t shear can be always observed at two locations of $q=2$ for stable steady-state discharges with q_{min} lower than 2 as shown in Fig.5. Even though the toroidal rotation speed at two $q=2$ layers is almost the same, no double tearing mode has been observed.

3. Discussion

The q_{min} gradually decreases with the increase in the pressure gradient in ITB, and it finally approaches 2 and decreases lower than 2. In the ITB region for reversed shear plasmas, an intrinsic positive feedback has a possibility to work as follows: [step-1] The reduction of the thermal diffusivity enhances the pressure gradient, [step-2] The local bootstrap current is

enhanced by the increase in the pressure gradient, [step-3] The decrease in q reduces further the thermal diffusivity, and then goes back to [step-1].

When this positive feedback loop exists, two control methods can be considered to avoid disruption: one is the stability control at $q=2$ (e.g. v_t shear control as shown in section 2), and the other one is the direct control of q_{\min} value by the externally applied current-drive. In JT-60U the reversed shear plasma with ITB was kept full-noninductively for $I_p=0.85$ MA and β_N of ~ 1.0 within ~ 5 sec by the 2.5 MW Lower Hybrid Current Drive[10], where q_{\min} was kept a little above 2. Since the pressure gradient in ITB has strong relation with q_{\min} as shown in Fig.1, an active counter current drive by ECCD in ITB should be tested to suppress the bootstrap current) with braking the intrinsic positive feedback.

4. Conclusions

Hard disruptions at $q_{\min}\sim 2$ and β_N lower than the ideal limit observed for reversed shear plasmas with Internal Transport Barrier has been investigated in JT-60U. Toroidal rotation shear at $q_{\min}=2$ or $q=2$ has been observed when hard disruptions are avoided.

References

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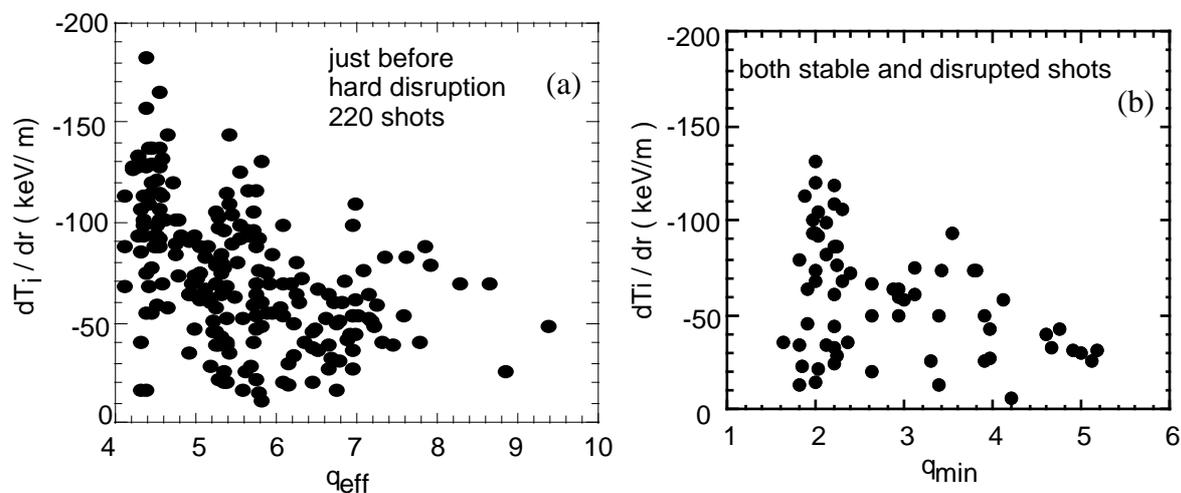


Fig.1(a) dT_i/dr at ITB versus q_{eff} ($q_{95}\sim 0.72q_{\text{eff}}$) for disrupted discharges. (b) dT_i/dr at ITB versus q_{\min} .

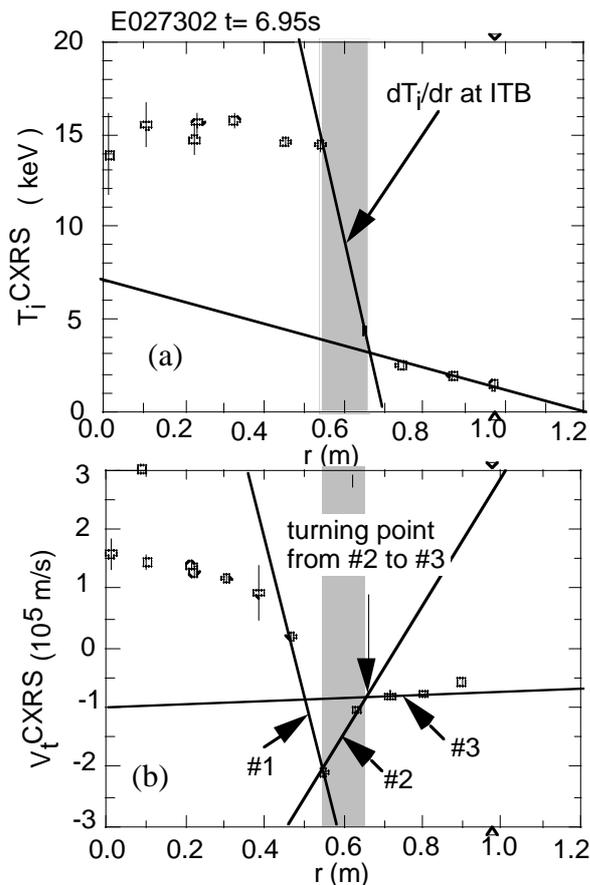


Fig.2 Radial profile of (a) T_i and (b) v_t . Rotation shears in regions #1~#3 are investigated. The location of the turning point from #2 to #3 is defined as r_x .

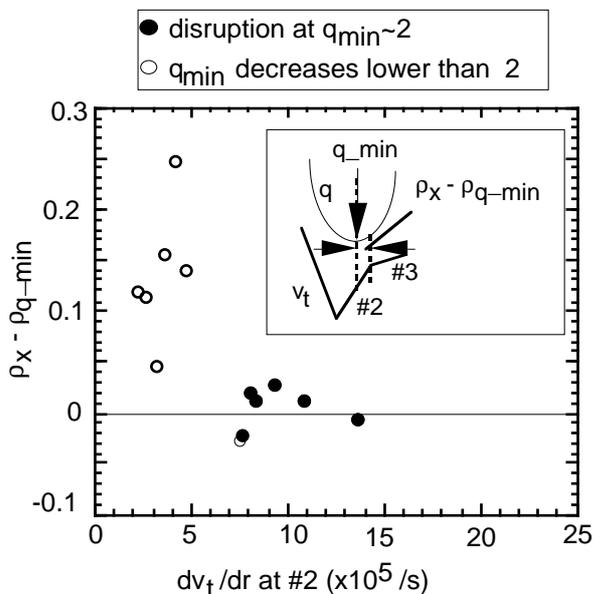


Fig.4 The location of the turning point of the toroidal rotation shear compared with that of q_{min} ($\rho_x - \rho_{q_{min}}$) versus v_t shear in #2 region for disrupted and stable discharge when q_{min} approaches 2. $\beta_N < 1.9$.

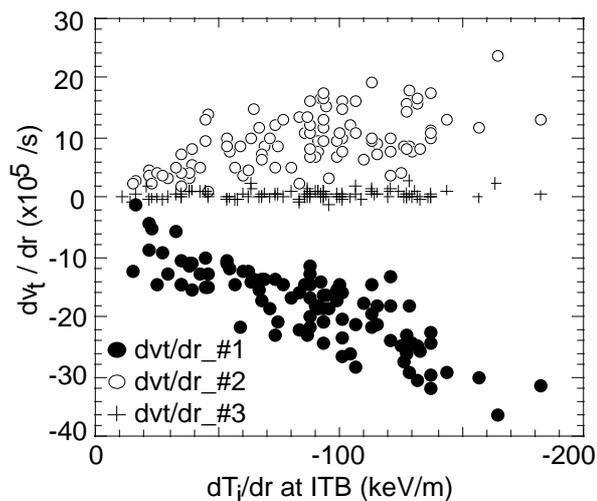


Fig.3 The relation between the toroidal rotation shear in regions #1~#3 and dT_i/dr at ITB.

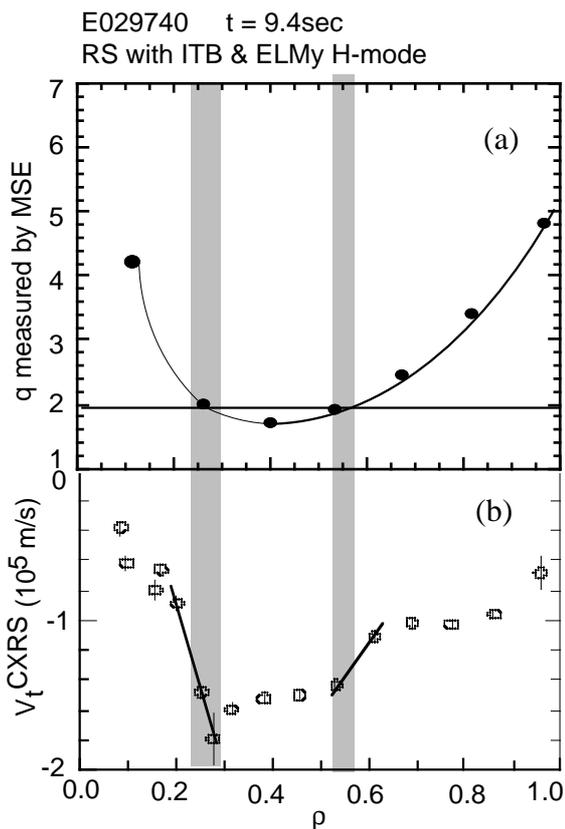


Fig.5 Profiles of (a) q and (b) v_t for a reversed shear plasma with $q_{min} < 2$.