MHD instabilities observed in extremely reversed shear discharges on JT-60U
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A reversed shear (RS) plasma is expected as a discharge of advanced scenario of ITER because it has good confinement and large bootstrap current fraction. It is understood that disruption at \( q_{\text{min}} \sim 2 \beta_n \sim 2 \) is caused by stability limit of \( n=1 \) ideal kink ballooning mode. However RS plasma with strong ITB disrupts frequently even at lower \( \beta_n \). By now, low beta disruption is explained by double tearing mode [1] or resistive interchange mode [2], and these are MHD instabilities at \( q_{\text{min}} \) and around ITB. However these cannot explain all of observed low beta disruption. Figure 1 shows two typical wave forms of these RS plasmas. The shot of E39387 (a red solid line in Fig. 1) reached to \( Q_{\text{br}} \sim 1 \), \( H_{\theta} \sim 3 \) and \( b_n=1.44 \) with \( B_t=4.05 \text{T} \) and \( I_p=2.56 \text{MA} \) just before disruption at \( t \sim 6.85 \text{s} \). Typically pressure gradient of these type of RS plasma is very large at \( r \sim 0.6 \) (ITB layer) and flat in the region around \( \rho < 0.5 \) (Fig. 2(a)). The current profile is characterized by the current hole and two peaks around the ITB layer and the peripheral region (Fig. 2 (b)). The current peak at peripheral region is formed by current ramping up for producing the RS profile because the
peripheral plasma current decrease after stopping current ramping up (Fig. 3). The case of the early disruption is also plotted in Fig 1. The shot of E39389 (a blue dotted line in Fig. 1) disrupted whether $b_n$, $b_p$ and also stored energy were decreasing and they are smaller than those of E39387 at same time. We mainly observed two type of disruptions. One is the disruption with $n = 1$ precursor of $1/\gamma > 100$ ms. The m/n=4/1 magnetic fluctuation starts at $t \sim 6.1s$ and grows before disruption in disruptive E039389 discharge and not in no disruptive E39387 (Fig. 4(a)). The other is the disruption without precursor at $q_{surf} \sim$ integer. No growing magnetic fluctuation was detected before disruption as shown in Fig. 4 (b).

To explain observed low beta disruption of extreme reversed plasma, we introduce a simple model as below; "Disruption of RS plasma with strong ITB and central pressure plateau Disruption occurs when the both MHD instabilities at plasma surface and at safety factor being equal to surface mode are simultaneously unstable" [3]. By using this model, observed disruption can be explained by two processes, one is the discrete change of relative location of ITB and the rational surface in the RS region (surface mode triggered disruption), the other is the continuous change of pressure gradient of the rational surface, which is determined by the surface mode (internal mode triggered disruption). This simple model can well the
explain experimental results. Figure 5 shows the $\beta_N$ vs $q_{\text{eff}}$ when disruption occurred. Almost all observed disruptions without precursor (blue triangle) and with precursor (red square) can be categorized into the surface mode triggered disruption and the internal mode disruption, respectively. The disruption without precursor observed when surface $q$ is not integer cannot explain by the surface mode triggered disruption. A lot of them might disrupted due to double tearing mode, because $q_{\text{min}}$ of them are $\sim 2$ (green open circle), however still future work remains.

It is reasonable to think the disruption without precursor caused by ideal MHD instability. However it is by now predicted that the ideal limit is larger than $\beta_n > 2$. The actual plasma has a relatively large peripheral current and current hole. We have performed the ideal MHD stability calculation for the plasma with these characteristics by using the ERATO code. The input profile for the calculation is drawn in Fig. 6. The $\beta_N$-$q_{\text{edge}}$ diagram of ideal MHD stability for changing edge safety factor from 4.5 to 5.5 derived from ERATO code is shown in (Fig. 1). Instability window exists from $q_{\text{edge}}$ $\sim 4.8$ to $\sim 5.0$ at low $\beta_N$. However the eigenvalue is very low and marginal. The eigenfunction in this region shows external kink mode is destabilize. As the $\beta_N$ increases the amplitude of internal modes increase and change to kink ballooning mode. Moreover, we check the eigenvalue on the peripheral plasma current. As the peripheral plasma current increase, the eigenvalue becomes larger. In the case of no peak of
peripheral plasma current, the kink mode is stable. This calculation shows that it is reasonable that ideal disruption of this kind of plasma occurs. However many plasmas can survive in this region. We explain this survive and no-survive by the simple model described above. We also calculate the ideal stability by changing the pressure gradient at internal q=4 to know if the ideal stability can explain the our simple model. The eigenvalues are $\gamma = -6.4 \times 10^{-4}$ for the plasma with q=4 at large pressure gradient and $\gamma = -6.3 \times 10^{-4}$ for q=4 at pressure flat region. Eigenfunction for each plasma are also almost same as shown in Fig. 9. Ideal stability calculation cannot confirm our simple model. Other mechanism plays the role for the simple model.

This low beta disruption can be avoided by decreasing peripheral plasma current.

The conducting wall near the plasma also stabilize this instability as shown in Fig. 10.

References