MHD instabilities leading to disruption in JT-60U reversed shear plasmas

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Abstract. High performance reversed shear discharges with strong internal transport barrier (ITB) and flat pressure profile in the plasma core region disrupt frequently even with low beta. We analyzed MHD instabilities leading to low beta disruption with measuring magnetic fluctuation and current profile. It is found that except for well known double tearing mode, disruptions are triggered by surface MHD instabilities, which are coupled with internal mode in the reversed shear region at the rational surface of which safety factor is equivalent to the mode number of the surface mode. Most of observed disruptions can be explained by two processes. One is that the internal rational surface is changed by change of the surface mode number and the other is that the pressure gradient of the internal rational surface in the reversed shear region is changed continuously.

1. Introduction

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. Especially in JT-60U RS plasma, very high confinement (Q_{DT}>1) is achieved. It is considered that RS plasma does not attain high β_N (<2) due to its low internal inductance, though recently it is found that RS plasma with current hole can attain high β_N (~5) [1]. However, RS plasma with strong internal transport barrier (ITB) is frequently terminated by disruption. It is understood that disruption at q_{min}~2 β_N~2 is caused by stability limit of n=1 ideal kink ballooning mode. However RS plasma with strong ITB disrupts even at lower β_N. By now, low beta disruption is explained by double tearing mode, which is obtained numerically [2], or resistive interchange mode [3], and these are MHD instabilities at q_{min} and around ITB. However these cannot explain all of observed low beta disruption. Consequently, to understand the cause of the low beta disruption, we scrutinize the MHD instabilities of RS plasmas with strong ITB and central flat pressure by measuring precious plasma current profile and MHD fluctuations.

2. Experiment

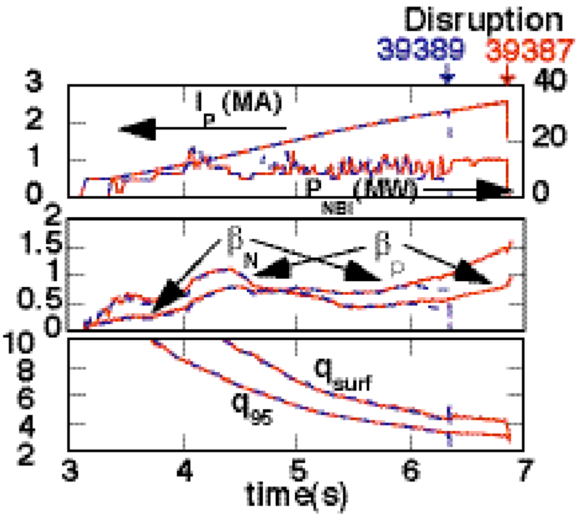

Fig. 1 High performance plasma with extereme reversed magnetic shear and ITB. Disruptions ouuered at t~6.85s (39387; red solid line) and t~6.34s (39389; blue dotted line). Time evolution of (a) Ip and NB power, (b) normalized beta and poloidal beta.

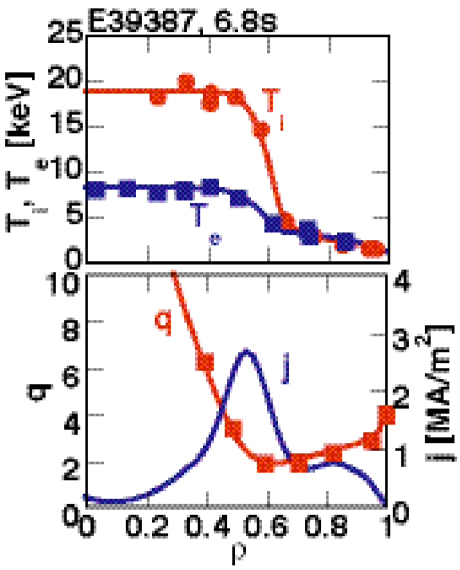

Fig. 2 Radial profiles of Ti and Te (a) and q and j(b) just before disruption of E39387at t~6.8s

2.1 Experimental condition and disruption.

Plasmas with extereme reversed magnetic shear have strong internal transform barriar and very good confinement. 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_{DT}~1, H_{89}~3 and β_N=1.44 with Bt=4.05T and Ip=2.56MA just before disruption at t~6.85s. The Radial profiles of ion temperature (Ti), electron temperature (Te) safty factor (q) and current density (j) at t~6.8s of E39387 are shown in Fig. 2. Typically pressure gradient of these type of RS plasma is steep at ρ~0.6 (ITB) and flat in the region around ρ<0.5 (Fig. 2(a)). The current profile is characterized by the current hole around ρ<0.3 and two peaks around ITB and peripheral region (Fig.2 (b)). A RS current profile is made with current increaseing (so-colled current ramping up) and simultaneously injecting neutral beam (NBI) during current ramping up as shown in Fig. 1 (a) and current peak at peripheral region is also formed by current ramping up. When the shot of E039387 disrupted, minimum of q is q_{min}=1.82 and q at plasma surface is q_{surf}=4.06. It can be considered that this disruption is caused by double tearing mode because q_{min} is just below 2. It is found that no this type of RS plasma with q_{surf} < 4 was observed without disruption or mini colapes, therefore no plasma current of this type of RS plasma with Bt=4T reaches more than Ip=2.6MA. However, many shots disrupt before q_{surf} > 4. The case of the early disruption is also plotted in Fig 1. The shot of E39389 with Bt=4.05T (a blue dotted line in Fig. 1) disrupted at t~6.34s, and, β_N=0.72, Ip=2.33MA, q_{surf}=4.23 and q_{min}=2.36. It shoud be noted that E39389 disrupted whether β_N, β_p and also stored energy were decresing and they are smaller than those of E39387 at same time. To see more than hundred discherges, it is found that disruption of this kind of RS plasma has characteristics as shown below; 1. There is maximum value of attainable plasma current. 2. Disruption occurs at similar plasma current. 3. Disruption occurs even at low beta and during beta damping phase. 4. Precursors with various growth rates are observed or no precursor is observed. To explain these disruption caracristics we analize in detail fluctuations of magnetics and eletcton temperature and plasma current profile with MSE.

2.2 Safty factors at disruption

The plasma of E39387 disrupted at q_{min}=1.82 and q_{surf}=4.06. It can be said that the disruptin of E39387 was induced by DTM because q_{min} is just below 2. A lot of plasmas disrupted around q_{surf}~4. However most of these plasmas do not disrupt due to DTM. Safety factors at disruptions with q_{surf}~4 are shown in Fig. 2 (a). Values of q_{min} scattered from 1.5 to 2.5 and it is difficult to say that disruption is related to MHD instability around q_{min}=2. This is corresponding to the fact that plasma current cannot be larger than 2.6MA for B_t=4.05 T while

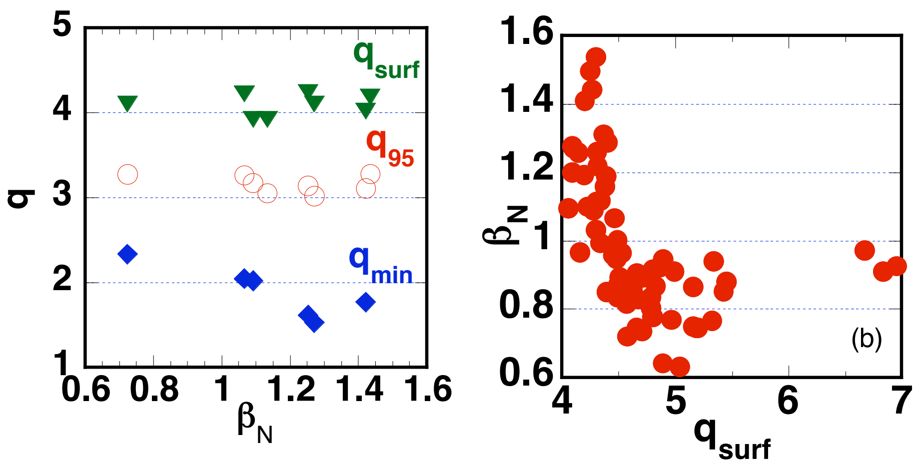

Fig. 3 (a) Surface safety factor (q_{95} and q_{surf}) and q_{min} at disruption of various β_N. q_{min} scatters from 1.5 to 2.5 in spite of q_{surf} ~ 4. Disruption is determined by rather surface safety factor than q_{min}. (b) β_N and q_{surf} at disruption while plasma current is rumping up. Disruptions occurred at q_{surf} ~5 even with low β_N,. The value of q_{surf} cannot decrease below 4.

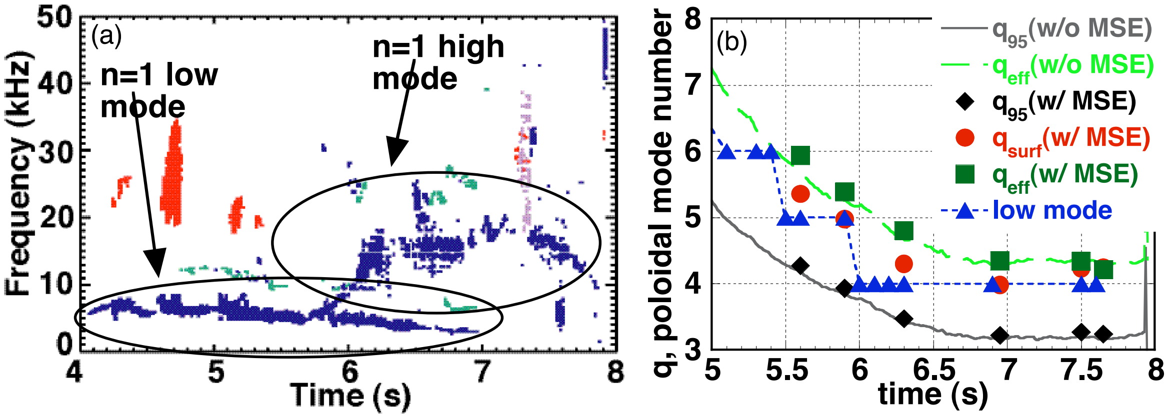

Fig.4 (a) Magnetic fluctuations observed in the high performance RS plasma. Poloidal mode number of the n=1 low mode and safety factor at plasma surface.

plasma current is ramping up. Disruptions occurred frequently at q_{surf}~5. It can occur even at very low β_N as shown Fig. 2 (b). These experimental results imply that MHD instabilities around plasma surface trigger the disruption.

2.3 Observed fluctuations

More precious analysis can be performed with magnetic analysis of higher poloidal mode number and higher frequency and new ECE with high spatial resolution and large signal-noise ratio. MSE measurement of higher spatial resolution and new reconstruction method also helps detailed analysis. Two n=1 mode with frequency of f~5kHz (low mode) and 10<f<20 kHz (high mode) are observed with Mirnov probes in almost all these RS plasmas (Fig. 4 (a)). Poloidal mode numbers of the n=1 low modes are equal to maximum integer of surface safety factor as shown Fig. 4 (b). For instance, low mode changes from m=5 to m=4 when q_{eff} dips below 5. This indicates that the low modes exist at plasma surface. These surface modes are thought to be driven by peripheral large current shown in Fig. 2 (a). We do not observe saturated m<4 mode and q_{surf} cannot decrease below 4.

3 Introducing new working hypothesis

To explain observed low beta disruption of extreme reversed plasma, which cannot be explain by present model, we introduce a new working hypothesis as below; "Disruption of RS plasma with strong ITB and central pressure plateau is triggered by the surface MHD instability, when stability at internal rational surface in the reversed shear region is unstable. The internal rational surface is equivalent to the mode number of surface mode, which is determined by surface safety factor." 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 tirggered 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).

3.1 Surface Mode Tirggered Disruption

In the case of discrete change of relative location of ITB and the rational surface in the RS region,the mode number of surface mode changes at discrete numbers as surface q changes. And then the position of corresponding rational surface in the RS region changes discretely. For instance, when surface mode changes form m=5 to m=4, the corresponding internal rational surface changes discretely. Since pressure gradient around q=4 is very large because of ITB, disruption takes place while that of q=5 is stable due to central flat pressure profile (Fig. 4 (a)

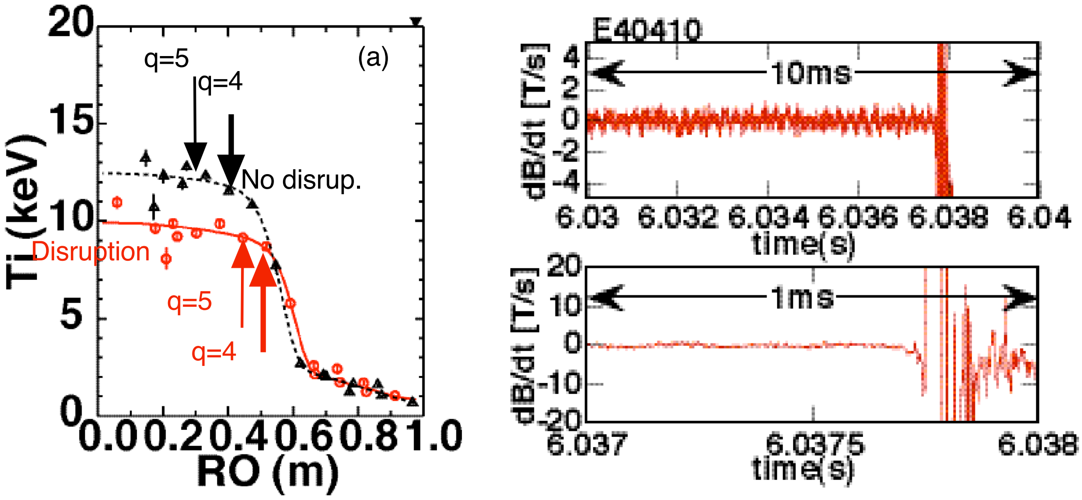

Fig. 4 (a) T_i and q profile when the discharge E40410 disrupted (solid line) when q_{surf} went down below 5. E40417(broken line) didn't disrupt at same time. (b) Magnetic fluctuation before disruption of E40410. No precusor was detected.

solid line). If the ITB is far from the internal q=4 surface, disruption does not occur (#40417 broken line in Fig. 4 (a)). The disruption is occurred in the ideal time, because before disruption no clear precussor is observed. It is consistent that the mode which triggers disruption is ideal kink mode. Figure 5 shows the radial distance Δr between the ITB shoulder and the q=4 surface. Δr<0 indicates that the q=4 surface exists within ITB layer. This figure indicates that when the internal q=4 surface is close to or in ITB, disruptions tend to occur. When q_{surf} went down below 4 and surface mode changes from m=4 to m=3, MHD instability at internal q=3 surface is always unstable because q=3 is in the ITB layer, therefore no plasma can survive any longer. For the relatively low β_N plasma, mini collapse was observed at q=3 rational surface in the core region (Fig.6). After this collapse, mode coupling between internal and surface q=3 mode was observed.

3.2 Internal Mode Triggered Disruption

In addition to discrete change of surface mode number, disruption can occur when the pressure gradient increase or relative position of internal rational surface and ITB changes gradually. In Fig. 7 (a), pressure gradient of the q=4 surface is flat when surface mode changes from m=5 to m=4 (t=6.0s). However, pressure gradient of the rational surface increase, and then disruption occurs (t=7.2s). E39389 in Fig. 1 also disrupted by the same reason. The q=4 surface in the

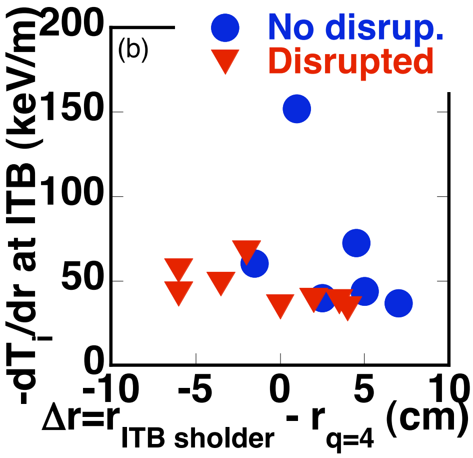

Fig. 5 The radial distance Δr between the ITB shoulder and the q=4 surface. Δr<0 indicates the q=4 surface exists within ITB layer.

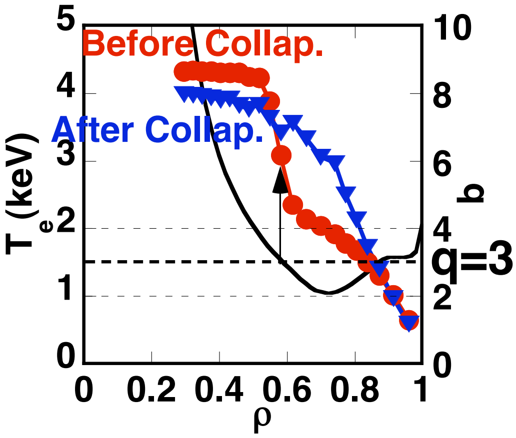

Fig. 6 T_e and q profile before and after collapse when q_{surf} went down below 4. The mini collapse occurred at internal q=3 rational surface.

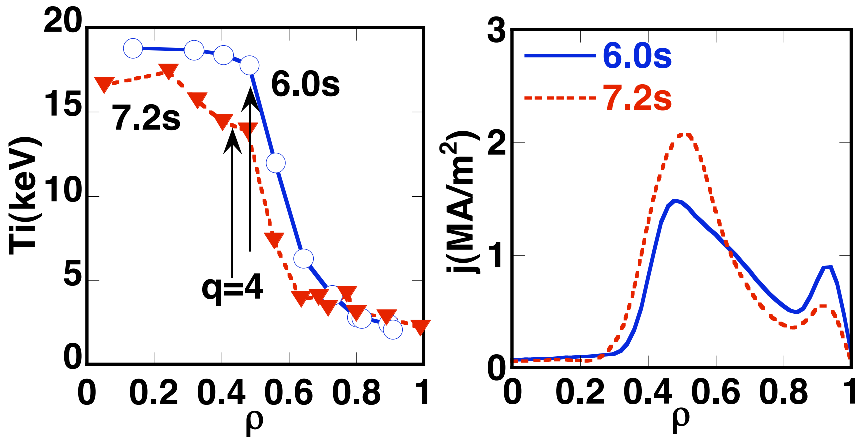

Fig. 7 Profile of ion temperature(a) and current density (b). Disruption did not occur at t~6.0s because of small pressure gradient at q=4. After increasing pressure gradient, disruption occurred at t~7.2s

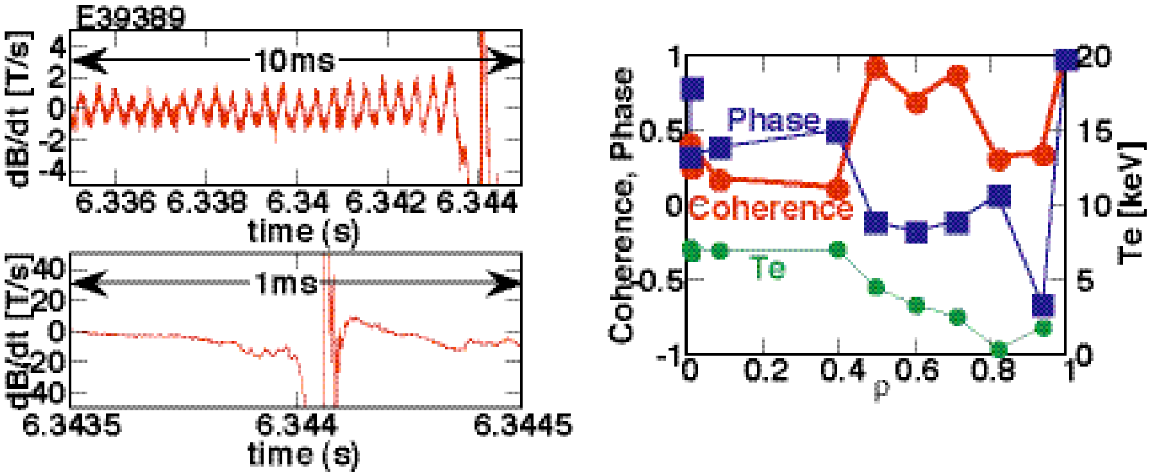

Fig. 8 Profile of ion temperature(a) and current density (b). Disruption did not occur at t~6.0s because of small pressure gradient at q=4. After increasing pressure gradient, disruption occurred at t~7.2s

positive shear region is within ITB layer in E39389 at disruption, in contrast to that of E39387 is in the flat pressure region at the same time. Before this type of disruption, precausor of magnetic fluctuation is observed(Fig. 8(a)). This precausor is obserbed in electron temperature. The coherence between magnetics and electron temperature is large at ITB layer and plasma surface (Fig. 8 (b)). The phase is changed between plasma surface and ITB region and between ITB layer and pressure plateu region. This mode is thought to be coupled mode of resistive interchange mode at the ITB shoulder and surface mode, because this precausor grawth in the resistive time (Fig 8(a)).

4 Conclution and Summary

As mentioned above, this model can explain experimental results well. It has already been found from stability analysis that surface mode and infernal mode of same mode number can be coupled. It is planned to do further calculation and quantitative evaluation. This model implies that the stability of high performance RS plasmas with current hole is brought by central pressure plateau.

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