Evolution of locked mode
in the presence of non-axisymmetric fields in KSTAR

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Abstract. We have investigated the effect of non-axisymmetric (NA) fields on the evolution of magneto-hydrodynamic (MHD) instabilities and resulting disruption processes in various discharges such as pure Ohmic and neutral beam (NB) heated L-mode discharges. Previous experiments in pure Ohmic discharges have found that when the mode amplitude reaches a certain level, the \( n = 2 \) NA field begins to interfere with the growth of the \( n = 1 \) locked mode. As a result, the \( n = 2 \) NA field can delay the \( n = 1 \) error field (EF) induced disruption. In NB-heated discharges, the overall effect of \( n = 2 \) NA field appears to be similar to that in the Ohmic discharges. However, the detailed evolution towards major disruption was somewhat different. With the \( n = 2 \) NA field, initial minor disruptions were much weaker than those in the reference discharge without the \( n = 2 \) NA field. To reach the same level of minor disruptions as in the reference discharge, we needed stronger \( n = 1 \) EF in the discharge with the \( n = 2 \) NA field. Electron cyclotron emission imaging (ECEI) showed different patterns of minor disruption depending on the presence of \( n = 2 \) NA field. As in the Ohmic discharge, the resulting major disruption was delayed in the NB-heated discharge as well. A series of experimental results in various discharge conditions show the possibility of using NA fields to control or delay the plasma disruption process.

1. Introduction

Although the tokamak device is fundamentally based on a toroidally axisymmetric field configuration, it has been demonstrated that a small amount of non-axisymmetric (NA) field could play a crucial role in transport characteristics and magneto-hydrodynamic (MHD) stability [1]. Recently, the effect of NA field has been studied intensively for suppressing edge localized mode [2] in addition to traditional interest on intrinsic error field (EF) [3].

Error field penetration and the subsequent plasma disruption are major threats to the operation of tokamak-type fusion devices. The error fields are expected to have a wide spectrum, but the influence of the mutual interaction among different NA fields, i.e., different toroidal mode numbers, has not been fully understood yet [4][5]. Since the 2013 KSTAR campaign, we have been investigating the effect of NA fields on the evolution of MHD instabilities and the resulting disruption phenomena by using NA field coils that are mainly designed for the EF correction coils. Recently, we have also started to focus on the growing need to better understand the process of thermal quench during disruptions especially in relation to the suppression of runaway seeds. It is well known that the MHD instabilities and turbulent fluctuations during the thermal and initial current quenches have a dominant effect on the generation of seed runaway electrons [6].

In the discharge studied, locking and EF penetration were induced by the torque imbalance between the intrinsic rotation and external magnetic braking. Further increase of the \( n = 1 \) EF
resulted in minor and major disruptions. As anticipated by the magnetic braking effect, the stronger \( n=2 \) NA field case exhibited earlier EF penetration and locking. However, subsequent minor and major disruptions were delayed and even avoided by the stronger \( n=2 \) NA field [7].

Analysis of the \( n=1 \) locked mode amplitude revealed that the \( n=2 \) NA field started to hinder the growth of \( n=1 \) locked mode when the mode amplitude reached certain level in Ohmic discharges. The starting level for this effect appears to depend on the \( n=2 \) NA field strength. More interestingly, fast growth of the \( n=1 \) mode was recovered just before minor disruption. The pure \( n=1 \) EF case without \( n=2 \) NA field did not show clear change of the growth rate after locking but exhibited gradual increase of the locked mode towards the minor disruption. A kinematic model of tearing-kink interaction is in qualitative agreement with the experimental observations in the pure Ohmic discharges.

After the promising disruption-control results in pure Ohmic cases, the study was extended to NB-heated discharges. In this work, we will mainly describe disruption scenarios in the presence of \( n=2 \) NA fields in NB-heated discharges. We will also briefly discuss the differences observed in Ohmic and NB-heated experiments.

2. Experimental set-up

![Diagram](image)

Fig. 1. a) Possible configurations of the FEC coils in toroidal and poloidal directions. b) Two distinctive configurations of \( n=2 \) top/bottom NA field with \( n=1 \) mid NA field: namely \( n=2 \) even and odd configurations.

As shown in figure 1, KSTAR has three pairs of picture frame coils designated as top, middle, and bottom field error correction (FEC) coils in the poloidal direction [8]. Each FEC coil is toroidally divided into four segments, thus the maximum applicable toroidal mode, number \( n \) of the NA field is two. The parity of each picture frame coil refers to the outward or inward radial direction of the generated field and the combination of coil parities specifies the resulting toroidal mode number and phase of the NA field. Similarly, the relation among the toroidal phases of the top, middle, and bottom FEC coils determines the poloidal phasing, i.e., the pitch of the resulting NA field with respect to the equilibrium field.

In the neutral beam (NB) heated L-mode discharges, only the \( n=2 \) even configuration of the top and bottom FEC coils was used for applying an \( n=2 \) NA field along with the \( n=1 \) EF of the
middle FEC coils. In this work we use the term “EF” to explicitly refer to a specific NA field that induces plasma locking and disruption.

3. Experimental result

Figure 2 illustrates a delayed major disruption of the n=1 EF penetration while the n=2 NA field is applied. Here, all experimental conditions including target plasmas were the same except for the presence of an initial n=2 NA field. We can understand these experimental conditions as a situation where locking and plasma disruption occur by n=1 EF in an experiment with n=2 resonant magnetic perturbation for edge localized mode control. The middle FEC coil applied gradually increasing n=1 EF to cause error-field-induced locked mode as shown by black and green lines of figure 2b. On the other hand, the n=2 NA field, which was applied by the top and bottom FEC coils, maintained a constant level during the rise of the n=1 EF. Locking and EF penetration were induced by the torque imbalance among the NB-supplied torque, intrinsic rotation, and external magnetic braking. Further increase of the n=1 EF resulted in minor disruptions and eventually a major disruption as shown in figures 2 and 3.

![Fig. 2. Delayed major disruption when the n=2 NA fields is overlapped with the n=1 EF induced locked mode in NB-heated discharges. a) Plasma current, b) applied currents in the FEC coils, c) n=1 mode amplitude, d) core electron temperature, e) core and edge toroidal rotations, and f) NB heating power.](image)

In figure 2, the n=1 mode amplitude appears to be saturated at a similar level regardless of the presence or absence of the n=2 NA fields after increasing suddenly following the locking and EF penetration. The difference between the pure Ohmic and NB-heated discharge cannot be explained by rotational stabilization effect of large NB torque since the overall rotation profile goes to zero after the locking as shown in figure 2e.
Fig. 3. Minor and major disruptions due to n=1 EF penetration depending on the presence of n=2 NA field in NB-heated discharges: #12925 (without the n=2 NA field) and #12927 (with the n=2 NA field). a) n=1 mode amplitude of #12925, b) n=1 mode amplitude of #12927, c) core electron temperature of #12925, and d) core electron temperature of #12927.

Figure 3 illustrates the detailed differences between the discharges shown in figure 2. With n=2 NA field, initial minor disruptions were much milder and slower than those in the reference discharge without the n=2 NA field. The level of minor disruption was quantified by the drop in core electron temperature and the change in n=1 mode amplitude. To reach a comparable level of minor disruptions observed in the reference discharge, we needed a stronger n=1 EF in the discharge with the n=2 NA field. Eventually, violent minor disruptions appeared at high amplitude n=1 EF and a major disruption followed.

Fig. 4. Comparative study of the n=1 EF penetration depending on the underlying n=2 NA field strength in pure Ohmic discharges. Red line: no current in the n=2 FEC coil. Green line: 1 kA/turn current in the n=2 FEC coil. Blue line: 2 kA/turn current in the n=2 FEC coil. a) Core electron temperature and b) n=1 locked mode amplitude.

In NB-heated discharges, the overall effect of the n=2 NA field appears to be similar to that
in the Ohmic discharges. As in the Ohmic discharges, the resulting major disruption was delayed in the NB-heated discharges as well. However, the detailed evolution towards minor and major disruptions were somewhat different when compared with the pure Ohmic discharges. The n=1 mode amplitude was not significantly different regardless of the n=2 NA field unlike the Ohmic discharges. Recall that in the Ohmic discharges shown in figure 4, the n=1 mode amplitude changed with n=2 NA field strength even for the same n=1 EF amplitude because the n=2 NA fields hindered the growth of n=1 mode.

4. Progress of minor disruptions

It is generally known that the thermal quench follows a series of detailed steps [9]. The temperature profile collapses first within the q=2 surface and then outside, although the process sometimes may take multiple steps. Here, q depicts the safety factor of magnetic field. In minor disruptions, only a momentary thermal quench occurs at a limited level which does not proceed to full thermal and current quenches. Electron cyclotron emission imaging (ECEI) shows fairly different patterns of minor disruption and turbulence phenomena around the MHD mode structures depending on the presence of the n=2 NA field.

4.1 Progress of minor disruptions without an n=2 NA field

![Fig. 5. Progress of the minor disruption when there is no n=2 NA fields: violent and fast minor disruption in KSTAR shot #12925 even at a low n=1 EF strength (1.8 kA/turn in mid-FEC coil current).](image)

As mentioned in the above, the reference discharge without the n=2 NA field exhibits violent and rapid minor disruptions from the early phase with relatively low n=1 EF strength. Here, the thermal collapse starts from q>2 region and expands to the core region. Then the q>2 region is further cooled. The collapse pattern seems to be somewhat different from the generally known thermal quench pattern as briefly described earlier. However, these differences may be explained by the various collapse patterns discussed in the following subsections where it is suggested that the thermal collapse pattern may vary greatly depending on the driving and stabilizing effects along with the discharge condition.
4.2 Progress of minor disruptions with an n=2 NA field

Fig. 6. Progress of the minor disruption when there exists an initial n=2 NA field: mild minor disruption in KSTAR shot #12927 at low levels of n=1 EF (1.5 kA/turn in mid-FEC coil current).

Fig. 7. Progress of the minor disruption when there exists an initial n=2 NA field: violent minor disruption in KSTAR shot #12927 at high levels of n=1 EF (3.4 kA/turn in mid-FEC coil current).

In the discharge with the n=2 NA field, the thermal collapse is divided into two distinct patterns depending on the n=1 EF strength. At a relatively low n=1 EF strength shown in figure 6, the interchange-like phenomena occurs near the m/n=2/1 locked mode structure where m and n represent poloidal and toroidal mode numbers, respectively. Then the heat flux flows across the q=2 surface. This kind of collapse shows a very mild and slow thermal collapse.

On the other hand, as the n=1 EF strength gradually increases, the thermal collapse pattern starts to resemble the pattern in the reference discharge without the n=2 NA field. Under these conditions, the stabilizing effect of the n=2 NA fields appears to be overwhelmed by the destabilizing effect of the locked mode. Note that although the collapse of figure 7 occurs at much higher n=1 EF strength, figures 5 (1.8 kA/turn) and 7 (3.4 kA/turn) have almost the same collapse pattern.
5. Discussion and summary

As mentioned in the previous sections, the results of the delayed major disruption in NB-heated discharges are the same as those in Ohmic discharges, but there are many differences in details. The cause of this difference is still unclear, but looking at the fundamental differences between the two experiments may help explain the possible mechanisms. The main difference is that the NB-heated discharge is more turbulent than pure Ohmic discharge due to the increase in free energy from the auxiliary heating. Therefore, the interaction between the small-scale turbulence and the large-scale MHD instability could have a strong influence on the plasma disruption phenomena in NB-heated discharges [10]. On the other hand, in Ohmic discharges, how the disruption proceeds is thought to be solely determined by the strength of the MHD instability rather than by an interaction between turbulence and MHD stability.

Fig. 8. Coherence sum between 0-100 kHz during 20 mili-seconds. a) Reference discharge without the n=2 NA fields. b) Comparative discharge with n=2 NA fields: early phase at t=5.920 sec and late phase at t=7.099 sec.

In order to understand the disruption phenomena in detail, we examined the strength of the turbulence in each case. Figure 8 below shows the turbulence quantified by the coherence sum around the magnetic island formed by the locked mode. As shown in figure 8a, strong turbulence is observed from the early phase with a low n=1 EF strength. On the other hand, the mild minor disruption phase in figure 8b shows that the turbulence around the island is much weaker although the n=1 EF strength does not much differ. This weak turbulence can be a sign that the local gradient around the magnetic island is relatively low. As the n=1 EF strength increases, a strong turbulence appears again at the end similar to the change in the collapse pattern. It should be emphasized that the overall equilibrium and profiles are nearly identical, but the addition of the n = 2 NA field causes this difference to occur. The detailed mechanism such as poloidal flow change near magnetic island needs to be further investigated.

A series of experimental results in various discharge conditions show the possibility of using NA fields to control or delay the plasma disruption process. The result could improve our understanding of disruption phenomena in the presence of disparate NA fields and may be
applicable to disruption avoidance or mitigation scheme, which is the most urgent issue in ITER operation.

References