KINK MODE STUDY IN EAST HIGH BETAP PLASMA

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Abstract

Hybrid scenario with extended regions of low-magnetic shear profile and $q_0 \sim 1$ is one of the baselines of ITER. This plasma regularly exhibits with 1/1 helical quasi-interchange mode but no effective sawtooth crash. The presence of those 1/1 helical mode have both positive and negative effects to plasma confinement. They can expel high-Z impurities in the core and preventing sawtooth crash as a positive role, however, they can also lead to amount of confined energetic ions losing and decrease the toroidal rotation in the core. In EAST, 1/1 helical modes in high betap hybrid plasma manifest itself as quasi-interchange long lived mode. The destabilization of long-lived mode in the high betap plasma will replace the regular sawtooth crash. 2/2 or 3/3 harmonics of long-lived mode are regularly destabilized. Three-dimensional resistive nonlinear simulation with realistic magnetic configuration of Tokamak has reproduced the long-lived mode instability. Nonlinear simulation results show this mode has a nature of ideal interchange and the growth rate independent with resistivity. The developing of long-lived mode can drive a strong 0/0 zonal flow, which indicates a huge change of radial electrical field. The change of radial electrical field hints the happening of flux pumping as well as a change of safety factor profiles in the core. In this sense, the presence of helical mode is favorable to the formation of extended region with low magnetic shear and $q_0 \sim 1$ in the core.

1. INTRODUCTION

High-performance steady-state, hybrid scenarios with core q-profile is relatively flat and qmin close to unity are proposed as one of ITER’s advanced modes of operation [1]. The high betap and core q -profiles of hybrid discharges are also favorable for destabilizing of 1/1 internal kink mode [2].

Saturated 1/1 mode with helical cores have been found to impact confinement in both positive and negative ways. Theoretical predictions and supporting experimental observations from MAST find that fast ion confinement degrades significantly with helical cores [3] and data from EAST show 2/1 neoclassic tearing mode (NTM) trigger by 1/1 mode via mode coupling [4]. On the other hand, the flux pumping mechanism [5] keeps the q profile above unity without sawteeth crashes and is beneficial for maintaining high performance hybrid discharges [6] and is helpful for avoiding of high-Z impurities accumulation [7, 8]. An example of neutron loss caused by helical 1/1 mode is shown in Fig.1. The loss of gamma rays in the Fig.1 indicate the fast ions confinement degrades significantly, which is consistent with MAST observation. The developing of 1/1 helical mode also leads huge change of toroidal electric field.

In this work, long-lived helical mode will be experimentally and numerically studied at EAST tokamak. In high betap plasma, sawtooth instability was replaced by a saturated 1/1 internal kink mode which either manifests itself
as a long-lived mode which is associated to the core safety factor at $q_0 \sim 1$. The present of those 1/1 internal modes are beneficial to the sustain of hybrid scenario with extended regions of low-magnetic shear profile and $q_0 \sim 1$, because of that they can expel high-Z impurity and can make flux pumping. The presence of 1/1 internal kink mode without sawtooth crash and the nature of ideal mode of 1/1 kink instability have been reproduced by 3D magnetohydrodynamic nonlinear simulations with the M3D code. 3D nonlinear simulation of M3D code also show the developing of long-lived mode can drive a strong 0/0 zonal flow, which indicates a huge change of radial electrical field. The change of radial electrical field hints the happening of flux pumping as well as a change of safety factor profiles in the core. In this sense, the presence of helical mode is favorable to the formation of extended region with low magnetic shear and $q_0 \sim 1$ in the core.

2. EXPERIMENTAL OBSERVATIONS IN EAST HIGH BETAP PLASMA

Hybrid scenarios with weak of revised shear in the core is thought to be a strong candidate for ITER operation, due to its high-performance steady-state and endurable impurities accumulation level. However, hybrid scenarios regular exhibiting with 1/1 helical modes due to the core safety factor only slightly above unity. A long-lived mode (LLM) was found in EAST high betap hybrid plasma. A typical helical mode is shown in the left plane of Fig. 2. The right plane of Fig. 2. shows the minimum $q$ in the core is 1.01 which is very close to unity. The neutron loss caused by helical mode is also shown in Fig.2. Two important features of LLM can be drawn from the data shown in Fig. 3. 1. The frequency of LLM is close to the plasma toroidal rotation at magnetic axis, 2. Harmonic of 1/1 LLM so-called 2/2 mode is usually present together with 1/1, and a mode with mode number
2/1, can be detected by edge Mirnov coils. The second feature is not surprise, since the m=2 component of 1/1 kink mode is not small in torus configuration due to the toroidal effect. The first feature implies that LLM could be an ideal mode. Note that sawtooth crashes are absent during LLM process. The LLM appear after the increase of betaP due to the heating of neutral beam injection (NBI) as shown in the left of Fig.3.

$\beta_p = 1.8, \beta_N = 1.9$

In EAST tokamak, the together of tomography of multi-array soft x-ray and SVD can give MHD mode structure in the plasma core. 1/1 mode structure and its second harmonic 2/2 mode structure are clearly shown in the right of Fig.3. which are constructed by tomography of soft x-ray diagnostic. The data in EAST also show the 1/1 and 2/2 mode will be phase locking when the plasma toroidal rotation becomes flat from axis to the outside of q=2. Note the frequency of helical mode chirps down when amount of neutron loss.

FIG.2. Long lived mode in EAST plasma with $q_0 > \sim 1$, mode frequency chirps down and amount of neutron loss

FIG.3. 2/2 harmonic mods of internal mode are regularly found in EAST high betap hybrid operation, tomography of soft x-ray reconstructed 2/2 mode structure
3. M3D SIMULATION

Nonlinear MHD simulation code M3D with realistic tokamak geometry was used for LLM simulation. The experiment magnetic equilibrium and Te, Ne profiles are employed. 1/1+2/2 mode structures are found, which is consistent with experiment and theoretical predictions. The nonlinear running of M3D code also confirm the absences of sawteeth crashes. The initial mode structures are plotted in Fig.4.

![Image of mode structures and sawtooth-free helical state](image)

**FIG. 4.** 1/1+2/2 mode structures and sawtooth-free helical state simulated by M3D code.

M3D nonlinear results show that the growth rate of LLM are independent to resistivity respect to the experimental value region ($\eta = 10^{-9} - 10^{-7}$). This is a very strong evidence of the ideal nature of LLM. Furthermore, a clear shift of pressure axis, but no clear shift of magnetic surface is found during LLM process, which is also support that LLM have ideal feature.
The right of Fig.5 shows that 2/2 mode comes after 1/1 helical mode and the third harmonic mode 3/3 is the latest one. The nonlinear MHD simulation show 2/2 harmonic can be dominant as in the left of Fig.5. The burst of 2/2 mode modelled by 3D MHD nonlinear simulation agrees very well with experimental observations. During the mode process, the plasma profiles including electron temperature, electron density, plasma current and safety factor will be changed. As plotted in Fig.6., the initial core weak shear safety factor profile will be completely flat in the core when 2/2 mode destabilization. The change of safety profile in the core indicate a transition of poloidal flux to toroidal flux in the core, which is named toroidal flux pumping. The toroidal flux pumping is helping for to keep the minimum safety factor above unity and favorable to hybrid scenarios operation.
A very interesting result was found during the helical mode evolution simulated by M3D. A large 0/0 flow was produced by helical mode and its harmonic modes. This 0/0 flow has a strong radial component of electric field. The large 0/0 flow indicates a huge change of $E_r$. The change of $E_r$ will give a change of rotation change of helical mode in the laboratory frame and a change of run-away electrons. The produced 0/0 flow as well as the change of $E_r$ are located in the plasma core, as shown in Fig. 7. The huge change of $E_r$ during helical mode process is responsible for the frequency chirps down and gamma loss observed in EAST (Fig.1.).

4. SUMMARY

The long-lived helical mode is experimentally and numerically studied at EAST tokamak. In high beta-p plasma, sawtooth instability was replaced by a saturated 1/1 internal kink mode which either manifests itself as a long-lived mode which is associated to the core safety factor at $q_0 \sim 1$. The present of those 1/1 internal mode is beneficial to the sustain of hybrid scenario with extended regions of low-magnetic shear profile and $q_0 \sim 1$, because of that they can expel high-Z impurity and can make flux pumping. The mechanism responsible for the flux pumping caused by kink mode was numerically in nonlinear 3D magnetohydrodynamic simulations using the M3D code. The harmonic modes are simulated by nonlinear 3D MHD simulation also. The main observations of helical mode in EAST and the simulation results are summarized in Table 1.
TABLE 1. SUMMARY OF OBSERVATIONS AND SIMULATIONS

<table>
<thead>
<tr>
<th>EAST Observations</th>
<th>M3D Simulations</th>
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<tbody>
<tr>
<td>1/1 helical mode only, sawtooth free</td>
<td>Sawtooth free and 1/1 internal kink mode</td>
</tr>
<tr>
<td>Frequency chirping</td>
<td>Large 0/0 flow driven by 1/1 helical mode and Er drop</td>
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<tr>
<td>Neutron loss</td>
<td>Er drop</td>
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<tr>
<td>qmin &gt;1</td>
<td>Q flat in the core and qmin&gt;1; with 2/2</td>
</tr>
<tr>
<td>2/2 appears after 1/1</td>
<td>m=2 component of helical kink is strong in q=1 surface in torus</td>
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<tr>
<td>1/1 and 2/1 are phase locking when rotation flatten</td>
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REFERENCES