Nonlinear evolution of multi-helicity neoclassical tearing modes in HL-2A low rotation plasmas

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The neoclassical tearing modes (NTMs) are driven by the local reduction of the bootstrap current due to the pressure flattening across the island [1,2]. The presence of NTMs in the plasma core is one of the critical issues for both the standard ELMy H-mode and advanced scenarios in present and next step devices such as ITER. In particular, Simultaneous onset and phase locking of different helicity NTMs can lead to the change of rotation profile, enhanced transport or even disruption [3,4]. NTMs are metastable, requiring a ‘seed’ perturbation in order to be excited. A seed island of an NTM is produced by other MHD instabilities, such as edge localized modes (ELMs), sawteeth and fishbones. However, NTMs can be seeded by resonant error field. Error fields due to PF and TF coils imperfections and misalignments, feeders and in-vessel ferritic material components, can lead to mode locking and rotation braking [5]. Reduction of error fields is a requirement for avoiding non-rotating magnetic island (NTMs) formation and for maintaining plasma rotation.

On the other hand, one of the challenges of the burning plasma regime in ITER and DEMO due to the difference in current plasma conditions is the low toroidal rotation (torque). The slower plasma rotation and smaller rotation shear at rational surfaces may remove the stabilizing effect of the flow shear that NTMs occur. Preliminary analysis suggests decreased plasma rotation could be reducing the small island polarization current threshold and thus making the \( m/n=2/1 \) NTM unstable at lower \( \beta \) in slow plasma rotation. Understanding the nonlinear dynamics of coupled NTMs and interaction with sheared flow are important issues in future tokamak devices [6-8]. In HL-2A [9], non-rotation multi-helicity magnetic islands, \( m/n=2/1 \) and \( 3/2 \), formatted by error field penetration have been observed in low density, low rotation plasmas. The results can provide evidences for NTMs stability predictions and their
nonlinear dynamic in the low flow plasmas.

In HL-2A, multi-helicity tearing modes, \( m/n = 2/1 \) and \( 3/2 \), have been observed in low rotation plasmas. The experiments were performed in low and high confinement mode plasmas heated by electron cyclotron resonant heating (ECRH) and neutral beam injection (NBI), plasma current \( I_p \sim 300\text{kA} \), toroidal magnetic field \( B_T \sim 2.4\text{T} \). Figure 1 shows the typical discharge waveforms with multi-helicity islands. The typical H-mode plasma with type-III ELMs is heated by 1.8 MW ECRH and 0.8 MW NBI. As shown in the frequency spectrum of the Mirnov coil in figure 1(d), rotating \( m/n=2/1 \) and \( 3/2 \) modes are observed at \( t = 410\text{ ms} \). The \( 2/1 \) mode is suppressed when the mode frequency increases. And the \( 3/2 \) island survives. After the ECRH is switched off at \( t = 610\text{ ms} \), the amplitude of \( 3/2 \) island drops and disappears following the decreasing of electron temperature and \( \beta_p \). The \( 3/2 \) mode clearly shows the neoclassical nature driven by plasma pressure, that the saturated island

![Image](image_url)

Figure 1. Typical experimental results with the multi-helicity islands, 2/1 and 3/2 onset in HL-2A. (a) ECRH and NBI power waveform. (b) Lined averaged density and stored energy. (c) Central temperature and \( D_e \). (d) Time evolution of the mode frequencies by spectrogram of the Mirnov coils.

![Image](image_url)

Figure 2. Evolution of amplitudes of odd toroidal mode (\( m/n=2/1 \)) and even toroidal mode (\( m/n=3/2 \)) obtained from magnetic signals.
width is the linearly dependence between poloidal beta $\beta_p$.

For understanding the mechanism, the detail of magnetic islands onset process has been surveyed. Firstly, we found the multi-islands are always triggered in low toroidal rotation plasmas. The intrinsic toroidal rotation in the absence of NBI has been observed in many machines. In HL-2A Ohmic or ECRH heating plasmas in the absence of any auxiliary torque input, the spontaneous core rotation is count-current directed. As shown in figure 3, the direction of the tangential NBI in the co-plasma current direction is overlook counterclockwise. Balanced the intrinsic rotation by the co-current direction NBI, the plasma with a very low toroidal rotation can be carried out. As shown in figure 4, after the co-current
NBI system turns on, the count-current rotation can reverse to co-current direction. The plasma toroidal rotation was measured by a charge exchange recombination spectroscopy (CXRS) \cite{10} with a spatial resolution $\approx 1.5$ cm. During this process, a very low rotation plasma can be obtained, as shown in the figure 4(c), $t=510$ ms, $V_0 < 10$ km/s. And the multi-helicity islands are always triggered during this low toroidal rotation phase. In HL-2A, significant decrease of toroidal rotation velocity in the core plasma is always observed when ECRH power is added to Ohmic heated or NBI heated plasmas. So the low rotation plasmas can be easily carried out and maintained for a long time (tens of milliseconds) with ECRH heating as shown in figure 1.

The development of an NTM requires a seed island whose island width must exceed a critical width. The seed islands can be generated by other MHD instabilities, such as sawtooth activities, ELMs, fishbones. However, as shown in figure 1(d), no visible MHD mode is observed before the 3/2 NTM onset. For understanding the role of NTM onset, the detailed studies on development of the two modes have been performed. In the discharges with multi-helicity islands, a minor disruption during low rotation phase are always observed, sudden contraction of temperature profile $T_e$, soft X-ray sharply decrease and a spike in the total radiated power, as shown in figure 5. These observations suggest that this event is a minor disruption. For investigating the role of the minor disruption, we calculated the amplitudes of the modes. It is found that the static 2/1

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Time traces of signals show the minor disruption during multi-helicity islands existing in the plasma. (a) The line averaged density and central electron temperature. (b) Central soft-X ray and total radiation power. (c) Time evolution of magnetic perturbation. (d) Amplitude of the m/n=2/1 perturbation field measured by Mirnov coils.}
\end{figure}
and 3/2 islands (modes frequency ~ 0) onset before the disruption, and the phase locked multi-helicity islands induce the minor disruption.

Another important character of the multi-helicity islands simultaneous onset is always observed at the relatively low line averaged density plasmas with the similar plasma parameters and heating power. As shown in figure 6, a set of similar discharges with different plasma density is compared. The result shows a clear critical value of density (line averaged density $n_e < 2.2 \times 10^{19} \text{m}^{-3}$) for the modes onset. Two discharges with similar plasma parameters and $P_{\text{NBI}}$ are shown in figure 7. It can be seen that multi-helicity islands are not observed in relatively high density ($n_e > 2.7 \times 10^{19} \text{m}^{-3}$) plasma.

Figure 6. The critical plasma line averaged density at the multi-helicity islands onset versus the heating power, $P_{\text{NBI}}$, modes onset (red), without modes onset (black).

Figure 7. Comparison of density with (red) and without (blue) modes onset. No multi-island triggered is observed in high density ($n_e > 2.7 \times 10^{19} \text{m}^{-3}$) plasma.

Another important character of the multi-helicity islands simultaneous onset is always observed at the relatively low line averaged density plasmas with the similar plasma parameters and heating power. As shown in figure 6, a set of similar discharges with different plasma density is compared. The result shows a clear critical value of density (line averaged density $n_e < 2.2 \times 10^{19} \text{m}^{-3}$) for the modes onset. Two discharges with similar plasma parameters and $P_{\text{NBI}}$ are shown in figure 7. It can be seen that multi-helicity islands are not observed in relatively high density plasmas. Furthermore, the phase of the static islands can be determined by a toroidal array of Mirnov coils. In figure 8 (a)-(d), the time evolution of m/n=2/1 mode is drawn from the time from stationary state to rotating state for four discharges. One can see that the spatial phases of 2/1 and 3/2 modes are exactly same. The modes (static) before rotation later, are locked at a fixed position. This feature is consistent with the locked modes induced by intrinsic error field penetration.
Error fields is derived from intrinsic and externally non-axisymmetric coils. The intrinsic field asymmetries caused by small structural asymmetries in a nominally axisymmetric device. And an externally applied non-axisymmetric magnetic field is one of the simplest and most direct approaches to control of MHD instabilities. \cite{11} Many tokamaks and reversed-field pinch devices now have single or multiple rows of non-axisymmetric coils, external or internal to the vacuum vessel, that provide the capability to apply magnetic perturbations with toroidal mode numbers \( n \geq 1 \) and amplitudes of order \( \delta B/B \geq 10^{-3} \). These magnetic field asymmetries may affect stability indirectly through braking of plasma rotation, as well as directly by stimulating tearing modes or kink modes. The response of the plasma to a non-axisymmetric field includes screening and amplification effects, and possibly formation of magnetic islands. The cross-machine extrapolations were based on experiments with differing plasma configurations and error field harmonic structures. Error field penetration threshold is low in low density operation, and is low in low rotation operation due to the weak rotation shielding. \cite{12,13}

As described above, the non-rotating multi-helicity islands have been observed in

![Figure 8. The multi-helicity islands with same locked phase in four discharges.](image)

![Figure 9. Time traces of 2/1 and 3/2 mode amplitude evolution influenced by the sheared flow arising from the momentum injection.](image)
low density, low rotation plasmas. And, the static islands onset with a stationary spatial phase. These features are consistent with the multi-helicity islands triggered by intrinsic error field penetration. The 3/2 island seeded by error field penetration has the typical neoclassical character.

The influence of toroidal sheared flow arising from the co-$I_p$ NBI on the nonlinear evolution of the multi-helicity NTMs has been investigated in HL-2A. The 2/1 mode is always suppressed due to the injected momentum. However, the 3/2 mode survives, as shown in figure 1 and figure 9.

Two or more different helicity magnetic islands (TMs or NTMs) can simultaneously onset in plasmas. The interaction of multi-helicity islands is a very serious issue for tokamak plasmas, which can lead to the change of rotation profile, enhanced transport or even disruption. In HL-2A low toroidal rotation and relatively low density plasmas, the critical threshold of the intrinsic error field penetration will be decreasing. And the multi-helicity islands can be seeded by the non-axisymmetric error field penetration, and lead to the change of rotation profile, enhanced transport or even disruption. Sheared flow arising from momentum injection can suppressed the coupled islands. For understanding the experimental results, numerical modelling will be carried out by means of reduced magnetohydrodynamic simulations. These results provide important evidence for NTMs stability predictions and their nonlinear dynamic in the low flow plasmas, such as ITER.

Reference.