Investigation of the role of Energetic particle in the driving of long-lived saturated internal mode on HL-2A tokamak

DENG Wei1), LIU Yi1, WANG Xian-Qu2, CHEN Wei1, Dong Yun-Bo1, S.Ohdachi3, JI Xiao-Quan1, SHEN Yong1, CAO Jian-Yong1, ZHOU Jun1, FENG Bei-Bing1, LI Yong-Gao1, HUANG Xian-Li1, GAO Jin-Ming1, HAN Xiao-Yu1, XIA Zi-Wei1, HUANG Mei1, WANG He1, DUAN Xu-Ru1, WANG Xiao-Gang4 and HL-2A team

1Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, China
2School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, China
3National Institute for Fusion Science, 322-6 Oroshi-cho, Toki-shi 509-5292 Japan
4School of Physics and State Key Lab of Nuclear Physics&Technology, Peking University, Beijing, 100871, China

a) E-mail contact: dengw@swip.ac.cn

Long-lived saturated internal mode (LLM), observed during neutral beam injection (NBI) with weakly reversed or broad low magnetic shear, is considered as a pressure-gradient driven MHD mode triggered by energetic particles. It often results in rotation flattening in the core plasma, and degrades fast-ion confinement. Different scenarios have been investigated in various devices. The major focuses of LLM scenarios study are its underlying mechanism and effective control [1,2].

On HL-2A, we have also often observed an \( n = 1 \) long-lived saturated mode with higher toroidal mode harmonics (\( n = 1 \)-4) during NBI. The frequency evolution of the mode is closely related to the central toroidal rotation. This mode can persist for 10-400ms or longer on HL-2A with a frequency in the range of 10-20kHz during the interval of 400-450ms in Figure 1. The typical initial linear growth time is in the range 0.4-6ms and depended on NBI power. When the LLM occurs, a reduction in the electron density, and the plasma stored energy, are usually observed. The neutron rate following the mode onset remains lower than that before the onset for the rest discharge period, indicating an enhanced level of fast ion losses which would reduce the effective NBI heating power.

On HL-2A, it is observed that LLM appears as the safety factor profile has a weak shear in a broad range with \( q_{\text{min}} \) around unity. Thus the ideal interchange can become marginal stable due to the weak magnetic shear or even weakly unstable if \( \Delta q = 1 - q_{\text{min}} \) reaches a critical value [3]. By increasing the electron cyclotron resonant heating (ECRH) power, we have found experimentally that the \( n = 1 \) mode is more unstable with respect to \( \Delta q \) induced by ECRH than the higher harmonics, for instance, the \( n = 1 \) harmonics can be stabilized only with ECRH power up to 1.25MW while the \( n = 4 \) harmonics has been stable.

Figure 1. Fourier spectrogram of soft X ray singal showing LLM during NBI(480KW) on HL-2A. LLM can be suppressed by ECRH (\( r/a = 0.4, 0.2, 0.5, 0.7, 0.9, 1.1, 1.25 \)MW).
at an ECRH power of only 0.7MW. Such ECRH experiment not only demonstrate the effect control of LLM, but also deduce a dependence of stability of each LLM harmonics on $\Delta q$, which is in agreements with the calculation on MAST [2].

Then the marginal stable or weakly unstable mode can be excited by the energetic particles during NBI. The dispersion relation of the mode can be written as

$$-i\omega \sqrt{3} \omega - \omega_{\alpha} / \omega_{\alpha} = -[\delta W_{\text{MHD}} + \delta W_{\text{K}}]$$

where $\omega_{\alpha} = V_{s} / R_{s}$ is the Alfven frequency, $\omega_{\alpha}$ is the ion diamagnetic frequency, the mode frequency $\omega = \omega_{\alpha} + i\gamma$, magnetic shear $\dot{s} = (\epsilon q'_{s})$, and the MHD contribution is $\delta W_{\text{MHD}} \approx 3\pi \Delta q r_{c}^{2} (\beta_{i}^{2} - \beta_{p}^{2}) / R_{0}^{2}$, where $\beta_{p}$ is the critical value of plasma beta $\beta_{p}$ for the mode, the kinetic contribution from the energetic particle can be written as

$$\delta W_{K} = \hat{\beta}_{h} \omega / \omega_{\alpha} \ln (1 - \omega_{tm} / \omega)$$

The dependence of growth rate on the energetic particles beta for LLM is shown in Figure 2. In the region of $\hat{\beta}_{h} < \hat{\beta}_{h} (-2 \times 10^{-3})$, we can see that the ideal pressure-driven mode is stable for the MHD branch with parameters of HL-2A. When the $\hat{\beta}_{h}$ is larger than $\hat{\beta}_{h}$, the effect of energetic particles destabilizes the mode, and the growth rate of mode increase with $\hat{\beta}_{h}$ in the EP branch. The $\delta W_{\text{MHD}}$ and the $\text{Re}(\delta W_{K})$ are also shown in this figure, with $\gamma > 0$ as $\delta W_{\text{MHD}} + \text{Re}(\delta W_{K}) < 0$.

The LLM, due to its pressure-driven feature, is destabilized by a large pressure gradient in the low shear region during NBI. To avoid the instability, it is thus necessary to maintain finite shear in the interior of the plasma or to broaden the pressure profile so that the pressure gradients are reduced in regions of low shear [3]. In HL-2A experiments, it is observed that LLMs can be suppressed by ECRH, and by applying supersonic molecular beam injection (SMBI) or cluster jet injection (CJI) effectively. The control of LLMs may also be related to the change of $\Delta q$ or the pressure profile induced by the local heating or fuelling.

References