First Observation of Persistent Small Magnetic Islands on HL-2A

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Abstract. On HL-2A, the spontaneous and persistent small islands have been first experimentally observed by Mirnov probe. The experimental characteristics and preliminary numerical modeling results of the small island are presented in this paper. The small islands can exist for the whole discharge flat top period with wide range of plasma parameters, and the corresponding normalized island width, W/a, is always saturated at a few percent. The small islands exhibiting a typical frequency of 5kHz are affected by the local plasma parameters and tangential NBI. With strongly localized heating by ECRH, m/n=2/1 and 3/2 neoclassical tearing modes led by small island have been observed in HL-2A. Using the model based on the two-fluids equations, numerical calculations of the linear drift tearing modes have been performed in HL-2A. Preliminary numerical modeling results show that one type of island can grows and saturates at a width about 0.01a, which is in agreement with experimental observations.

1 Introduction

Tearing mode instabilities, which can lead to confinement degeneration, even discharge disruption, play an important role in tokamaks. Tearing modes in tokamak plasmas have been studied for many years[1]. And the experimental research for tearing modes was focused on the large island, which have a sufficiently large width islands. The classical tearing mode instability is arose from the free energy of an unstable current profile. For a high pressure tokamak plasma, the perturbed bootstrap current due to the plasma pressure perturbations usually drives the nonlinear growth of neoclassical tearing mode (NTM) [2]. In recent years the research efforts on the tearing modes have mainly been devoted to the NTMs[3-6], including the threshold for their onset, the nonlinear growth and saturation of the mode and the effect of the perturbed bootstrap current on the double tearing mode, the interaction between NTMs, and the stabilization of NTMs by RF waves.

Different from the usual TM/NTM, a type of spontaneous and persistent small islands has been first experimentally observed in the HL-2A tokamak. The small islands are always saturated at a few percent and then sometimes lead to NTMs. This phenomenon challenges the existent theoretical model for NTMs, which indicates that small island will be stabilized by the ion polarization current and a sufficient large seed island is required to trigger the NTMs.

For a small island, much more complicated physics is involved due to the finite pressure gradient around the rational surface. As described in ref.[8,9], including of the electron perpendicular heat transport, a new type of tearing mode is found destabilized by a sufficiently large electron temperature gradient for a certain range of the electron diamagnetic drift frequency. This numerical results provide a possible explanation for the small island and NTMs grow spontaneously. In this paper, the experimental characteristics of the small island in HL-2A are described, and the preliminary modeling results are presented.

2 Experimental setup

The HL-2A tokamak[10] (with major radius of R=1.64m and minor radius of a=0.4m) has a axisymmetric single-null divertor. The achieved operation parameters on HL-2A are as follows: the toroidal magnetic field is 2.7 T, the plasma current is 450 kA, the electron and ion temperatures are 5 keV and 1.5 keV, respectively, and the plasma density is 8×10^{19} m^{-3}. ELMy H mode has been obtained in single null divertor configuration plasmas heated by electron cyclotron resonant heating (ECRH) and neutral beam injection (NBI) in 2009 experiment campaign.

One set of Mirnov probes is equipped on HL-2A[11]. A poloidal array of 18 pick-up coils is used to determine the poloidal mode number. The distance between two adjacent probes in poloidal direction is 10.5^0, as shown in FIG.1. They can be used to determine poloidal mode number of $m\leq17$. 10 Mirnov coils arranged along toroidal direction are employed to detect the toroidal mode. The toroidal Mirnov coils can recognize $n\leq4$ mode.

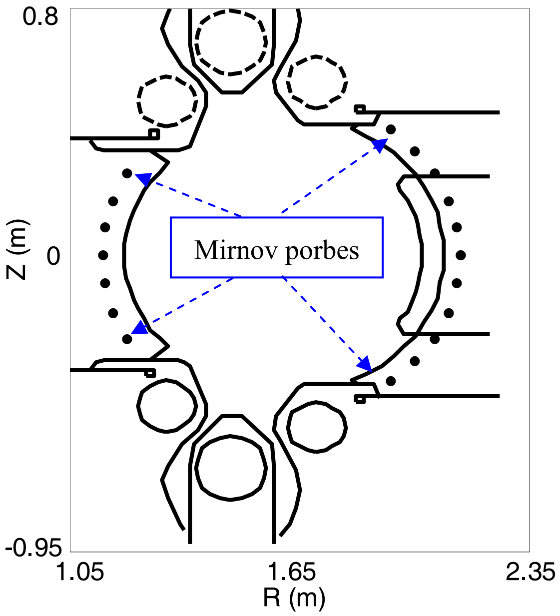

FIG.1. Location of poloidal Mirnov probes on HL-2A, 1th~18th.

3 Experimental characteristics of small island

3.1 Typical characters of the small island

On HL-2A, the spontaneous and persistent small islands have been observed by Mirnov probes in the most discharges with wide range of plasma parameters, such as plasma current I_p=100-350kA, toroidal magnetic field B_t=1-2.7T, line average electron density n_e=0.2-6*$10^{19}$$m^{-3}$. The typical characters in an Ohmic discharge with small islands are shown in FIG.2, shot 10036, I_p=185 kA, B_t=1.42T, safety factor at the edge q_{95}~3.8. As shown in FIG.2(d), the amplitude of the modes, nearly the noise level, almost can't be observed by the raw Mirnov signal. The time frequency spectrum of a Mirnov signal in FIG.2(e) shows two MHD modes m/n=2/1, 3/1 and their harmonics are detected. The small MHD activities can exist for the whole discharge flat top period and keep constant amplitude and frequency if the plasma parameters, such as electron density and temperature, do not change, indicating that the islands are saturated. The islands propagate in the direction of the electron diamagnetic drift. The saturated amplitude of the small MHD perturbation is $\tilde{B}_\theta / B_\theta \approx$ 0.03 ~ 0.08 %. The corresponding normalized island width, W/a, is estimated as a few percent. This is very different from the usual TM/NTM observed on HL-2A, which saturates at a much larger amplitude with $W/a = 0.1 \sim 0.2$.

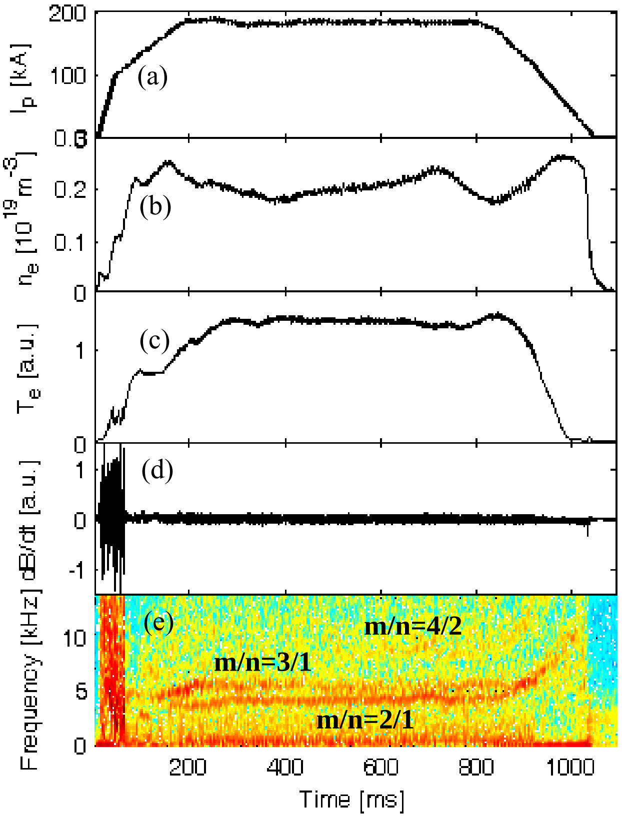

FIG.2. Typical parameter waveforms from the top down are, the plasma current, electron density (by HCN interferometer), electron temperature (by ECE), Mirnov signal and the spectrogram of Mirnov signal, respectively.

3.2 Mode frequency

The small islands have the typical frequency of ~5kHz, as shown in FIG.2(e), the 2/1 mode at ~4kHz and 3/1 at ~6kHz. However, the mode frequency of the small islands is affected by plasma parameters. The relations between the mode frequency and the central plasma parameters (measured by ECE and HCN interferometer) are shown in FIG.3. With similarity plasma parameters, I_p~180kA, B_t~1.33T, the frequency of the 2/1 mode increases with increasing density and decreasing temperature. The frequency of the 3/1 mode, however, decreases as the density increases. The mode frequencies depend on the local plasma

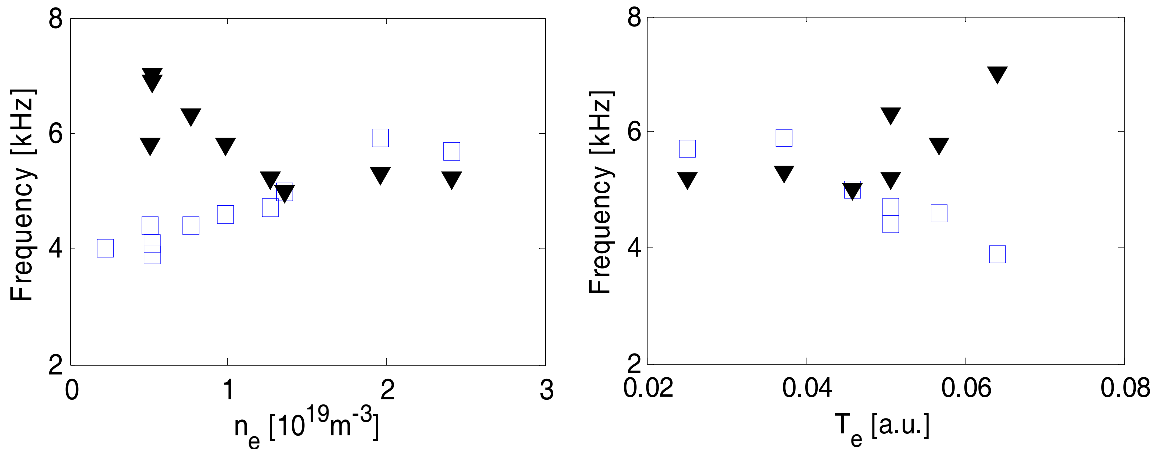

FIG.3. The frequency of the MHD mode versus electron density and temperature. Rectangle “□” and triangle “▼ ”mean the m/n = 2/1 and 3/1 modes respectively.

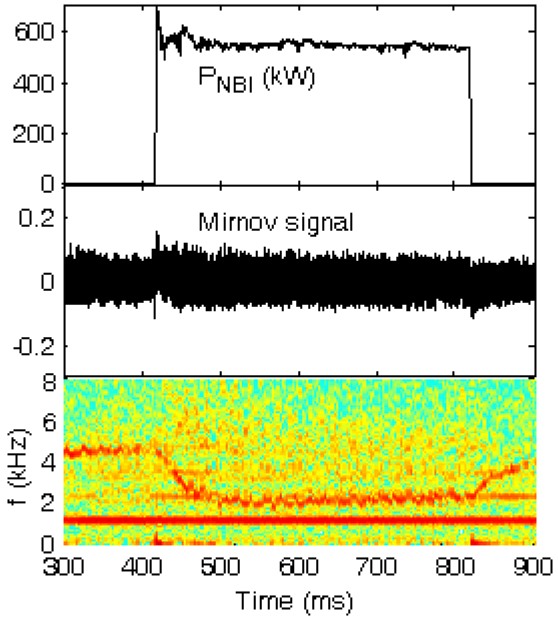

FIG.4. The frequency of small island decrea due to tangential NBI.

parameters where the magnetic island locates. The changes of the central parameters lead to the corresponding changes in the local plasma parameters and profiles.

For large islands, such as TMs, the frequency will be affected by the tangential neutral beam injection. In HL-2A, TM frequency always decreases during NBI. Here the NBI is injected from the co-current direction (count-toroidal magnetic field). Similar to TM, the frequency of small island is always effected by the tangential NBI. As shown in FIG.4, the frequency of 2/1 small island decreases from 4.8kHz to 2.4kHz due to the tangential NBI. After NBI turn off, the mode frequency increases again.

3.3 density limit disruption initiated by growth of small island

For small islands, the influence on confinement is always not much serious because of the small saturated amplitude. But in some discharges with high density (such as $n_e > 2.5 * 10^{19} m^{-3}$, $I_p \sim 160kA$), plasma minor disruption leading by the sharply growth of the small islands is observed. As shown in FIG.5, shot 10090, I_p=160kA, 2/1 small island is observed before minor disruption at t=422ms, and the frequency increases with increasing density. FIG.5(c) illustrates the spectrogram of Mirnov probe. When the line average electron density

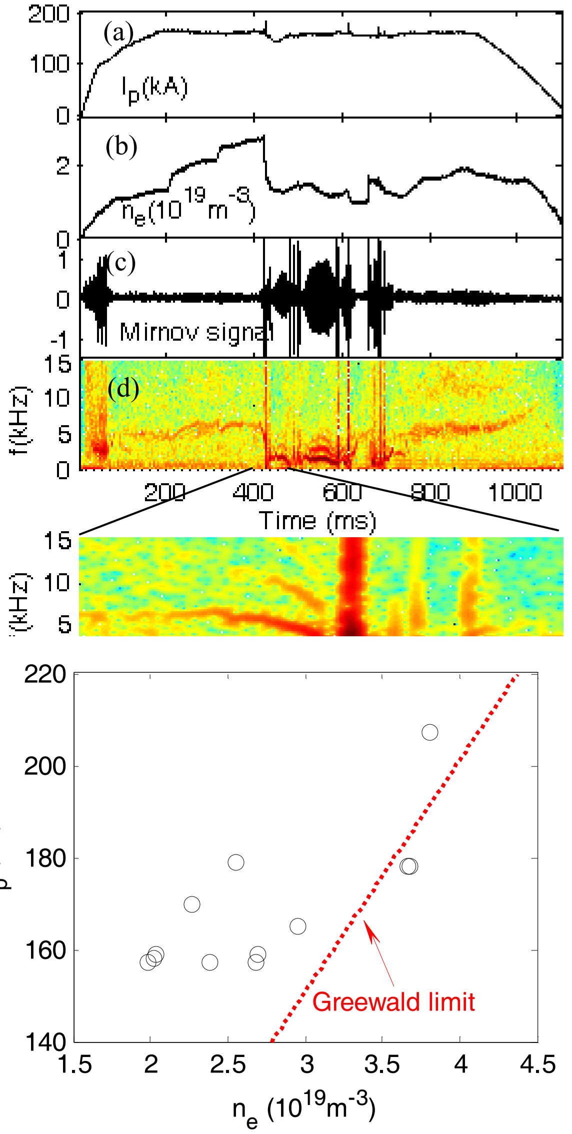

FIG.6. The disruption leaded by the growth of small island limits the density achievement.

increases up to 2.7*10^{19}m^{-3}, the amplitude of the small island grows with a typical growth time of about 10ms, and at the same time the frequency decreases from 6kHz to 2kHz shown in the zoom windows. At t=422ms, the amplitude of the island grows up to W/a~0.2 and disruption occurs, the density sharply decreases from 2.7*10^{19}m^{-3} to 1.35*10^{19}m^{-3}. The plasma currents are always not quenched by this kind disruption.

In FIG.6, the density before the disruption occurs is plotted against plasma current in Ohmic discharges. The density which can be achieved is higher when the plasma current is increased. The dashed line in FIG.6 shows the Greenwald density limit, $\bar{n}_G = I_p / \pi a^2$, where $\bar{n}_G$, I_p and a are in units of 10^{20} m^{-3},MA and m. From the results, it seems like that the density limit disruption is caused by the growth of small island.

3.4 NTMs trigger by small islands

Since the neoclassical drive of an island is reduced by the effects of an incomplete flattening of the pressure profile and polarization currents, an NTM requires a seed island whose width has to exceed the critical island width for a positive growth. Such seed islands are usually provided by sawteeth, fishbone or ELMs[3][12-13]. But spontaneous NTMs are observed in ASDEX-Upgrade, T-10, TCV and TFTR. On HL-2A, the m/n=2/1 and 3/2 neoclassical tearing modes have been observed with strong central ECRH. The NTMs are triggered by sawteeth crash with m/n=1/1 precursors, which are toroidal coupled with small scale m/n=2/1 mode. An example of a large m/n=2/1 island (NTM) shown in FIG.7, growing from a small 2/1 mode coupled with an m/n=1/1 oscillation in ECRH heated discharge, is shown in Fig.7. One can see the significant difference in the 2/1 mode amplitude before and after t = 770 ms, indicating the existence of small island before it grows to a large one.

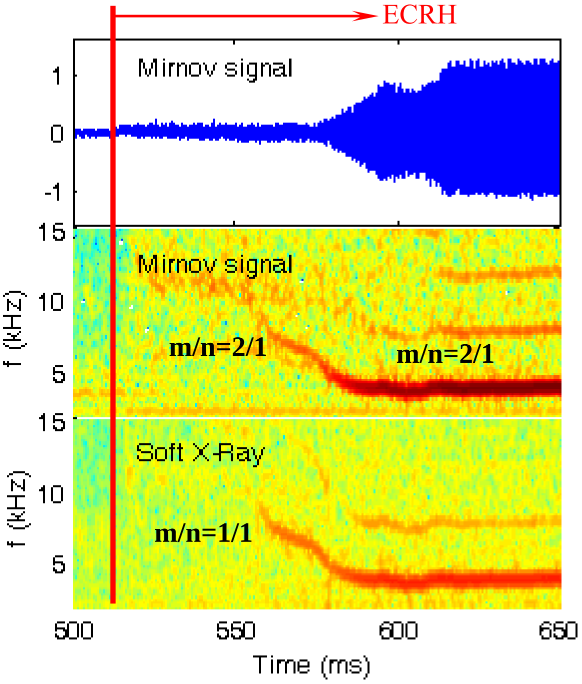

FIG.7. A large saturated m/n=2/1 neoclassical tearing mode is triggered by sawtooth crash with 1/1 precursor, which is toroidal coupled with small scale 2/1 mode.

4 Preliminary modeling results

To understand the experimental results, numerical modeling has been carried out by using the following normalized nonlinear two fluid equations[8,9],

$$\frac{dn_e}{dt} = d_1\nabla_\parallel j - \nabla_\parallel(n_e v_\parallel) + \nabla\cdot(D_\perp\nabla n_e) + S_n\,, \tag{1}$$

$$\frac{d\psi}{dt} = E - \eta(j - j_b) + \Omega[\nabla_\parallel n_e + 1.17(1+\alpha)\nabla_\parallel T_e]\,, \tag{2}$$

$$\frac{dv_\parallel}{dt} = -C_s^2\nabla_\parallel P/n_e + \mu\nabla_\perp^2 v_\parallel \quad , \tag{3}$$

$$\frac{dU}{dt} = -S^2\nabla_\parallel j + \mu\nabla_\perp^2 U\,, \tag{4}$$

$$\frac{3}{2}n_e\frac{dT_e}{dt} = (1+\alpha)d_1\nabla_\parallel j - T_e n_e\nabla_\parallel v_\parallel + n_e\nabla\cdot(\chi_\parallel\nabla_\parallel T_e) + n_e\nabla\cdot(\chi_\perp\nabla_\perp T_e) + S_p\,. \tag{5}$$

In Eqs. (1)-(5) $dt/dt = \partial/\partial t + v_\perp\cdot\nabla$, ψ is the helical flux function, j is the plasma current density, j_b is the bootstrap current density, n_e and T_e are the electron density and temperature, $U = -\nabla_\perp{}^2\phi$ is the plasma vorticity, μ the plasma viscosity, χ the heat conductivity, and D the particle diffusivity. The ion velocity $v = v_\parallel e_\parallel + v_\perp$, where $v_\parallel$ and $v_\perp = \nabla\phi\times e_t$ are the parallel (to the magnetic field) and the perpendicular velocity, respectively. P=$n_e T_e$, the subscripts || and ⊥ denote the parallel and the perpendicular components, respectively, and α=0.71. S_n, S_p and E are the particle and heat source and the equilibrium electric field, respectively. The Normalization scheme is as the following: the length to the minor radius a, the time t to τ_R, ψ to aB_{0t}, **v** to a/τ_R, and T_e and n_e to their values at the magnetic axis, where $\tau_R = a^2/\eta$ is the resistive time. The cold ion assumption is made.

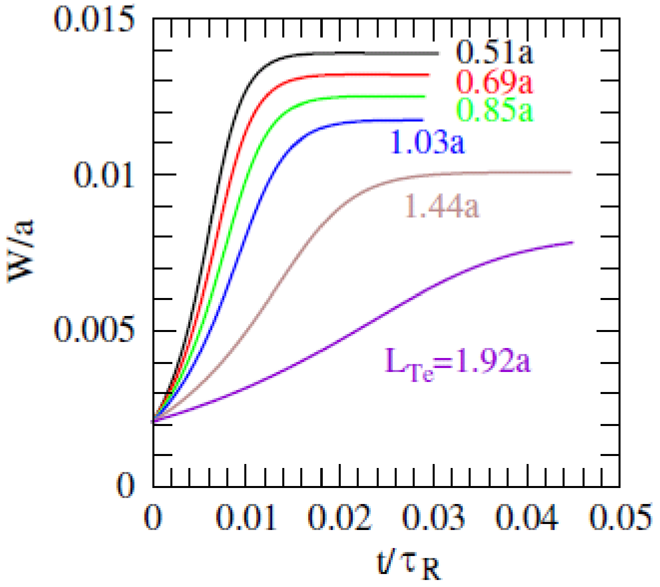

FIG.8. The nonlinear time evolution of the normalized island width, W/a. The island grows and saturates at a width about 0.01a, in agreement with experimental observations.

The parameters in equations (1)-(5) are given by $d_1=\omega_{ce}/\nu_e$, $\Omega=\beta_e d_1$, $C_s=[T_e/m_i]^{1/2}/(a/\tau_R)$, and $S=\tau_R/\mathbf{v}_A$, where $\beta_e=4\pi n_e T_e/B_{0t}^2$, ω_{ce} and ν_e are the electron cyclotron and the collision frequency, and $\tau_A=a/v_A$ is the toroidal Alfven time. The corresponding plasma in HL-2A has the following parameters: T_e=400eV, $n_e=0.5\times10^{19}m^{-3}$, and B_{0t}=1.33T, and Z_{eff}=2, leading to $S=2.19\times10^7$, $d_1=5.56\times10^6$, $\Omega=1.27\times10^3$, $C_s=4.64\times10^5$, and $\chi_{\parallel}=3.6\times10^9a^2/\tau_R$. $\mu_{\perp}=\chi_{\perp}=0.1m/s=0.42a^2/\tau_R$ and $D_{\perp}=\mu_{\perp}/6$ are taken. The bootstrap current density fraction is nearly 0. The safety factor q profile is monotonic with a negative value of Δ' for the 2/1 mode. The q=2 surface is at 0.586a.

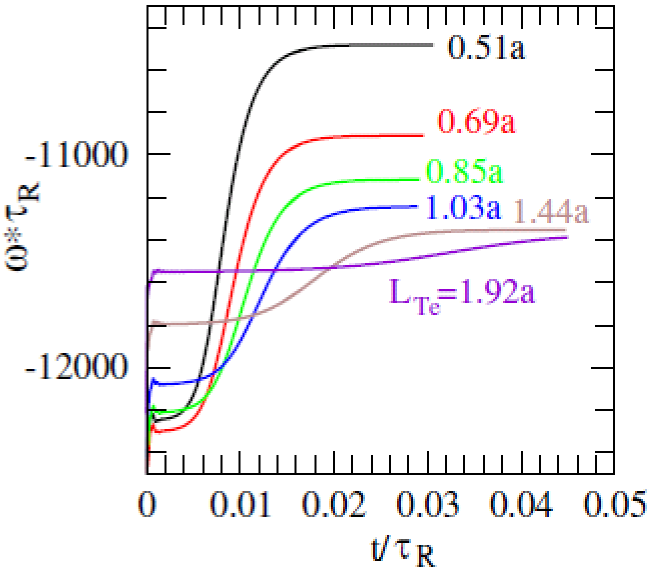

FIG..9. The time evolution of the normalized mode frequency with different electron temperature gradient.

The nonlinear time evolution of the normalized island width, W/a, is shown in FIG.8. Due to the uncertainty in the experimental data for electron temperature profile, our calculations are performed for the local equilibrium electron temperature gradient length at the q=2 surface, $L_{Te}=T_e/(dT_e/dr)$, equals 1.92a, 1.44a, 1.03a, 0.85a, and 0.51a. The local equilibrium density gradient length at the rational surface, $L_n=n_e/(dn_e/dr)$, is taken to be 0.42a. It is seen that the island grows and saturates at a width about 0.01a, in agreement with experimental observations. A large electron temperature gradient leads to a larger saturated island width. The local electron temperature gradient is decreased by the island, which in turn leads to the mode saturation.

Corresponding to FIG.8, the time evolution of the normalized mode frequency is shown in FIG.9. The mode frequency approaches a lower value for a larger island case due to the change of the local electron diamagnetic drift frequency (electron temperature gradient).

5 Summary and discussion

In summary, the experimental characteristics and preliminary modeling results of the small island observed in HL-2A are presented in this paper. The small islands can exist for the whole discharge flat top period with wide range of plasma parameters, and the corresponding normalized island width, W/a, is always saturated at a few percent. NTMs triggered by small island is observed in HL-2A. Preliminary numerical calculations of the plasma in HL-2A show that a type of tearing mode instability can be unstable and saturated at small island level, which is in agreement with experimental observations.

The numerical calculations show that the saturated width and frequency of the island depend on the local equilibrium electron temperature gradient length. In HL-2A, the measurement of local electron temperature profile is difficult. But the mode frequency changing with electron temperature or density are observed. In the future work, further research on the characters of the small island and comparison with numerical calculation will be preformed.

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