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EXPERIMENTAL OBSERVATIONS OF MAGNETOHYDRODYNAMIC INSTABILITIES IN HL-3 LOW CURRENT HIGH-β_N PLASMAS

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Abstract:

The value of normalized toloidal beta (β_N) can reach to 3.7, 4.9 and 3.0 in the induced, hybrid and high-q_{95} operation scenarios (OSs) in HL-3 low current (∼260-300 kA) plasmas, respectively. Many kinds of magnetohydrodynamic (MHD) instabilities, which are internal kink mode (sawtooth, fisbone (FB) and Long-live mode (LLM)), neo-classical tearing mode (NTM), Alfvén eigenmodes (AEs) and so on, are found in the high-β_N plasmas. It can be found that the core localized m/n=1/1 FB or LLM can co-exist with the strong multi-branches NTMs, e.g., m/n=2/1, 3/2 and 4/3 NTMs in the induced OSs. The co-existence of low-frequency internal kink modes and NTMs can even lead to disruptions; The m/n=2/1 NTMs can be induced by fishbone. The strong core FBs, moderate m/n=3/2 NTMs and weak AEs are presented when β_N reach to its maximum 4.9 in the hybrid OSs; There are only single FBs are found in high-q_{95}(∼7-9) OSs. The abundant MHD instabilities limit the achievement of β_N ($\beta_{N,Max}$∼3.7) in induced OSs. Because of the FB and moderate m/n=3/2 NTMs, the value of β_N can reach to 4.9 in hybrid OSs. Though the low β_N can only reach to 3.0 in high-q_{95} OSs, the poloidal beta (β_p) can reach to 2.7 in the high-q_{95} plasmas.

1.Introduction

The toroidal beta (β_t) of the magnetic fusion plasmas, defined as $\beta_t = P/(B_t^2/2\mu_0)$, is an important parameter to characterize the performance and economic efficiency of a fusion reactor, where $P = \frac{3}{2}nk(T_i + T_e)$ and $B_t^2/2\mu_0$ is the plasma thermal pressure and magnetic pressure, and B_t, n, T_i and T_e represent the toroidal magnetic field, plasma density, ion and electron temperatures. For comparing the values of β_t from different devices, it can be normalized as the dimensionless parameter $\beta_N = \beta_t/(I_p/aB_t)$, where I_p and a is the plasma current and the minor radius of the device [1]. High β_N is favorable for achieving plasma ignition, for the "triple product" is proportional to β_N, i.e., $nT_i\tau \propto (\beta_N I_p B_t/a)(H\tau_{scale})$, where H and τ_{scale} represent the H-factor and confinement time, respectively; The fusion power (P_{fus}) is also proportional to the square of β_N ($P_{fus} \propto \beta_N^2 I_p^2 B_t^2$); In addition, the bootstrap current fraction (f_{bs}) is proportional to β_N ($f_{bs} \propto C_{BS}\beta_N q_{95}$, where C_{BS} is a coefficient, and q_{95} is the safety factor at the rational surface containing 95% of the magnetic flux) [2]. According to the operation scenarios (OSs) in International Thermonuclear Experimental Reactor (ITER), there are clear requirements

for β_N in the induced, hybrid and steady-state OSs, e.g., the non-inductive current drive fraction should be 15%, $\sim$ 50% and 100%, and the corresponding β_N need to reach to $\sim$1.8, 2.0-2.5 and $\geq$2.6, respectively [3].

Because the high pressure (and its gradient), high fraction of non-inductive current and high population of energetic particles in the high-β_N plasmas. Many kinds of magnetohydrodynamic (MHD) instabilities which can degrade the confinement had been found, e.g., internal kink modes (IKMs) (including, sawtooth (ST), fisbone (FB) or Long-live mode (LLM)), neo-classical tearing modes (NTMs), Alfvén eigenmodes (AEs), and so on, especially for the m/n=2/1 NTMs, where m and n are poloidal and toroidal mode numbers, which can lead to the direct disruption in the high-β_N (pressure) plasmas [4, 5]. The β_N can reach to 3.8 by taking the advantages of double transport barriers (DTBs) in ASDEX-U n_e/n_G $\sim$0.8-0.9 high-density plasmas, where n_e and n_G is the electron density and Greenward density. The n=1 FBs and n=2 modes are found in the high β_N plasmas [6]. There are strong effects of NTMs on confinement, e.g., the β_N decreases from 3.0 to 2.4 obviously during the appearance of m/n=3/2 NTMs combined with 2/2 NTMs [7]. In the B_t=1.7 T hybrid plasmas in JET, the value of β_N is limited as 2.7 by the MHD instabilities [8]. A comparison in DIII-D proved that the m/n=3/2 NTMs will reduce β_N obviously, and the 2/1 NTMs will cause collapses [4]. In the high self-induction (l_i) plasmas in DIII-D, the β_N can be higher than 5.0, and the n=1 NTMs are dominant [9]. The m/n=2/1 and 3/2 NTMs will cause the decrease of β_N, and even degradation from H-mode to L-mode in HL-2A $\beta_N$$\sim$2.0-3.0 plasmas [10, 11]. The toroidal/beta-induced Alfvén eigenmodes (TAEs/BAEs) occur regularly in high-β_N region and cause large type-I edge localized modes (ELMs) burst in HL-2A hybrid plasmas [12, 13].

The high-β_N had been reached in the induced, hybrid and high-q_{95} OSs in HL-3 low current (260-300 kA) plasmas, respectively. Various MHD instabilities, e.g., IKMs (FBs and LLMs), NTMs, AEs, and even the co-existence among them, can be found in the high-β_N induced plasmas, espeically. The β_N is limited by the MHD instabilities, especially for co-existence of LLM and NTMs, and multi-mode NTMs. The β_N are limited to 3-4 because of abundant MHD instabilities in induced plasmas. The core FBs, moderate m/n=3/2 NTMs and weak AEs are found in the hybrid OSs. Taking advantage of these moderate MHD instabilities, β_N can be in the high level of 4-5. Only the single FBs are found in high-q_{95}($\sim 7-9$) OSs. The β_N can only reach to 3 in the high-q_{95} (or high-B_t) plasmas. The effects of the MHD instabilities on limitation of β_N will be introduced in detail in the different OSs.

2.Experimental Results

HL-3 is a medium size tokamak for magnetically controlled fusion research, with major and minor radius R=1.78 and a=0.65 m [14]. The design parameters are I_p=2.5-3 MA, B_t=2.2-3 T, the elongation and triangularity are in the range of $\kappa \leq$1.8 and $\delta \leq$0.5. The neutral beam injection (NBI) [15], electron cyclotron resonant heating (ECRH) [16] and low hybrid current deriving (LHCD) [17] systems had been equipped in HL-3. The neutral beams co-inject into plasma with an injection angle of 38.6°, the designed energy of beam ions (E_b) are $\sim 30-80$ keV. There are two NBI systems equipped on HL-3, and the total power of NBI (P_{NBI}) can reach up to 5 MW, recently. Up to now, the capability of radio frequency heating and current drive system has been improved to 6 MW, including the ECRH of 4 MW and LHCD of 2 MW.

The high-β_N plasmas can be achieved in the induced, hybrid and high-q_{95} OSs, and the corresponding discharge parameters and their spectrogram in typical shots 10315, 12469 and 12369 are shown shown in Fig.1 (left), (middle) and (right) panels, respectively.

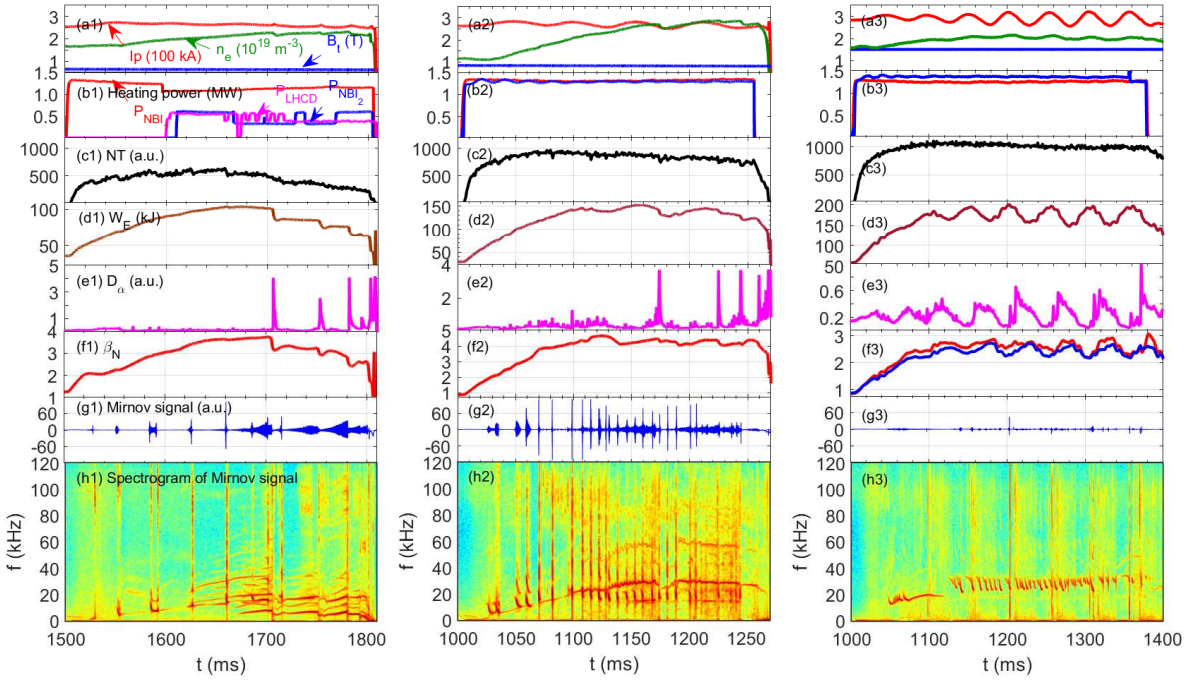

FIG. 1: Typical examples of high-β_N plasmas in induced, hybrid and high-q_{95} OSs for shots 10315, 12469 and 12369 in the left, middle and right panels. (a) discharge parameters of I_p , n_e and B_t, (b) heating power: P_{NBI} and power of LHCD (P_{LHCD}), (c) neutron flux (NT, black-curves), (d) stored energy (W_E, brown-curves) (e) Deuterium α-light signal(D_α, pink-curves), and (f) β_N (red-curves) and poloidal β (β_p, blue curves).

TABLE I: Comparisons among the parameters and performance in high-β_N plasmas with induced, hybrid and high-q_{95} OSs in HL-3.

OSs	Induced	Hybrid	high-q_{95}
I_p (kA)	260	260	300
n_e (10^{19}m^{-3})	1.6-2.3	1.1-2.8	1.6-2.1
B_t (T)	0.6	0.8	1.6
κ	1.45	1.35	1.35
δ	0.5	0.45	0.5
q_{95}	3-4	4-5	8-10
P_{NBI} (MW)	1.7	2.6	2.6
P_{LHCD} ((MW))	0.6	0	0
W_E ((kJ))	103	152	200
$\beta_{N,max}$	3.6	4.9	3.0
IKMs	STs, FBs or LLMs	FBs or LLMs	FBs or LLMs
NTMs (m/n)	Y (4/3, 3/2, 2/1)	Y (3/2, 2/1)	N
AEs	Y	Y	N
ELMs	Free, Type-I	Small, Type-I	Small

The rough discharge parameters and comparisons of shots are presented in Table.I. The corresponding β_N can reach to 3.7, 4.7 and 3.0 in the three shots. There are obvious difference for the amplitude presented by Mirnov signals and its spectrogram caused by MHD fluctuations, as shown in Fig.1 (g) and (h). It can be observed that the amplitude of the Mirnov signal is strongest, moderate and weakest in the induced, hybrid, and high-q_{95} OSs, respectively. From the spectrogram of Mirnov signal, there are multiple low-frequency instabilities (STs, FBs/LLMs and many branch NTMs) and high-frequency AEs in the induced OSs, and low-frequency MHD instabilities (FBs and one branch NTM) and weak AEs followed in the hybrid OSs. While only FBs in the high-q_{95} OSs. The difference of the achieved β_N are caused by the amplitude and variety of MHD instabilities for the induced and hybrid OSs. Because of the high B_t in the high-q_{95} OSs, the value of β_N is small compared with the other two OSs. But, the β_p can reach to 2.7 in the high-q_{95} OSs.

2.1 MHD Instabilities in High-β_N Induced OSs

There is a typical example of high-β_N plasmas in shot 10315 in induced OSs, as shown in left part of Fig.1. The I_p and n_e are in the range of 260±5 kA and(1.6-2.3)×10^{19} m^{-3}, and B_t keeps as ∼0.63 T, as shown in Fig.1 (a1). The heating power of NBI and LHCD are in the range of ∼1.3-1.7 MW and ∼0.3-0.6 MW, and the power and input sequence NBI and LHCD can refer to Fig.1 (b1). The W_E rise rapidly form 35 to 90 kJ since the input of 1.3 MW NBI during t=1500-1600 ms, and the W_E increase continuously from 90 to 102 kJ after the startup of 0.6 MW LHCD and combined with total 1.7 MW NBI during t=1600-1705 ms, as shown in pannel (d1). The plasmas transit from L-mode to ELM-free H-mode at t=1555 ms, and then transit into Type-I ELM H-mode after t=1705 ms, presented by D_α signal in pannel (e1). The n_e increases continuously from1.67×10^{19} m^{-3} to2.26×10^{19} m^{-3} during the period of ELM-free H-mode. The W_E increase to the top of 104 kJ at t=1660 ms, and then W_E decreases to 100 kJ when t=1705 ms, slightly. The neutral flux also decreases obviously after t=1660 ms. The β_N can reach to the top of 3.7 at the end of the ELM-free H-mode. There are obvious drops of W_E and β_N just after the bursts of ELMs when plasmas transit into the Type-I ELM H-mode after t=1705 ms (panels (d1-f1)).

Abundant MHD instabilities with different kinds, frequencies (wave length), locations and mode numbers, e.g., STs, FBs, LLMs, NTMs, AEs and ELMs, which can effect the confinement and limit the achievement of β_N, are found in induced OSs, as shown in Fig.2. The slight effects of STs or FBs on confinement are observed. The STs are labeled by the blue dashed lines. When the strong ST bursts at t=1660 ms (ST_3), there is a obvious small drop of W_E and β_N. While the other small-burst STs can only weaken the growth rate of β_N. The dramatic drops of β_N or W_E caused by ELMs (labeled by the pink dashed lines) can be found obviously.

There are mainly low-frequency MHD instabilities, e.g., FBs, LLMs and NTMs in the ELM-free H-mode period, as shown in Fig.2 (left). The core FBs and LLMs can be found during the NBI heating. The mode numbers for the FBs and LLMs are m/n=1/1. There are 3 branch NTMs, with frequencies in the range of 5-9 kHz, 14-21 kHz and 25-35 kHz, and the corresponding mode numbers are m/n=2/1, 3/2 and 4/3, which are labeled on the spectrogram. The strong m/n=4/3 and weak 3/2 NTMs appear when β_N rises to 3.4 after the burst of ST_2. The strong LLM (or FB), m/n=4/3 and 3/2 NTMs co-exist during ST_2 and ST_3. The strong m/n=2/1 NTM appears when β_N reach to 3.6 after ST_3. The 3 NTMs with mode numbers m/n=2/1, 3/2 and 4/3 and LLM (or FB) co-exist during ST_3 and ST_4. The coexistence of multi-mode MHD reduces the growth rate of β_N, and the β_N reaches to 3.7 hardly. It can be found that the m/m=1/1 LLM and 4/3

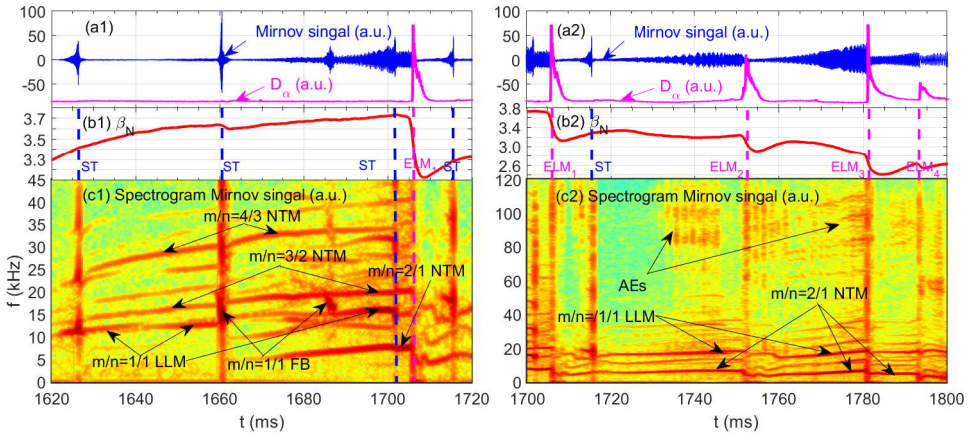

FIG. 2: MHD instabilities in the (left) ELM-free and (right) Type-I ELM H-mode plasmas in induced OSs. (a) Mirnov and D_α signals, (b) β_N and spectrogram of Mirnov signal, on which the name and mode numbers of the instabilities are labelled.

NTM disappear suddenly after the burst of ST_4, because the 2 modes locate on the core and can be effects by the ST. And then, the edge m/n=3/2 and 2/1 NTMs are broken by strong influence of ELM_1, which indicates the two modes located on the edge compared with 1/1 LLM and 4/3 NTM.

With the increase of n_e, the plasmas transit from ELM-free H-mode to type-I ELM H-mode after t = 1705 ms. The obvious effects of ELMs on β_N (and W_E) can be found during the type-I ELM H-mode period. The ratio of W_E drops (ΔW_E) to W_E, i.e., $\Delta W_E/W_E$, caused by the 3 ELMs is in the range of $(12.9 - 15.7)\%$. There are mainly core LLM and m/n=2/1 NTM, and 80-120 kHz high-frequency AEs in the type-I ELM H-mode, as shown in the right part of Fig.2. There are obvious decrease of β_N during the cover of the low-frequency MHD modes and AEs. The nonlinear interactions have not been found between them. There maybe a strong synergy between the core low-frequency modes and the edge high-frequency AEs, which reduces the confinement performance.

The effects of MHD instabilities on β_N can be estimated by the fluctuated amplitudes of Mirnov signals caused by a certain MHD instabilities and the corresponding tendency of β_N (rise or drop). The fluctuated amplitude of the MHD instabilities can be obtained by the method of narrowband filtering method, as shown in Fig.3. There are the evolutions of β_N, original Mirnov signals, D_α signal and the fluctuated amplitude of the MHD instabilities in the ELM-free and type-I ELM H-mode high-β_N plasmas in left and right panels. There are m/n=4/3 NTMs, 2/2 modes, 3/2 NTMs, 1/1 FBs/LLMs and 2/1 NTMs in the ELM-free period. The fluctuated amplitudes of them are obtained by the wave filtering though passband of 30-35, 30-33, 17-21, 14.8-17.5 and 5-9 kHz, as shown in panels (c1)-(g1). It can be found that the amplitude of m/n=3/2 NTMs, 1/1 FBs/LLMs and 2/1 NTMs reach to 8, 28 and 15 a.u.. The bursts of 3/2 NTMs and core FBs/LLMs at t=1685, 1686.5 and 1701.5 ms will cause the slight decrease of β_N. The amplitude of 2/1 NTMs is proportional to β_N, and the NTMs disappear suddenly after the burst of ELMs at t=1706 ms, in which there is a sharp decline of β_N. The amplitudes of m/n=4/3 NTMs and 2/2 mode are very small, and are close to 1 a.u., as presented in panels (c1)-(d1). The effects of them on β_N or confinement is very weak.

There are mainly low-frequency strong m/n=1/1 LLMs and 2/1 NTMs, and weak high-frequency AEs, which are filtered in passband 60-130, 14-20 and 3-8 kHz and pre-

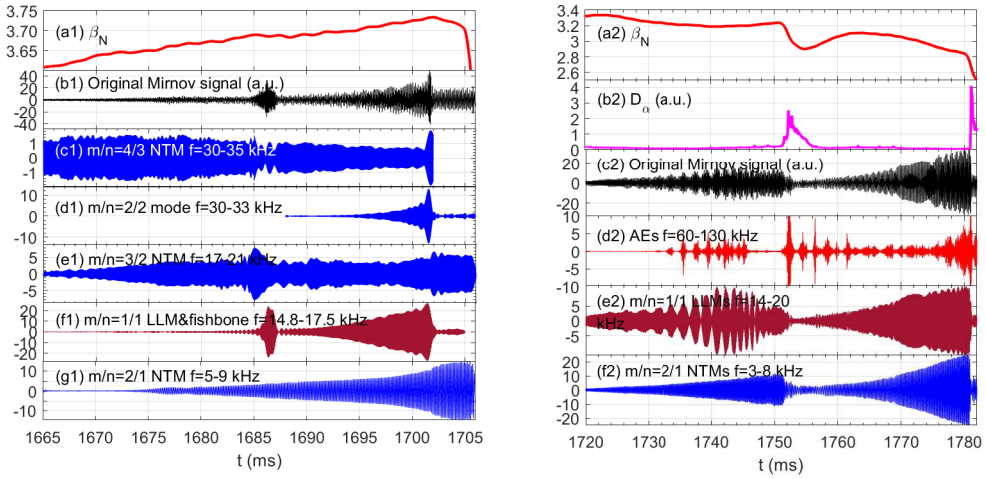

FIG. 3: Amplitudes of the MHD instabilities filtered by Mirnov signals in high-β_N ELM-free (left) and type-I ELM (right) plasmas. (a1) and (a2) evolutions of β_N, (b1) and (c2) original Mirnov signals, (b2) D_α signal, amplitudes of (c1) m/n=4/3 NTMs filtered by passbands of 30-35 kHz, (d1) m/n=2/2 modes filtered by passbands of 30-33 kHz, (e1) m/n=3/2 NTMs filtered by passbands of 17-21 kHz, (f1) m/n=1/1 FBs and LLMs filtered by passbands of 14.8-17.5 kHz, (g1) m/n=2/1 NTMs filtered by passbands of 5-9 kHz, (d2) AEs filtered by passbands of 60-130 kHz, (f1) m/n=1/1 LLMs filtered by passbands of 14-20 kHz, (g1) m/n=2/1 NTMs filtered by passbands of 3-8 kHz.

sented in panel (d2), (e2) and (f2) during type-I ELM H-mode periods. The fluctuated amplitudes of LLMs (e2) and AEs (d2) are weaker than that (f1) and very weak. While, the original Mirnov signals (c2) are stronger than that (b1) in left panels, which are contributed by the stronger fluctuated amplitudes caused by m/n=2/1 NTMs. The β_N decreases obviously during the increase of NTMs before ELM bursts. It is indicated that strong m/n=2/1 NTMs play a key role on limitation of β_N.

2.2 MHD Instabilities in High-β_N Hybrid and High-q_{95} OSs

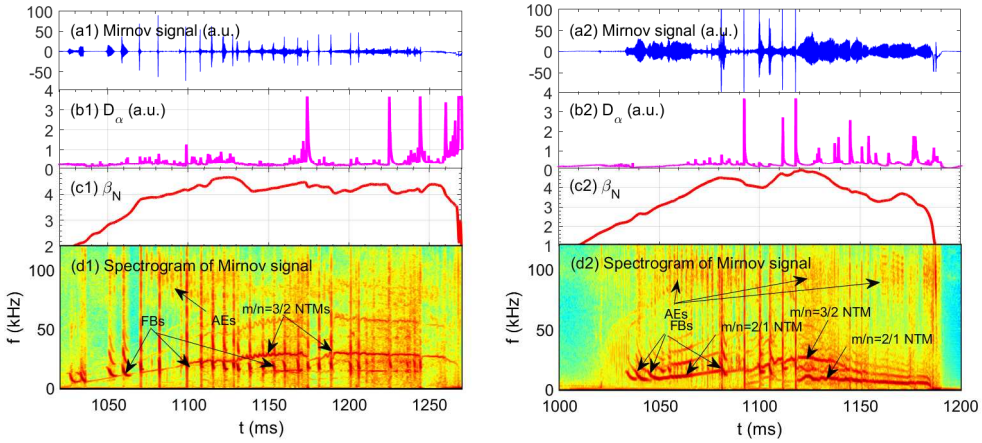

FIG. 4: MHD instabilities observed in hybrid OSs in shot 12469 and 12504. (a) Mirnov signals, (b) D_α signals, (c) β_N and (d) spectrogram of Mirnov signals in which the name and mode numbers of MHD instabilities are labeled.

The β_N can reach to 4-5 in hybrid OSs. There are the typical examples in shot 12469

and 12504, as shown in Fig.1 (middle) and Fig.4 (left) and (right). In shot 12469, the I_p and n_e are in the range of $250-280$ kA and $(1.1-2.8)\times10^{19}$ m^{-3}, and B_t keeps as $\sim$ 0.83 T, as shown in Fig.1. The NBI inject into plasmas at t=1005 ms with the $P_{NBI}=2.6MW$. The plasma transit into small ELM H-mode during t=1135-1174 ms, and then transit into Type-I ELM H-mode after $t=1174$ ms, presented by D_α signal in pannel (e2). The W_E rise continuously form 28 to 145 kJ during $t=1005-1108$ ms, and then W_E keeps in a high level of 110-152 kJ during t=1080-1260 ms (e2). The β_N keeps higher than 4 during during t=1086-1200 ms, and the β_N can reach its maximum of 4.7 at t=1126.7 ms (f2).

There are core FBs, m/n=3/2 NTMs and weak AEs in hybrid OSs shot 12469, as shown in Fig.4 (d1). The FBs appear just after the injection of NBI, and the m/n=3/2 NTMs emerge when the value of β_N close/higher to/than 4. The strong FBs and m/n=3/2 NTMs appear together when β_N is close to its maximum (4.7), and the co-existence of the MHD instabilities cause obvious decrease of β_N during t=1120-1140 ms. The outbreaks of type-I ELMs lead to the rapid drops of β_N. The FBs, m/n=2/1, 3/2 NTMs and high-frequency AEs are found in an other hybrid OSs shot 12504, and the β can reach to 4.9, as shown in Fig.4 (right). The m/n=2/1 NTMs are triggered by the 3^{rd} FB-burst after the injection of NBI. There are core FBs and weak 3/2 NTMs near t=1120 ms, during which the maximum β_N achieved in hybrid OSs. Then, the 2/1 NTMs are triggered by ELM, and the β_N decreases obviously (from 4.9 to 3.4) after the emerging of 2/1 NTMs. The amplitude of MHD instabilities, e.g., FBs and NTMs, are in the range 10-40 (a.u.) presented by Mirnov signal (Fig.1 (g2) and Fig.4 (a)).

Compared with the amplitude of MHD instabilities in induced OSs, the size of MHD instabilities in hybrid OSs is small. The maximum of β_N (4.9) can be achieved in hybrid OSs, because of the few kinds and small size MHD instabilities.

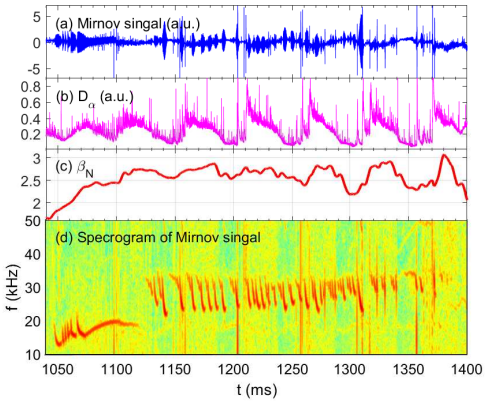

FIG. 5: MHD instabilities observed in high-q_{95} OSs in shot 12369. (a) Mirnov signals, (b) D_α signals, (c) β_N and (d) spectrogram of Mirnov signals.

The maximum value of β_N can only reach to $\sim$ 3 in the high-q_{95} OSs. There is a typical example in shot 12369, as shown in right pare of Fig.1. The I_p and n_e are in the range of $260-320$ kA and $(1.6-2.1)\times10^{19}$ m^{-3}, B_t keeps as $\sim$ 1.6 T, and P_{NBI}=2.6 MW, as shown in right parts of Fig.1 (a3)-(b3). The plasma transit into small ELM H-mode at t=1034 ms, presented by D_α signal in panel (e3). The W_E can rise to 200 kJ, but the β_N can reach only reach to 3.0 for the reasons of high B_t (1.6 T). On the other hands, the β_p can reach to 2.7. Only the core LLMs/FBs can be found in the high-q_{95} OSs, as shown in Fig.5 (d2). The amplitude of FBs are only 1-4 a.u. presented by Mirnov signal (Fig.5

(c2)), which is obvious smaller then that in induced (30 a.u.) and hybrid (29 a.u.) OSs. The q value plays an important role on determining the kinds and amplitude of MHD instabilities.

3.Summary

The high-β_N had been reached in the induced, hybrid and high-q_{95} OSs in HL-3 low-current (260-300 kA) plasmas, and the corresponding top of $\beta_{N,max}$ can reach to 3.7, 4.9 and 3.0. Various MHD instabilities, e.g., core IKMs (STs, FBs and LLMs), m/n=5/3, 3/2 and 2/1 NTMs, edge AEs, and even the co-existence of them, can be found in the high-β_N induced plasmas. The β_N is limited by these MHD instabilities, especially for co-existence of m/n=5/3, 3/2 and 2/1 NTMs, and even between low-frequency instabilities (core LLMs and m/n=2/1 NTMs) and AEs. The β_N can reach to 3-4 by the effects of MHD instabilities in induced plasmas. The core FBs, moderate m/n=3/2 NTMs and weak AEs are found in the hybrid OSs. The β_N can be in the range of 4-5 because of the weak MHD instabilities. Only the single FBs are found in high-$q_{95}(\sim 7-9)$ OSs. The β_N can only reach to 3 in the high q_{95} (or B_t plasmas), but the β_p can reach to 2.7. The comparisons among the parameters and performance in high-β_N plasmas with induced, hybrid and high-q_{95} OSs are shown in Table.I.

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