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

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The toroidal beta (β_t) of the magnetic fusion plasmas (defined as $\beta_t=P/(B_t^2/2\mu_0)$, where P is the plasma thermal pressure, $B_t^2/2\mu_0$ is the magnetic pressure, and B_t is the magnetic field) is an important parameter for characterizing the performance and economic efficiency of a fusion reactor. To compare β_t values from different devices, it can be normalized as the dimensionless parameter $\beta_N=\beta_t/(I_p/aB_t)$, where I_p is the plasma current, and a is the minor radius of the device. High β_N is favorable for achieving plasma ignition ($nT_i\tau\propto(\beta_N I_p B_t/a)(H\tau_{\mathrm{scale}})$, where n, T_i, and τ represent the plasma density, ion temperature, and energy confinement time, respectively). The fusion power P_{fus} is also proportional to the square of β_N ($P_{\mathrm{fus}}\propto\beta_N^2 I_p^2 B_t^2$). In addition, the bootstrap current fraction f_{bs} is proportional to β_N ($f_{\mathrm{bs}}\propto C_{\mathrm{BS}}\beta_N q_{95}$, where C_{BS} is a coefficient, and q_{95} is the safety factor at the rational surface containing 95% of the magnetic flux). According to the requirements of the hybrid operation scenarios in the International Thermonuclear Experimental Reactor (ITER), the plasma current needs to reach ~12 MA, with a non-inductive current drive fraction of ~50%, a high confinement factor H_{98}~1.0−1.2, β_N~2.0−2.5, and a power gain factor Q>5. For the steady-state operation scenarios, β_N needs to be above 2.6.

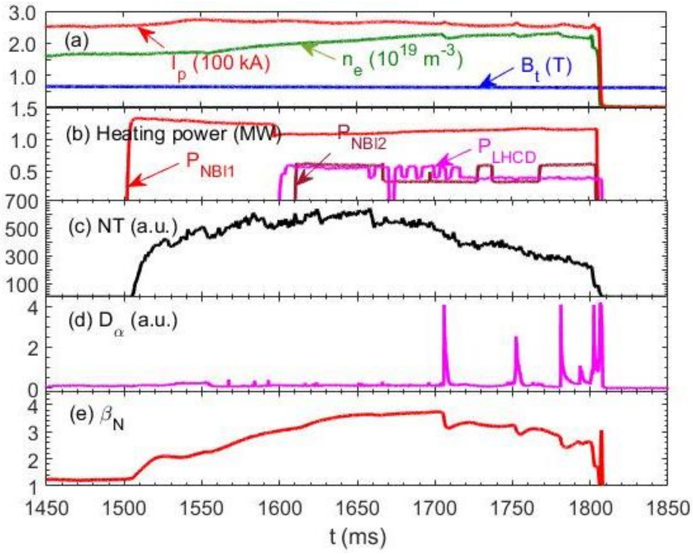

Fig.1 Typical examples of high-β_N plasmas in HL-3 low-current plasmas. (a) discharge parameters: plasma current (I_p (100 kA)), line-average electron density (n_e (10^{19} m^{-3})) and toroidal magnetic field (B_t (T)), (b) heating power: power of NBI heating and LHCD (P_{NBI} (MW) and P_{LHCD} (MW)), (c) neutron flux (NT (a.u.)), (d) stored energy (W_E (kJ)), (e) D_α signal (D_α (a.u.)),and (f) normalized beta (β_N).

There is a typical example of high β_N (~3.5-3.68) HL-3 plasmas, as shown in Fig.1. There curves present the evolution of discharge parameters in panels (a) plasma current, line-average electron density and toroidal magnetic field, (b) additional heating power, (c) neutron counts, (d) stored energy, (e) D_α signal, and (f) normalized beta arranged from the top to bottom panels. Under the conditions of ~1.1-1.9 MW neutral beam injection (NBI) heating and ~0.3-0.6 MW lower hybrid current drive (LHCD) injecting into the I_p~270 kA, B_t~0.79 T and n_e~(2.0-2.9)×10^{19} m^{-3} plasmas, the stored energy (W_E) can reach to 70-102 kJ, and the corresponding β_N can reach to 3.0-3.76 in ELM-free high confinement modes. There are obvious drops of stored energy and the corresponding β_N when strong ELMs appear.

Many kinds of magnetohydrodynamic (MHD) instabilities, with different frequencies, locating in different positions, different mode numbers and caused by various mechanisms, e.g., sawtooth, fishbone modes,internal kink modes, Alfvén eigenmodes (AEs), neo-calssical tearing modes (NTMs), and so on, are found in high β_N plasma. Some modes can co-exist from a long time, e.g., internal kink modes, NTMs and AEs, and there are nonlinear coupling among the modes, as shown in Fig.2.

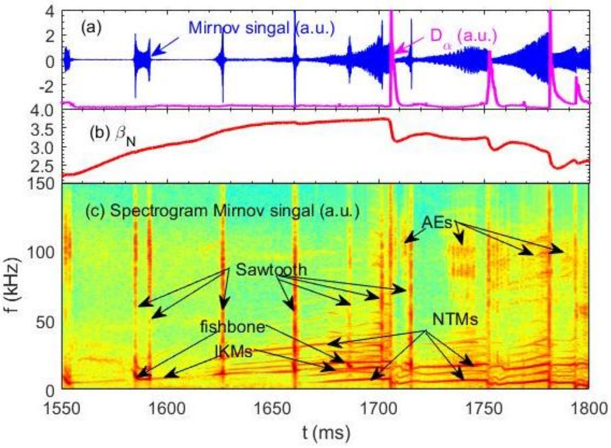

Fig.2 MHD instabilities observed in high-β_N plasmas and their effects on confinement. (a) poloidal Mirnov and D_α signals, (b) β_N and (c) spectrogram of Mirnov signals (main MHD modes are labeled on the sepctrogram).

It's found that the core NTMs will limit the achievement of β_N, and even cause the outbreak of ELMs. When the β_N is high enough, the NTMs will emerge. The amplitude of NTM is propotional to the value of β_N. NTMs can slow down the grow rate of β_N, cause the saturation of β_N, and even lead to the outberak of ELMs and disruptions. The sawtooth collapse can slow down the increasing rate of β_N. There are smaller effects of sawtooth collapse on the drops of β_N compared with NTMs.

The results can help understanding the MHD instabilities in high β_N plasmas and their effects of on limitation the β_N.

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