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Sawtooth observations in ramp up experiments assisted by lower hybrid current drive in HT-7

B J Ding, J F Shan, F K Liu, M Wang, H D Xu, G R Zhang, M Jiang, F Huang, Z W Wu, L Q Hu, X Gao, B N Wan, Y P Zhao, G L Kuang, J G Li and HT-7 Team

Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, 230031, P. R. China

Abstract Current ramp-up experiments assisted with lower hybrid current drive (LHCD) have been performed with a newly developed multijunction grill in the HT-7 tokamak. A maximum of driven current (~107kA) by LHCD has been obtained with an incident lower hybrid wave (LHW) power of P_{LHW}~210kW. Analysis of sawtooth periods with different LHW power spectra indicates that the fastest plasma transport occurs at $\Delta\Phi = 0^0$, followed by $\Delta\Phi = 60^0$, and finally $\Delta\Phi = 150^0$. Studies show that the plasma transport indicated by the sawtooth period is mainly affected by the driven current density profile.

1. Introduction The sawtooth oscillation is a universal phenomenon in tokamak plasmas and naturally supposed to affect significantly the fusion plasma [1]. The sawtooth oscillation is a regular periodic re-organization of the core plasma surrounding the magnetic axis in tokamaks. Kadomtsev [2] first proposed a standard model of the sawtooth crash based on the magnetic reconnection due to the m=1/n=1 internal kink instability (m and n are the poloidal and toroidal mode numbers, respectively). Sawtooth crash is one of dominant process in which the plasma energy loss occurs. The sawtooth amplitude reflects how much is lost in one crash and the sawtooth period indicates how fast the plasma energy loss occurs. In this paper, the sawtooth characteristics in the current ramp-up experiment with lower hybrid current drive (LHCD) were investigated and analyzed through the LHCD simulation.

2. Experiment and analysis The current ramp-up experiments in HT-7 [3] were carried out with the following parameters: an ohmic plasma current I_{OH}= 100kA, a central line averaged plasma density $n_e = 1.5\times10^{19} m^{-3}$, a toroidal magnetic field B_T~1.84T, lower hybrid wave (LHW) power P_{LHW}=210kW, and LHW frequency f=2.45GHz, but with different phase difference ($\Delta\Phi=0^0$, 60^0, 150^0) between the adjacent waveguides, correspondingly, $N_{//}^{peak}$ = 2.35, 2.7 and 3.25 ($N_{//}^{peak}$ is the peak value of the parallel refractive index). The typical waves are shown in Fig. 1, in which the plasma current (I_P), n_e, and soft X-ray intensity (I_{SX})

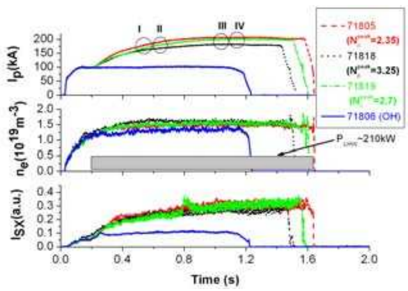

Fig.1 Typical waveforms of LHCD ramp up discharges

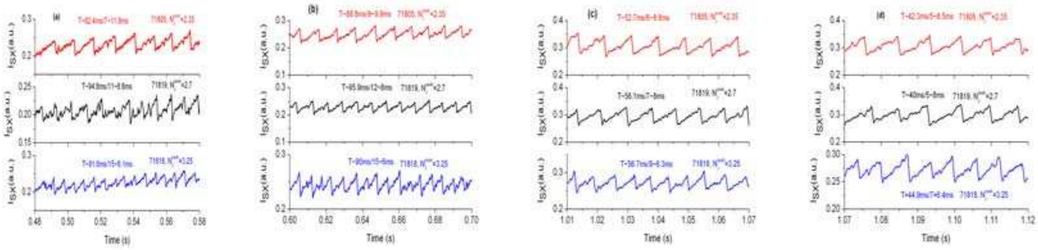

Fig. 2 Sawteeth periods evolution for the 3 ramp-up plasmas

are outlined from the top to the bottom frame. The P_{LHW} is also marked in the middle frame. It is seen that compared to the OH discharge (71806), an additional plasma current driven by LHW is achieved. It is seen that the largest driven current of 107kA is obtained when $\Delta\Phi = 0^0$(71805), then $\Delta\Phi = 60^0$(71819), and the smallest one is $\Delta\Phi = 150^0$(71818). In addition, the ramp-up rate defined as dI_P/dt is also different at different spectrum. It is seen that the fastest one is $\Delta\Phi = 0^0$(71805), then $\Delta\Phi = 60^0$(71819), and the slowest one is $\Delta\Phi = 150^0$ (71818). All these suggest the different current drive efficiency at different spectra.

Sawtooth oscillations are investigated in the ramp up experiments. For the OH plasma, no oscillation is observed whereas the sawtooth oscillation comes into being in the ramp up plasmas. In order to study the sawtooth evolution, four phases are investigated, i.e., phase I (480~580ms), phase II (600~700ms), phase III (1010~1070ms), and phase IV (1070~1125ms). With the ramping-up plasma development, as shown in Fig.2 (a), (b), (c) and (d), the sawtooth periods are distinct for the three cases, suggesting the different plasma transport process. In the case of $\Delta\Phi = 0^0$, the period corresponding to above 4 phases varies from 11.8ms to 9.9ms, then 8.8ms, at last 8.5ms, indicating that the plasma transport coefficient enhances gradually, then goes to a steady level. The corresponding values are 8.6ms, 8ms, 8ms and 8ms when $\Delta\Phi = 60^0$. For the case of $\Delta\Phi = 150^0$, the sawtooth periods in the 4 phase are 6.1ms, 6.4ms, 6.3ms and 6.4ms. Detailed comparisons show that the periods are the longest when $\Delta\Phi = 0^0$, then $\Delta\Phi = 60^0$, finally $\Delta\Phi = 150^0$, implying that the fastest transport occurs at $\Delta\Phi = 0^0$ and the slowest does at $\Delta\Phi = 150^0$.

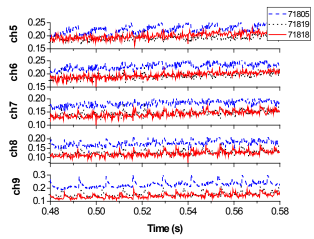

Fig.3 Swatooth reversion radius for the 3 discharges

It is known that the sawtooth period is associated with the position of q=1 (=m/n) surface, indicated by the sawtooth reversion radius. Multi-channel soft X-ray signals with a 1.5cm space resolution are shown in Fig. 3, from which it is seen that the sawtooth reversion occurs at channel 7 in 71805, and channel 6 in 71819 and 71818, correspondingly the radius is 9.0cm and 10.5cm. This possibly explains that why the sawtooth of 71805 is longer than that of 71819 and 71818. In addition, the reversion radius is almost same in 71819 and 71818, whereas the sawtooth period is different. This may be due to the limited measurement resolution.

The sawtooth reversion radius is an indicator of the q=1 surface, which is determined by the current profile. So, the discrepancy in the transport indicated by the sawteeth period is interpreted by the different driven current profile. It is known that the sawteeth are related to the increased current in the core region, especially inside a/2 region. That the current in the central region increases to a value that makes q=1 surface emerge is essential for the sawtooth oscillation. The simulated power deposition (see Fig. 4) by a ray tracing code [4] shows that the main power is absorbed by the electrons inside the a/2 region, as a result, an increased plasma current is obtained in the core region, as can be seen from the calculated driven current profile (see Fig. 5) by solving 2 dimensional Fokker-Planck equation [4]. Furthermore, figure 4 shows that the power deposition position is different for the three cases, i.e., the closest to the core region is $\Delta\Phi = 0^0$, then $\Delta\Phi = 60^0$, and the furthest is $\Delta\Phi = 150^0$. As a result, the current profile of 71805 is the peakest, followed by 71819 and 71818. These different current profiles result in the different q profiles, as indicated by the reversion radius. Simulations invoke that the sawtooth behaviour depends on the current profile, that is, the peaker the profile, the larger the period.

It is seen that for the case of 71805 and 71819, the periods vary from large to small values, whereas the value in 71818 increases from 6.1ms to 6.4 ms. This evolution of the sawteeth period may be related to the changing current profile, which is required for a steady plasma. Since the driven currents are mainly located in the central region in 71805 and 71819, with the time development, it is natural the total current diffuses outward so that a quasi-steady-state plasma is achieved, leading to a broadened current profile from a peaked one. In 71818, on the contrary, the deposited power is further away the magnetic axes, and the driven current is near the position of 0.5a. With the time evolution, the current penetrates

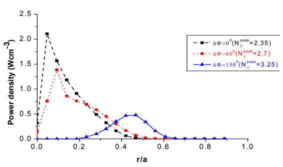

Fig. 4 Simulated power deposition

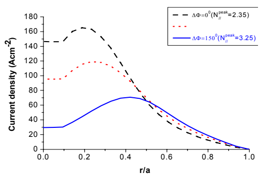

Fig. 5 Simulated driven current profile

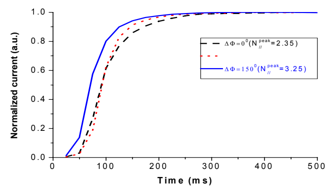

Fig. 6 Simulated driven current evolution

a little into the core region. Hence, the period increases a little in the process. It is also seen that in the case of $\Delta\Phi = 60^0$ and $\Delta\Phi = 150^0$, the sawtooth periods goes to a steady value in ~400ms, whereas it takes longer time (~800ms) to a saturated value when $\Delta\Phi = 0^0$, indicating that the different characteristic time is required for a steady current profile. There are two possible reasons affecting the time needed to reach a steady period. One is the current diffusion time (~100ms) leading to a steady profile, as described above. The other one is the saturated time needed to reach a steady driven current, which is about 200ms~300ms invoked by the simulation (see Fig. 6). It is seen that the time reaching to a saturated current is different for the three spectra, the fastest one is $\Delta\Phi = 150^0$, then $\Delta\Phi = 60^0$, and the longest is $\Delta\Phi = 0^0$. Since the former is smaller than the latter, and the simulated result is qualitatively in agreement with the experiment results of the different time reaching to a steady value in the case of different spectra, the time needed to a steady driven current plays an important role in determining the time to a steady sawtooth. However, this is not convincing because the difference between the experiment and simulation is very large. It is possibly due to the mutual inductance between plasma current and primary Ohmic heating current. The driven current changes the total plasma current, which in turn affects the Ohimic heating current through the mutual inductance. This interaction, which is not considered in our simulation, prolongs the time to a steady profile. Therefore, the combination of the time reaching a steady driven current and the mutual inductance between plasma current and primary Ohmic heating current may deominates the characteristic time to the steady sawtooth period.

3. Conclusion Analysis of sawtooth periods with different LHW power spectra in HT-7 indicates that the fastest plasma transport occurs at $\Delta\Phi = 0^0$, followed by $\Delta\Phi = 60^0$, and finally $\Delta\Phi = 150^0$. Studies show that the plasma transport indicated by the sawtooth period is mainly affected by the driven current profile due to the different spectra. The combination of the time reaching a steady driven current and the mutual inductance between plasma current and primary Ohmic current may dominates the characteristic time to a steady sawtooth period.

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References

[1]F.Porcelli, D.Boucher and M. N. Rosenbluth, Plasma Phys. Control. Fusion 38(1996)2163.

[2]B. B. Kadomtsev, Sov. J. Plasma Phys. 1(1976)389.

[3]J.K. Xie *et al.*, *Proc. 16th Int. Conf. (Montreal, 1996)* Vol. 1 (Vienna IAEA) p 685.

[4]B.J. Ding *et al.*, Acta Phys. Sinica, 51(2002) 2556 (in Chinese).