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Sawtooth-like electron density oscillations under laser blow-off and lower hybrid current drive in HL-1M tokamak*

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By using of a six-channel HCN laser interferometer, the sawtooth-like density oscillations without being exhibited in the ohmic phase plasma have been observed during lower hybrid current drive (LHCD) discharges in the HL-1M device. There are often accompanied by injected impurity with laser blow-off. Analyses show that this kind of density sawtooth-like oscillation comes from the mutual effect of LHCD and impurity. An available mechanism is the loss of superthermal electrons by the magnetic perturbation, which is caused by the crash of the central accumulated impurities.

Keywords: sawtooth-like density oscillations, laser blow-off, lower hybrid current drive, superthermal electrons

PACC: 5225F, 5270, 5265

1. Introduction

Experiments in many tokamaks have shown that the sawtooth oscillations of electron density can be used to study the particle behaviours of the central plasma. Density sawteeth have been observed and studied on the HL-1M tokamak. In HL-1M experiments, a new kind of sawtooth-like density variation has been observed during lower hybrid current drive (LHCD) discharge using a six-channel far infrared ray (FIR) laser interferometer, which has been also observed in such experiments in soft x-rays, H_α and bolometer signal measurements. An available mechanism is proposed in this paper, and a simple analysis is made.

2. Experimental results

HL-1M is a modification of HL-1 tokamak,[1] with R=1.02 m, a=0.26 m, B_t <3 T, I_p < 350 kA, $\bar{n}_e = (1-8)\times 10^{19}\,m^{-3}$ and $T_{e0} = (0.5-1.2)$ keV. The pulse duration is about 1 s for normal operations. The LHCD system (with a power up to 0.85 MW) was employed to study the confinement and current drive. A laser blow-off technique was used to observe the impurity transport. The six-channel FIR interferometer,[2] soft x-ray array,[3] multi-channel bolometer and H_α are used to study the sawtooth behaviour.

Impurity accumulation and the sawtooth-like density oscillation were observed for laser blow-off in LHCD plasma discharges with lower hybrid wave power about 0.3 MW, a relatively high q_a ($q_a > 7$), a lower plasma current (I_p <100 kA) and a middle electron density ($\bar{n}_e < 3\times 10^{13}\,cm^{-3}$). This relatively small injection power was added mainly for the central current drive and an improved confinement. The evolution of line integrated electron density of shot No.4838, as well as the soft x-rays, bolometer and H_α, during a typical HL-1M density sawtooth-like discharge is shown in Fig.1 with I_p=95 kA, B_t=2.27 T, $\bar{n}_e = 2.6\times 10^{13}\,cm^{-3}$, q_a=7.9. In plasma current flat-top phase at t=200 ms, the laser blow-off has been employed to inject LiF and C into the plasma, and at t=324 ms the lower hybrid wave system is supplied with a power 310 kW. At 10 ms later, the sawtooth oscillation appears on n_e, soft x-ray, H_α and bolometer curves. The density sawtooth-like period is about 14 ms and is fitted well with the signals of soft x-ray. The sawtooth collapse time is about 1 ms, and $\Delta n_e/n_e \approx 7\%$. The signals of the bolometer and H_α

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are observed anti-sawtooth and the delay is about hundreds of μs. On x-ray diode signals no sawtooth inversion is observed. After LHCD was terminated at t=420 ms, the sawtooth oscillation disappeared. The density profile of shot No.4838 during sawtooth collapse just before and just after a density sawtooth collapse is shown in Fig.2; the profile of density becomes broad after collapse.

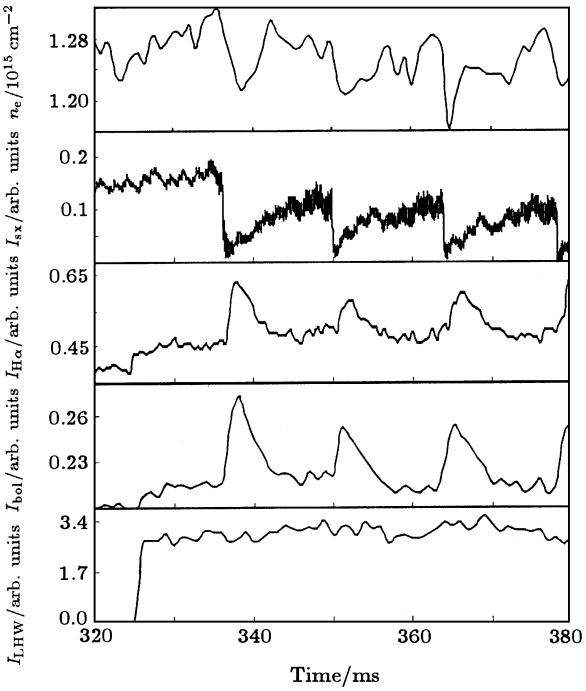


Fig.1. Sawtooth behaviour of several diagnostic signals during the LHCD discharge of shot No.4838 from t=320 ms. Note: (i) density sawtooth period fits well with it on soft x-ray; (ii) bolometer and H_α sawteeth are anti-sawteeth compared with density sawteeth, and are delayed about hundreds of μs.

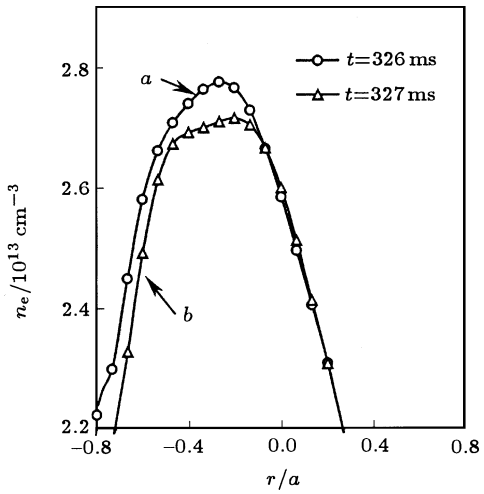


Fig.2. Density profile of shot No.4838 during sawtooth collapse. Curve a: just before, and curve b: just after a density sawtooth collapse. Note: the profile of density becomes broad after collapse.

Laser blow-off allows considerable impurities into plasma. Simultaneously, with these impurities a strong accumulation of input impurities is observed in the improved confinement in LHCD plasmas, which has been found in many tokamak experiments.[4] A characteristic feature of this phase is the pronounced sawtooth-like electron density evolution, which is accompanied by the peaks on the x-ray and bolometer curves. Information also can be obtained from vacuum ultraviolet and $Z_{\rm eff}$ bremsstrahlung measurements.

Because there is no sawtooth inversion in the x-ray signals and $q_{\rm a}$ is relatively high ($q_{\rm a}$=7.9), this kind of sawtooth-like electron density oscillation is not caused by the general m=1 instability. In addition, during the sawtooth-like oscillation, a high percentage of superthermal electrons are measured by electron convolute eradiation; the soft x-ray radiation is low and the electron density is relatively high ($\bar{n}_{\rm e}$=2.6×10^{13} cm^{-3}), which indicates that the sawtooth oscillation is non-thermal. As an explanation of the experimental results, we suggest a mechanism whereby when the impurity central accumulation reaches a relatively high concentration (for example, up to several per cent) and a peaked impurity profile, perhaps some perturbation (instability) would cause the profile collapse and an amount of impurities to suddenly escape outward across the magnetic surface like a snowslide. The magnetic field turbulence is intensive, and perhaps it can have $b_{\rm r}/B$ to be about $10^{-2}-10^{-3}$ as the turbulence in q=1 sawtooth relaxation,[5] which is much larger than that generally measured in plasma edge (about $10^{-4}-10^{-5}$).

3. Numerical model

Based on the above assumption, we take into account the loss of the fast electrons by magnetic field turbulence (if without the intensive magnetic perturbation, the fast electrons are in good confinement). The analysis shows that this loss mechanism can make the electron density decrease about 5%–7%; this fits well to HL-1M's experimental results.

For many tokamak discharges, because the characteristic time of the superthermal electron radial loss is much shorter than the electron collision time, the superthermal electrons in the tail of the velocity distribution will be lost rapidly. After depletion of the tail, the distribution will be almost an empty tail, and an ambipolarity electron field will appear. Electrons move intrinsically faster than ions along the field lines, thus a radial potential has to be set up to enforce

ambipolarity of the particle losses. The outward radial velocity component of the one-dimensional motion along the field lines is written as follows:

$$v_{\rm r}=\left[\left(v_{//}\frac{b_{\rm r}}{B}\right)^2-\frac{2eU}{m_{\rm e}}\right]^{1/2}=v_{\rm te}\frac{b_{\rm r}}{B}(\omega^2-X_{\rm e})^{1/2}, \quad (1)$$

where $v_{//}$ is the absolute value of the velocity along the lines, $\omega=\dfrac{v_{//}}{v_{\rm te}}$, $v_{\rm te}=\sqrt{\dfrac{T_{\rm e}}{m_{\rm e}}}$ the thermal velocity, and

$$X_{\rm e}=\frac{2eE_{\rm a}\Delta r}{T_{\rm e}\left(\dfrac{b_{\rm r}}{B}\right)^2},$$
$$U=E_{\rm a}\Delta r, \quad (2)$$

where $E_{\rm a}$ is the ambipolar electron field and Δr is the radial step of an electron deviating from its trajectory, with $\Delta r\approx\dfrac{b_{\rm r}}{B}L_{\rm c}$; and $L_{\rm c}\approx 2\pi qR$ is the length of a full toroidal revolution.

The perturbation field is generated by several different mechanisms, and its structure is largely unknown. Under the reasonable assumption that the spectrum of the perturbation is broad and nearly constant, the magnetic perturbation term can be written as $\dfrac{1}{r}\dfrac{\partial}{\partial r}rD_{\rm rr}\dfrac{\partial f}{\partial r}$, where

$$D_{\rm rr}\approx\frac{(\Delta r)^2}{\tau_{\rm c}}=2\pi qR\left(\frac{b_{\rm r}}{B}\right)\left|v_{//}\right|,$$

with $\tau_{\rm c}=\dfrac{L_{\rm c}}{\left|v_{//}\right|}$ being the characteristic time of the random walk. This expression is the appropriate one for superthermal electrons. Because the velocities of ions are $\left(\dfrac{m_{\rm e}}{m_{\rm i}}\right)^{1/2}$ times smaller, the ion diffusion coefficient is negligible.

For a simple analysis, we use a one-dimensional treatment of the velocity parallel to the magnetic field, but a correction factor for the two-dimensional effect of velocity space. The Fokker–Planck equation for the fast electrons ($|\omega|\gg 1$) in the presence of the ohmic DC electron field without taking into account the radial diffusion effect can be written as [6]

$$\frac{\partial f}{\partial(\nu_0 t)}+E_{\rm DC}\frac{\partial f}{\partial\omega}=\frac{\partial}{\partial\omega}D_{\rm ql}\frac{\partial f}{\partial\omega}+\frac{\partial}{\partial\omega}\left(\frac{1}{\omega^3}\frac{\partial f}{\partial\omega}+\frac{f}{\omega^2}\right), \quad (3)$$

where $D_{\rm ql}$ is the quasi-linear diffusion coefficient, and the DC electron field $E_{//}$ is normalized to the Drecier field

$$E_{\rm DC}=\frac{eE_{//}}{m_{\rm e}\nu_0 v_{\rm te}},$$

with $\nu_0=(Z_{\rm eff}+2)n_{\rm e}e^4\ln\Lambda/4\pi\varepsilon_0^2m_{\rm e}^2v_{\rm te}^3$. By assuming a rectangular spectrum, the normalized quasi-linear diffusion coefficient $D=\dfrac{D_{\rm ql}}{v_{\rm te}^2\nu_0}$ is inversely proportional to ω; $\omega D(\omega)=D_0$ can be assumed to be a constant within the interval $\omega_1<\omega<\omega_2$, and zero outside. Under the condition of weak DC electron field $\omega_2^2E_{\rm DC}<1$, and $\omega_1^3D\gg 1$ (this condition is equivalent to say that there is no interaction between runaway electrons and waves). The process will reach its time asymptotic state within a characteristic time of ν_0^{-1}, and the steady state solution of the equation is obtained as follows:

$$f(\omega)=\begin{cases} C{\rm e}^{-\frac{\omega^2}{2}-\frac{\omega^4}{4}E_{\rm DC}} & -\infty<\omega<0,\\ Cf_{\rm m}(\omega) & 0\le\omega<\omega_1,\\ Cf_{\rm m}(\omega_1){\rm e}^{\frac{E_{\rm DC}}{2D_0}(\omega^2-\omega_1^2)} & \omega_1\le\omega<\omega_2,\\ C\dfrac{f_{\rm m}(\omega_1)f_{\rm m}(\omega)}{f_{\rm m}(\omega_2)}{\rm e}^{\frac{E_{\rm DC}}{2D_0}(\omega_2^2-\omega_1^2)} & \omega_2\le\omega<+\infty, \end{cases} \quad (4)$$

where

$$f_{\rm m}(\omega)={\rm e}^{-\frac{\omega^2}{2}+\frac{\omega^4}{4}E_{\rm DC}},$$

and C is determined by $\displaystyle\int_{-\infty}^{\infty}f_{\rm m}(\omega){\rm d}\omega=1$, and is nearly equal to $\dfrac{1}{\sqrt{2\pi}}$.

The ratio of the amplitude of the density collapse to the plasma density can now be predicted. From Eq.(4) and ignoring the DC electron field, we can obtain

$$\frac{\Delta\bar{n}_{\rm e}}{\bar{n}_{\rm e}}=\frac{\displaystyle\int_{-\infty}^{-x_{\rm e}^{1/2}}f(\omega){\rm d}\omega+\int_{x_{\rm e}^{1/2}}^{\infty}f(\omega){\rm d}\omega}{\displaystyle\int_{-\infty}^{\infty}f(\omega){\rm d}\omega}$$
$$=\frac{1}{\sqrt{2\pi}}\left[\frac{2{\rm e}^{-x_{\rm e}/2}}{x_{\rm e}^{1/2}}+(\omega_2-\omega_1){\rm e}^{-\omega_1^2/2}+\frac{{\rm e}^{-\omega_2^2/2}}{\omega_2}-\frac{{\rm e}^{-\omega_1^2/2}}{\omega_1}\right]. \quad (5)$$

In the derivation of the formula, we have assumed $x_e > 1$ and $\omega_1 > x_e^{1/2}$. In the equation above, the first term comes from the loss of background electrons, which is determined mainly by the value of x_e: that is, mainly by the values of the perturbation of magnetic field and the electron temperature; the other terms are the addition of the loss of current carrying fast electrons.

By taking the basic parameters of HL-1M tokamak and assuming that[7] E_a=1–2 V/m, q=1–2, and $b_r/B \approx 10^{-2}$, one can obtain $x_e^{1/2}$ ≈2–4. Taking $\omega_1 \approx 3$, $\omega_2 \approx 9$, we obtain that the background loss is about 3%–5%, and the loss of the current carrying fast electrons is about 1%–3%; the total loss $\Delta\bar{n}_e/\bar{n}_e$ is about 5% to 7%, which fits well with the experimental results on HL-1M.

4. Discussion and conclusion

During LHCD and laser blow-off operation in the HL-1M device, we wondered how the injected waves affect the impurities efficiently and how the mutual effects cause the sawtooth-like oscillations of electron density. By Landau damping, i.e. the mutual effects between waves and plasma electrons, the current carrying fast electrons have been driven to form a non-induced plasma current. Many reports show that the sawtooth instabilities of m=1 mode can be suppressed by LHCD. But in our experiments, the so-called density sawtooth oscillation under laser blow-off and LHCD is a new kind of sawtooth oscillation. Its period is about 5–7 times longer than q=1 surface soft x-ray oscillations (whose location can be determined by plasma diagnoses, as, for example, in Ref.[8]). In the same discharge condition without the laser blow-off, there is no obvious sawtooth on all measured signals and the line-average electron density has a slight increase. When laser blow-off is employed, impurities are put into the plasma and the sawtooth oscillations appear, while the density shows no obvious increase. LHCD has an impact on the plasma confinement, its characteristic feature is the improved confinement. The mutual effect of confinement and diffusion causes such sawtooth-like density oscillations.

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