ECRH Experiments and MHD Instabilities on HL-1M

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Abstract. Off-axis electron cyclotron resonance heating (ECRH) research was carried out in the HL-1M tokamak. The heating efficiency at various electron densities, its effect on sawtooth activities and the stability property of the m/n=1/1 mode were studied. The combination of ECRH and lower hybrid waves allows further manipulation of the electron distribution function and provides useful insight into the wave–particle interaction mechanism. A qualitative explanation for the observation is presented.

Electron cyclotron resonance heating (ECRH) is a very reliable electron heating method in magnetized plasmas. The power deposition profile is localized and predictable. High power ECRH was used in the RTP tokamak [1] to achieve stable plasmas with hollow electron temperature profile $T_e(r)$. In the FTU tokamak [2], electron cyclotron waves were applied during the current up phase in order to prolong the current penetration time and maintain a stable plasma with a hollow j(r). Since the discovery of internal transport barriers in plasmas with reversed magnetic shear, ECRH has become a promising tool for maintaining and enlarging the reversed shear region and improving the overall confinement property of tokamaks. This is an active area of research in DIII-D, JT-60U, ASDEX-U, TCV and other tokamaks.

HL-1M is a circular cross section tokamak with major radius R=1.02 m, minor radius a=0.26 m. The electron density varies in the range of $(0.5–6)\text{x}10^{13}$ cm^{-3} for the experiments described in this paper. The maximum magnetic field on-axis is 2.8 T. A 75 GHz gyrotron provides ECRH power of up to 300 kW for fundamental electron cyclotron resonance (ECR) at B=2.68 T. Waves polarized at the ordinary mode are launched on the mid-plane from the low field side of the tokamak. Ray tracing and power deposition calculations show that the fraction of wave power absorbed in one single pass is 80% or higher, localized within a region of 3–4 cm. The purpose of the ECRH experiment on HL-1M is to study the electron heating effect on various MHD activities through changes in the plasma pressure profile and current density profile as well as wave–particle interaction with the energetic electrons produced by ECRH.

The electron temperature T_e is measured by the electron cyclotron emission (ECE) system consisting of a scanning 2 mm microwave receiver. During high power ECRH, a 30% increase in T_e above the Ohmic level is routinely achieved in HL-1M. The maximum rise in T_e is about 50% and usually occurs in a density range of $(1.0–1.5)\text{x}10^{13}$ cm^{-3}. Both T_e and n_e peak at the magnetic axis; therefore the absorption of O-mode waves is most effective when the cyclotron resonance is placed there. As one would expect from profile consistency in tokamaks, the electron temperature profile in HL-1M remains very similar even at our maximum ECRH power for all ECR positions when the electron density is below $1.5\text{x}10^{13}$ cm^{-3}. Figure 1 depicts the T_e profile for off-axis ECRH at 200 kW of source power. When n_e goes above $1.5\text{x}10^{13}$ cm^{-3}, the T_e profile becomes flat in the plasma core. With our existing power level, we cannot produce hollow $T_e(r)$ profiles like those in the RTP tokamak [1].

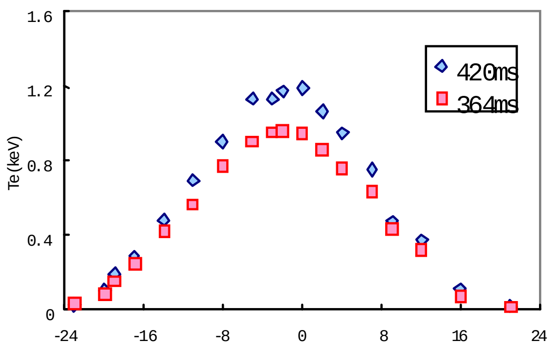


FIG. 1. Electron temperature profile in Ohmic stage and ECRH stage. During off-axis ECRH, B_T=2.5 T, n_e=1.4x10^{13} cm^{-3}, I_p=150 kA, P_{EC}=200 kW.

Besides conventional magnetic probes near the plasma edge, a 60-channel soft x-ray detector array at the top of the tokamak is our major diagnostic for MHD studies. This imaging system covers the entire plasma cross section through a 12.5 micrometre thick beryllium foil. When the ECR location is placed near the magnetic axis but slightly (1–2 cm) shifted towards the high field side, double sawteeth appear when the plasma current is at 200 kA or higher. Signals from the soft x-ray imaging system are shown in Fig. 2. It is interesting to note that the small crash takes longer than 0.5 ms while the large crash takes only 0.05 ms. We believe that the formation of double sawteeth is closely related to the q-profile at the plasma core. Although there is no q(r) diagnostic on HL-1M, we believe that it is modified by ECRH. Since the ECR location is on the high field side and near the magnetic axis, very few of the energetic electrons are trapped, and they can modify the current density profile near the magnetic axis. Two q=1 surfaces may have been formed during the time when double sawteeth appear.

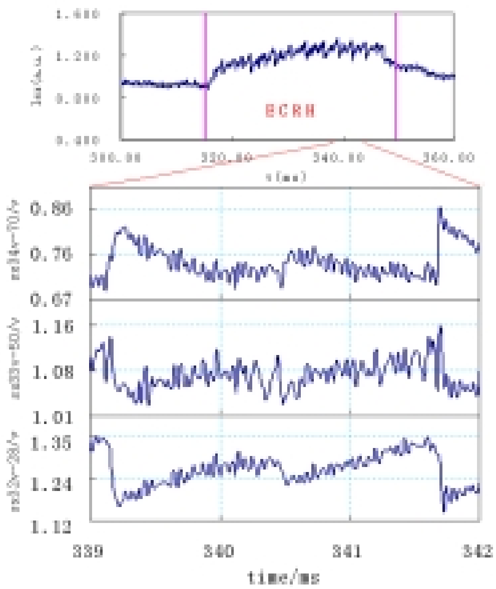


FIG. 2. Double sawteeth of soft x-ray signal with different chords appear during ECRH.

When the target plasma density is below $6\text{x}10^{12}$ cm^{-3}, sawtooth oscillations are completely suppressed by ECRH if the ECR position is on the high field side just within the q=1 surface (Fig. 3). At such a low density, absorption of O-mode waves by the bulk electrons is weak. The Ohmic electric field can produce runaway electrons, and we expect that a significant fraction of ECRH power is absorbed by runaway electrons. The runaway electrons and the reduction of magnetic shear may explain the sawtooth stabilization. In the density range of $0.6\text{x}10^{12}$ $\text{cm}^{-3} < n_e < 10^{13}$ cm^{-3}, saturated and partially saturated sawteeth are usually observed.

The MHD stability property of a tokamak plasma is determined by the profiles of plasma pressure and current density. While such experiments have been carried out for more than two decades, the kinetic effect of energetic electrons on MHD modes is a relatively new phenomenon discovered recently in DIII-D [3, 4]. The barely trapped energetic electrons participate in the excitation process, but the energetic ions from neutral beam injection also play a role in the DIII-D experiment. In HL-1M, we manage to excite the same instability with energetic electrons alone. The experiment was carried out with a 50 ms ECRH pulse of up to 250 kW power. Strong m/n=1/1 modes were observed during off-axis ECRH on HL-1M when the cyclotron resonance was located just outside the q=1 surface on the high field side of the magnetic axis. Figure 4 shows the raw data from the soft x-ray detectors. The 1/1 modes are precursors that appear just before a sawtooth crash. At low ECRH power, the amplitude of the precursor is enhanced and it appears at an earlier time. At high ECRH power, a burst of m=1 mode appears in the middle of the sawtooth and sometimes it separates from the precursor oscillation before the crash and appears as one single burst in the typical fishbone activities shown in Fig. 6 of Ref. [5]. Should the sawtooth period of HL-1M become longer, these would be fishbone activities similar to those observed in the PDX tokamak [5]. The m=1 mode studied here has a frequency of 8 kHz; it is distinctly different from the high frequency (250–450 kHz) fast particle instability observed in COMPASS-D [6].

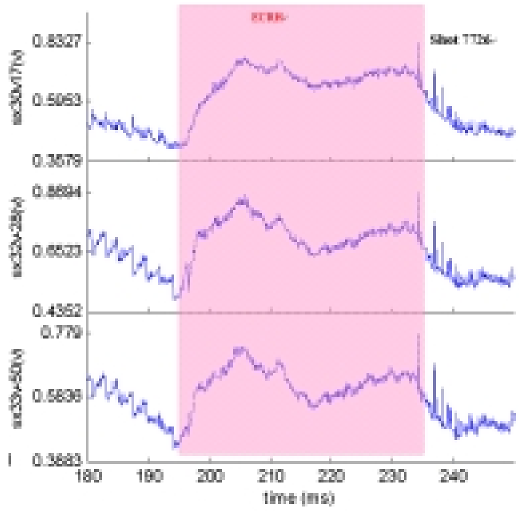


FIG. 3. Sawtooth oscillations are strongly suppressed by localized ECRH near the q=1 surface on the high field side, when plasma density is below

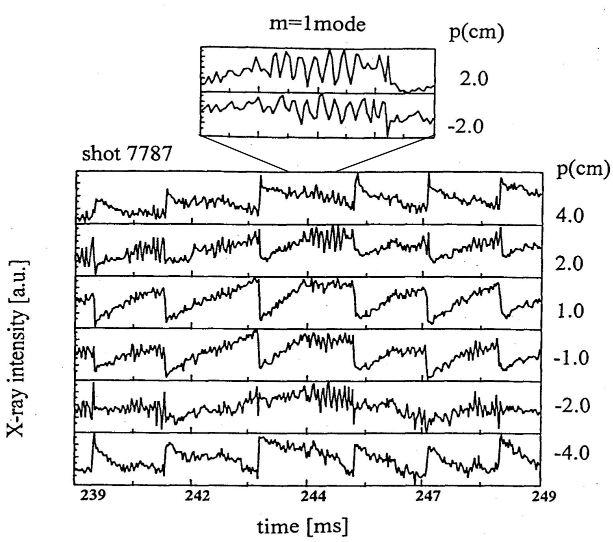


FIG. 4. Raw data from the soft x-ray imaging system showing the sawteeth and the m=1 mode with 230 kW of ECRH power.

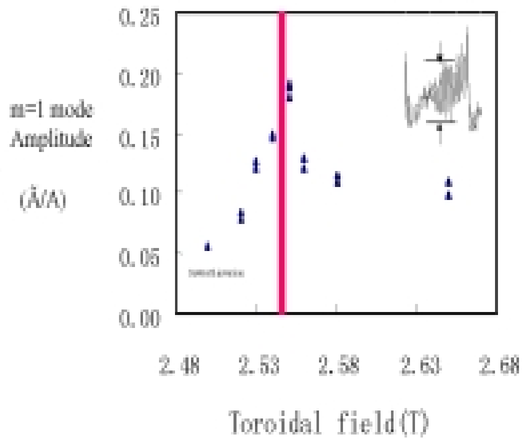


FIG. 5. Variation of the m=1 mode amplitude when the ECR location scans across the inversion radius. The amplitude peaks near the inversion radius.

Figure 5 shows the variation of the m=1 mode amplitude versus the toroidal magnetic field when the plasma current was held fixed at 180 kA. The peak amplitude occurs near the q=1 surface (taken to be the inversion radius in the soft x-ray signal). By varying the plasma current and the toroidal magnetic field, the ECR location was scanned repeatedly over a wide range, and excitation of the m=1 mode was observed only when the ECR location was on the high field side near the q=1 surface. When the resonance location is 2 cm or more away, the instability disappears. This is compelling evidence that the barely trapped energetic electrons drive the instability. Unlike the DIII-D experiment, there is no neutral beam injection here, and therefore this instability is purely driven by energetic electrons.

HL-1M is equipped with 1 MW of lower hybrid wave power at 2.45 GHz for lower hybrid wave current drive (LHCD) experiments. Only 250 kW was available during this experiment. The launcher has 2x12 waveguides phased 90 degrees apart. More than 90% of the wave power is launched parallel to the plasma current with $n_{||}$ in the range of 2.0–3.5. This power spectrum should flatten the electron distribution function for electrons with parallel energy between 20 keV and 64 keV. The waveforms for a typical shot with combined ECRH and LHCD are shown in Fig. 6. It depicts the temporal evolution of the loop voltage, plasma current, electron density, lower hybrid wave power, ECRH power, and hard x-ray emission in the energy range 15–150 keV. As expected, the loop voltage drops to near zero during LHCD, indicating that the wave driven current is comparable to the total plasma current. There is no significant change in electron density during combined ECRH and LHCD. Power deposition calculations with a ray tracing code indicate that the current driven by lower hybrid waves spreads over the plasma interior with a broad peak near the magnetic axis. Therefore, we expect an abundant supply of energetic electrons with parallel energy in the 50 keV range near the q=1 surface as indicated by the hard x-ray signal. The combined effect of ECRH and LHCD is shown in Fig. 7. The amplitude of the m=1 mode is larger when both RF sources are present. At low LHCD power, it takes only a few ms for the effect to appear. This is much shorter than the L/R time of the plasma current. It should be noted that the local change in current density J(r) can happen in a time interval much shorter than L/R. The fast response of the m=1 mode amplitude observed here is another indication that its excitation is due to kinetic effects from the

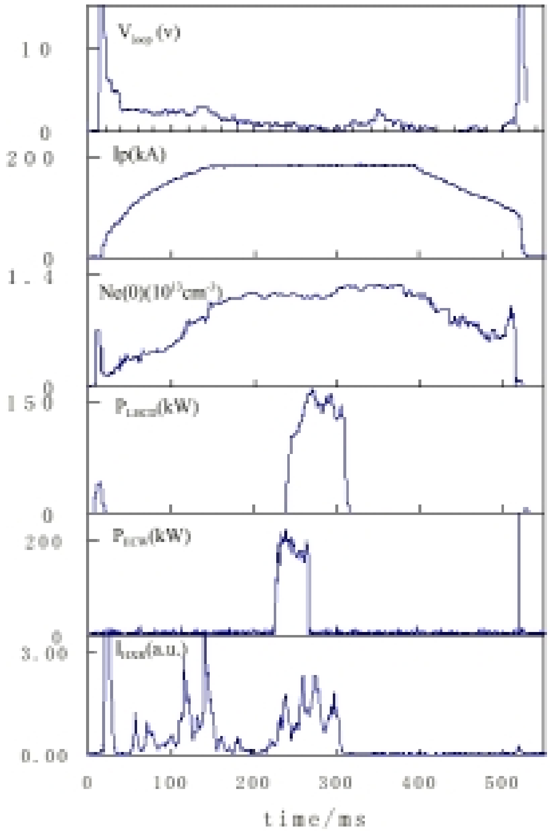
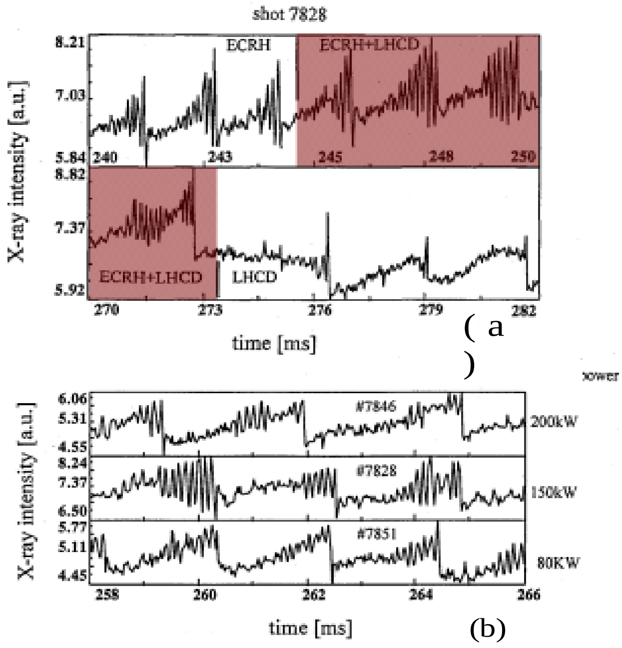


Fig.6 Waveforms from a typical shot (#7818) with ECRH and LHCD. (a) plasma loop voltage, (b) plasma current, (c) line-averaged electron density, (d) LHCD power, (e) ECRH power.

energetic electrons rather than the local change in q(r). At high LHCD power, the response time is even shorter. A strong m=1 mode appears in every sawtooth period, and it grows to large amplitude shortly after the sawtooth crash. Both ECRH and LHCD produce energetic electrons: ECRH raises the perpendicular energy of electrons, and LHCD raises their parallel energy. Figure 7(a) shows that the m=1 mode disappears immediately after the ECRH power is turned off. This is very compelling evidence that the energetic trapped electrons with large perpendicular energy are responsible for the excitation of the instability. With the ECRH power fixed at 230 kW, the LHCD power is varied from 80 to 200 kW and its effect on the m=1 mode is depicted in Fig. 7(b). It shows that the sawtooth period increases monotonically with the LHCD power, but the maximum m=1 mode amplitude appears at 150 kW of LHCD power. Quantitative modeling of the experimental data requires a three dimensional Fokker–Planck calculation of the electron distribution function, which is in progress.



. *Fig.7 (a) Response of the instability t bination of ECRH (200 kW) and LHCD . (b) Response of the instability to various I er levels.*

Acknowledgements

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