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THE ELECTRON CYCLOTRON RESONANCE HEATING EXPERIMENTS ON HL-1 TOKAMAK

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The electron cyclotron resonance heating (ECRH) experiments on HL-1 tokamak with 300 kW of power generated by a gyrotron are described. With ECE diagnostics, a 30% increase of electron temperature has been obtained. The following phenomena have been observed with various diagnostics during ECRH: increase of radiation intensity of soft X-ray; amplitude change and period elongation of sawtooth oscillation; MHD instability suppression; increase of Hα spectral line intensity and ionized impurity radiation from edge plasma; increase of the temperature and density of edge plasma. Although the total plasma energy content increases, the energy confinement time is decreased. Initial results of low voltage start-up experiments have also been obtained.

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I. INTRODUCTION

The electron cyclotron wave (ECW) is being widely applied in the experiments of plasma heating, current profile control, current drive and low voltage start-up due to its easily controllable localized heating effect. The central electron temperature increase from 2 to 10 keV with 2 MW ECRH was obtained on T-10[1], and 100kA plasma current was drived with 1MW on DIII-D. The H-mode operation was achieved only with 1MW ECRH on the DIII-D.[2] The transport of plasma energy has recently been studied in more detail on DIII-D.[3] The ECRH has been considered as one of important means in profile control, low voltage start-up and current drive in fusion reactor.

The ECRF assistant start-up experiments were carried out on HL-1 tokamak by using a domestic gyrotron in 1987[4] and the results of about one third reduction of volt-second consumption have been obtained. Recently, a new set of gyrotron including transmission line provided by Institute of Applied Physics, Russia, was used. The observation of plasma heating, effect of ECRH on MHD, and improvement of start-up phase have been studied on HL-1 tokamak again.

The new ECRH system used and some results obtained are described in this paper.

II. SET-UP OF EXPERIMENT

A. Gyrotron and quasi-optical transmission line

The gyrotron of 75 GHz, 300 kW, 30 ms pulse duration with output of horizontally polarized Gauss mode ($HE_{\parallel}$) accompanied with about 15% spurious mode has been installed on HL-1 as O-mode injection from the low magnetic field side (Fig. 1). In front of gyrotron, there are two ellipsoidal reflecting mirrors which not only change the beam direction but also focus the beam before it is launched into an oversize waveguide. At the end of the waveguide the power wave is coupled into the HL-1 tokamak by using an ellipsoidal and a plane mirrors. The efficiency of the transmission line is higher than 80%.

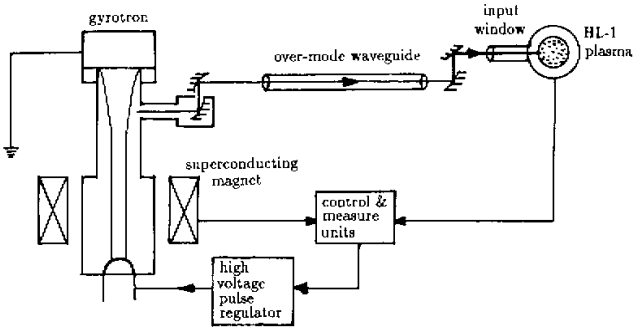

Fig. 1. Quasi-optical transmission line.

The superconducting magnet, which provides 2.92 T at a current of 40.29 A, for the production of uniform and stable magnetic field in the gyrotron is operated at liquid helium temperature (4.2 K).

B. High voltage pulse power supply

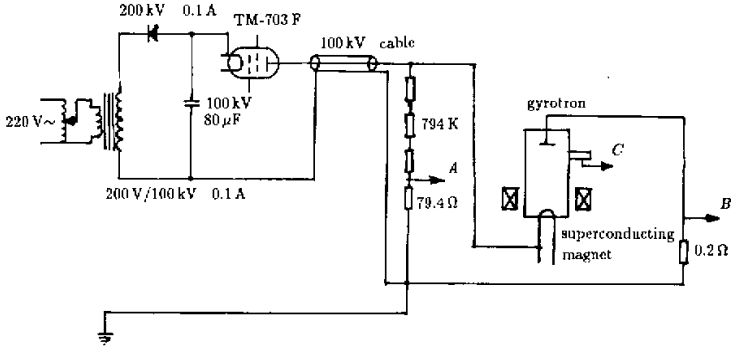

Fig. 2. High voltage pulse circuit of the gyrotron. *A*–measurement of gyrotron voltage; *B*–measurement of gyrotron current; *C*–measurement of microwave profile.

The high voltage is supplied by a modulator with a condenser bank of 100 kV, 80 μf. The high voltage unit is shown in Fig. 2.

At power waveform voltage of 58.4 kV and current of 16 A the power waveform is shown in Fig. 3. The microwave power is 250 kW and the pulse duratation is 30 ms.

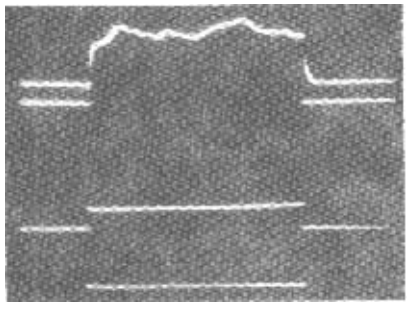

Fig. 3. Microwave profile of the gyrotron. Top line: microwave profile; mid: gyrotron voltage (20 kV/div); bottom: gyrotron current (10 A/div); time scale: 5 ms/div.

C. Experimental condition and diagnostics

HL-1 tokamak plasma[5] has been improved gradually in the past years and it is suitable for detailed heating experiments. The toroidal magnetic field of HL-1 has been set up at 2.7–2.8 T in order to keep the resonance at the location nearby the plasma center. The plasma density at plasma center is set between $(2\text{–}4)\times10^{13}$ cm^{-3} to guarantee the condition of optical thickness for ECE measurement. The microwave power is launched into plasma usually at 300 ms after the tokamak discharge starts except for start-up studies. All ECRH system is automatically controlled and monitored by a PC computer.

The diagnostics, such as soft X-ray detector array, visible and ultraviolet spectrometers, ECE, HCN interferometer, diamagnetic loop, superthermal microwave radiation (3 cm, 8 mm) and various probes had been used.

III. THE EXPERIMENTAL RESULTS

A. The increase of electron temperature

When the high power ECW is injected during the Ohmic discharge, the electron temperature increases and all diagnostic signals change. The typical experimental results are shown in Figs. 4 and 5. The parameters of shot No. 12550 are: toroidal magnetic field $B_t = 2.72$ T, plasma current $I_p = 119$ kA, loop voltage $V_l = 2.8$ V, discharge duration is 1050 ms and the microwave of 230 kW, 30 ms is launched into plasma at 300 ms after the tokamak discharge starts. Figure 4 shows that during ECRH intensity of ECE(1) increases, loop voltage drops, the signal intensity of central soft X-ray (SX1, SX2, SX3) is enhanced, intensity of OII spectral line (OF1) at plasma edge increases, total radiation (BOLOM1) rises, edge plasma

temperature (TP2) increases from 24 to 31 eV, edge saturating ion current $n_e T_e^{1/2}$ (TP1) increases (edge electron density increases from 1.1×10^{12} to $1.2 \times 10^{12}\,cm^{-3}$), the content of total plasma energy increases from 0.85 to 0.99 kJ and energy confinement time τ_e (TAUE) decreases from 5 to 3.8 ms.

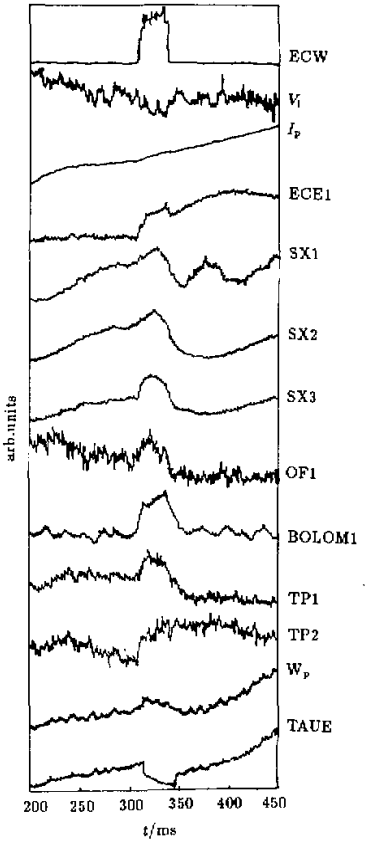

Fig. 4. The experimental results of shot No. 12550.

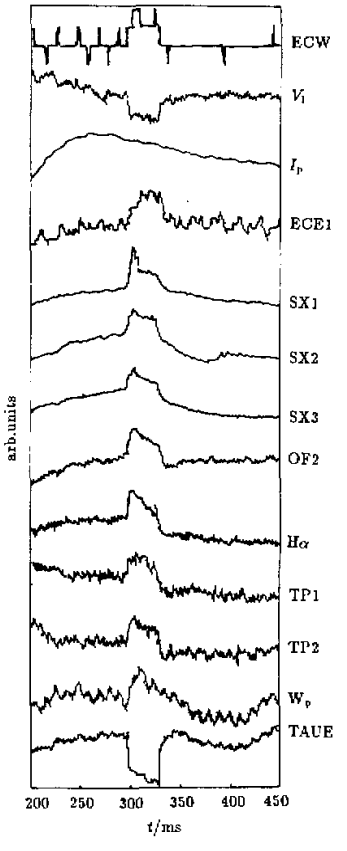

Fig. 5. The experimental results of shot No. 12195.

The experimental results of shot No. 12195 is similar to that of shot N. 12550. The intensity of OIII spectral line (OF2) and Hα at plasma edge increases, edge plasma temperature (TP2) increases from 14 to 19 eV, edge electron density n_e increases from 1.3×10^{12} to $1.4 \times 10^{12}\,cm^{-3}$, the content of plasma energy increases from 1.19 to 1.39 kJ and energy confinement time τ_e (TAUE) decreases from 6 to 4.3 ms.

Figures 6 and 7 are the evolutions of average plasma densities. During ECRH (from 300 to330 ms) there are drops on the density line and it seems that the higher the plasma density, the deeper the drop.

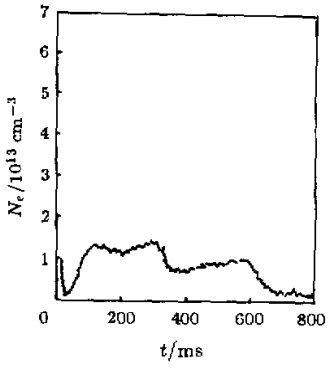

Fig. 6. The average plasma density of shot No. 12550.

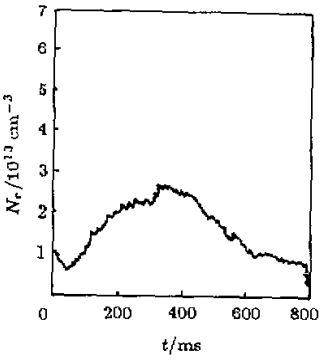

Fig. 7. The average plasma density of shot No. 12195.

From ECE measurement, the electron temperature increases by 30% during ECRH of 230 kW, 30 ms at average plasma density of 1.4×10^{13} cm^{-3}, and the following phenomena accompony the increase of electron temperature:

(1) The intensity of central soft X-ray increases.

(2) The intensity of the spectral line of impurity OVIII 633 and MoXIII 461 increases. The intensity of OVIII 633 of shot No. 12549 increases by 23%. In our experiments the average plasma density always drops, and therefore the increase of the intensity of OVIII 633 results not from the rising of plasma density but from the increase of electron temperature.

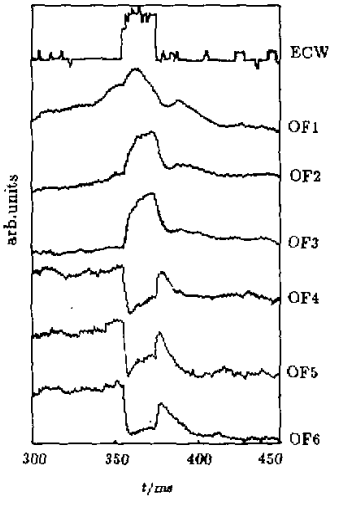

Fig. 8. The Hα signals of shot No. 12496.

(3) The change of intensity of Hα spectral line in the vicinity of plasma center is different

from that in the periphery during ECRH. The intensity of Hα spectral line (OF4, OF5, OF6 in Fig. 8) in the vicinity of plasma center decreases while that (OF1, OF2, OF3 in Fig. 8) in the periphery increases. The observed positions of OF1, $\cdots$, OF6 are from 18 cm (edge) to 0 cm (center), and the Hα signals are chord integration signals. The increase of Hα spectral line intensity in the periphery is due to the increase of edge plasma temperature which speeds up the ionization of hydrogen atom. However, the decrease of Hα spectral line intensity in the vicinity of plasma center is due to the increase of plasma temperature which makes the edge cooling plasma layer more thin.

B. The effect of ECRH on sawteeth

The intensity of soft X-ray increases obviously during ECRH (SX1, SX2, SX3 in Figs. 4 and 5). The amplitude change and periods elongation of sawtooth oscillation have been observed and in some cases the sawteeth were suppressed completely. For example, the sawteeth shown in Fig. 9 have been changed to higher amplitude and longer periods in the first 10 ms of microwave pulse for shot No. 12195, in which average plasma density $N_e = 2.5 \times 10^{13}\,\mathrm{cm}^{-3}$ and the resonant position of ECW (265 kW, 30 ms) is located at radius of 4.7 cm ($B_t = 2.8\,\mathrm{T}$) on the low magnetic field side while the sawtooth inverse radius is about 3 cm. For shot No. 12550 (Fig. 10) with the resonance position at 1.7 cm ($B_t = 2.72\,\mathrm{T}$) on the low magnetic field side and the inverse radius of about 2 cm, the sawteeth were suppressed completely. The sawteeth appeared again at 20 ms after the microwave pulse ended with opposite phase. It means that the sawtooth inverse radius is reduced due to ECRH.

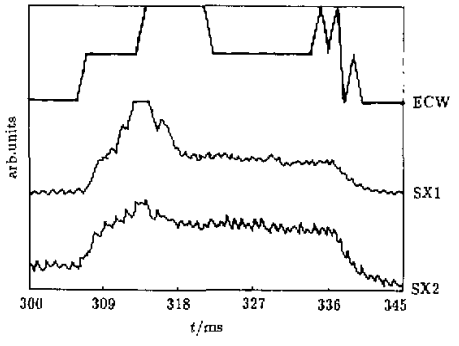

Fig. 9. Sawtooth oscillation of shot No. 12195.

The experiments show that the effects of ECRH on sawteeth are quite sensitive to the location of resonance at the position nearby $q = 1$ surface. When the resonance is located at the low magnetic field side, inside $q = 1$ surface and in the vinicity of it, the sawteeth are suppressed entirely. For the discharge with the resonance located outside the $q = 1$ surface, sawtooth periods are elongated and the effects diminished gradually with the resonance

position moving outwards to the plasma edge.

The obvious effects of ECRH on sawteeth seem to be caused by the reduction of magnetic shear in the vicinity of $q = 1$ surface which results from the change of the current profile due to thermal electrons produced by ECRH.

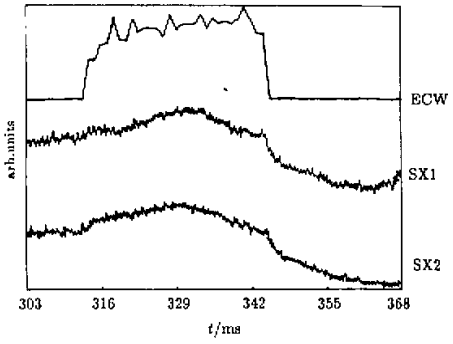

Fig. 10. Sawtooth oscillation of shot No. 12550.

C. Low voltage start-up[6]

The ECRF assistant start-up experiments were carried out using domestic Gyrotron in 1987 with the results that the volt-second consumption was reduced about one third. Recently, the experiments have been carried forward for the low voltage start-up . By launching of 240 kW, 30 ms microwave at 5 ms before the gas breakdown, the breakdown voltage dropped down from 52 to 25 V and the consumption of Volt-second reduced from 0.24 to 0.16 Vs, as shown in Fig. 11. The good reproducibility of plasma production and easily controlled initial plasma indicated that the ECRF assistant start-up might be important in fusion studies in the future. Our experiments have made progress in the low voltage start-up. This is necessary for a fusion reactor (such as ITER).

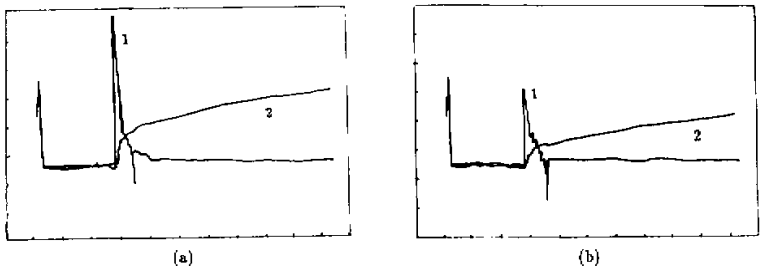

Fig. 11. Loop voltage and consumption of volt-second. (a) Shot No. 12005 without ECRH; (b) shot No. 12006 with ECRH of 240 kW, 30 ms. 1–loop voltage V_l (10 V/div); 2–consumption of volt-second (0.1 Vs/div); time scale–10 ms/div.

IV. CONCLUSION

The gyrotron of 300 kW, 30 ms, 75 GHz with horizontally polarized Gauss mode and a quasi-optical transmission line with an efficiency higher than 80% have been installed on HL-1 tokamak. The ECRH experiments with this system have been carried out. The obvious plasma heating have been observed: electron temperature increases 30%, loop voltage drops, edge plasma density and temperature are enhanced, the intensities of impurity radiation and edge Hα increase, the content of plasma energy increases and the energy confinement time decreases.

The effects of ECRH on sawteeth were very obvious. The intensity of soft X-ray increases remarkably. Amplitude change and periods elongation of sawtooth oscillation have been observed and in some cases the sawteeth were suppressed completely. The ECRF assistant start-up is quite efficient.

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