§3. Long-Pulse Plasma Sustainment up to 30 Minutes by Use of EC-Waves

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Until 2009, three high-power 77 GHz gyrotrons have been installed and applied to LHD experiment. In 2012, operating the three 77 GHz ones and 84 GHz one simultaneously (the injection power P_{inj} was 520 kW in total), discharges with the line average electron density n_{e_ave} over 1×10^{19} m^{-3}, duration time T_p of about 2 min. were sustained with the working gases of helium or hydrogen. Those discharges were terminated by intended turning off the power injection, not by any troubles from plasma conditions. Setting polarization of the EC-waves adequately to reduce non-absorbed power (this would be the cause of the gradual density increase occurred formerly for T_p of about 1 min., probably by unwanted outgas) was the key for the extension of T_p. However, internal pressure of 77 GHz gyrotrons continuously increased especially for 77 GHz (5.5-U injection), indicating that straightforward extension of T_p toward 1 hour was difficult.

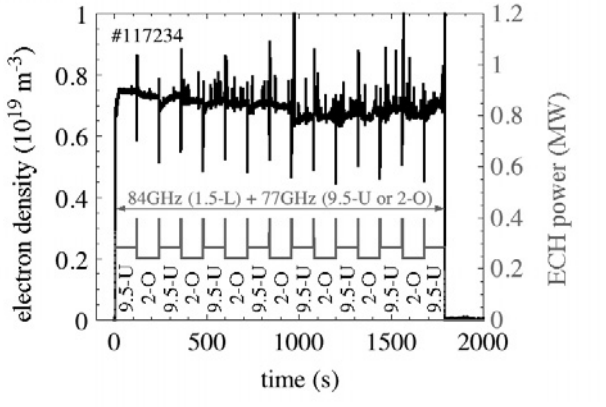

Fig. 1. Waveforms of the line average electron density (black) and the injection power of EC-waves (red) of the 30 min. discharge #117234.

For further extension of T_p, two 77 GHz gyrotrons (9.5-U and 2-O) were alternately operated with intervals of two minutes, with the 84 GHz gyrotron operated continuously. With this heating scheme, as seen in Fig. 1, a 30 min. long-pulse discharge with the line average electron density n_{e_ave} of 0.7×10^{19} m^{-3} and the central electron temperature T_{e0} of 1.5 keV was achieved by average P_{inj} of 240 kW, showing significant progress in sustained density from the former 65 min. discharge with n_{e_ave} of 0.15×10^{19} m^{-3} and T_{e0} of 1.7 keV by P_{inj} of 110 kW of 84 GHz wave. Most of the increasing spikes in n_{e_ave} synchronize with the spikes in the radiation from carbon (CIII), and the decreasing spikes in n_{e_ave} are caused by 2 sec. overlaps of operations of the two 77 GHz gyrotrons.

Figure 2 shows an expansion in time of waveforms of the 30 min. discharge at around its termination timing 1788.4 s. From these waveforms, it would be concluded that the termination process was originated at the plasma peripheral region. Radiation (temperature) started increasing (decreasing) from the outermost region and it propagated toward the inner side. The source of the radiation and the cause of the termination was not carbon. Observation in other discharges indicates that the source would be iron.

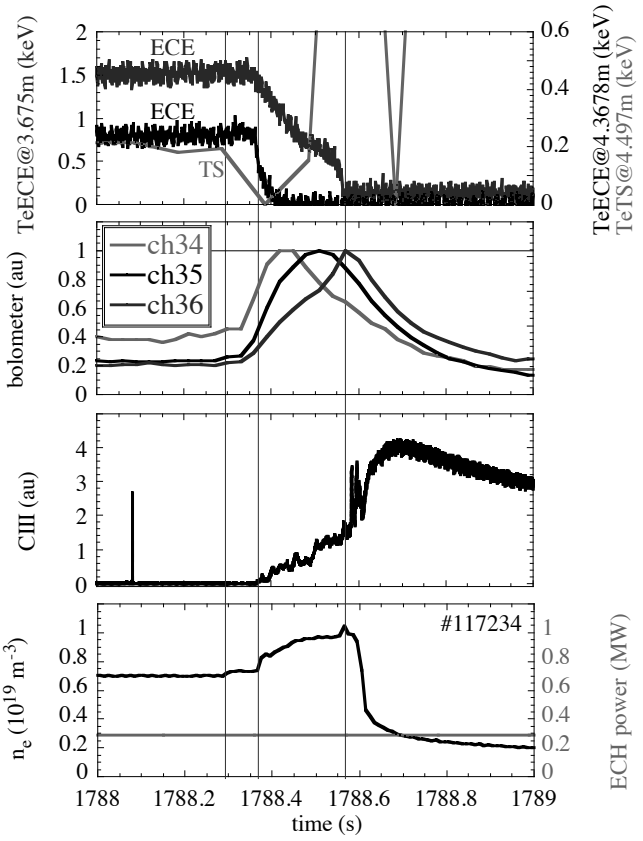

Fig. 2. Waveforms of top column: electron temperature at the magnetic axis (R = 3.68 m, blue) and the peripheral region (R = 4.37 m, black) measured with ECE, and the peripheral region (R = 4.5 m, red) measured with Thomson scattering diagnostics, second one: line integrated bolometer signals with the sightlines in the peripheral region (outermost: ch34 in red, secondly outermost: ch35 in black and the thirdly: ch36 in blue), third one: radiation power of CIII, and the bottom one: line average electron density (black) and the ECH power (red), at the termination timing of the 30 min. discharge.