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Heating and Current Drive by Lower Hybrid Waves Injection in High Density Plasmas of FTU Tokamak

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Introduction. The attainment of non inductive current drive is a crucial goal for the ITER project. With regards to that, lower hybrid (LH) waves capability of driving current has accomplished several tasks: proper shaping of current profile, for advanced or steady state scenarios; stabilization of MHD activity, in particular NTM [1,2,3,4,5]. It is thought that LH current drive will be an essential tool for steady state experiments. However, the present data base is restricted to densities and toroidal fields far from the values for a reactor relevant experiment. On the contrary, the FTU tokamak remains a unique experiment: it is a high density ($\bar{n}_e$ up to $3.0 \cdot 10^{20}$ m^{-3}), high toroidal field (up to 8 T) tokamak and the LH frequency (8 GHz) was expressly chosen to cope with high-density regimes. This experiment can then extend the exploitation of the issues of non-inductive current drive and heating at high density. Moreover at these densities the expected increase in collisionality leads to a significant transfer of energy from electron to ion.

Experiments. The LH system is currently able to deliver a maximum power of 2.4 MW at the antennas, for optimized coupling conditions. It works routinely at 2.0 MW, corresponding to a net power density of 5.6 kW/cm^2 at the waveguides mouth with a reflection coefficient of about of 10%. The FTU data base for full current drive extends, to the domain $0.5 < \bar{n}_e < 0.8 \cdot 10^{20}$ m^{-3}, plasma current (I_p) 0.4÷0.5 MA. At $\bar{n}_e$ of $0.8 \cdot 10^{20}$ m^{-3}, I_p of 0.36 MA, full current drive has been reached (fig. 1), with the electron temperature (T_e) going from 1.5 to 3.5 KeV and $Z_{eff} \approx 2$. The sawtooth activity is fully stabilized. The launched $N_{\|}$ spectrum was peaked at 1.82. At this density the collisionality causes an increase of a factor of 5 in the neutron yield corresponding to an ion temperature (T_i) increase from 0.9 to 1.1 KeV (fig. 2). At that time during high power LH injection, impurity influx was caused by hot spot formation on in vessel diagnostic supports and all the discharges ended up in disruptions. These supports have been subsequently removed. On this discharge the toroidal field (B_t) was on purpose swung from 5 to 7.2 T to spread the thermal load. As soon as the field became again constant a rapid impurity influx is observed as pointed out from the increase in Z_{eff} and loop voltage (V_L); the discharge ended up equally in a disruption. In Fig. 3, the results for a higher density discharge are shown, $\bar{n}_e$=1.0•10^{20} m^{-3}, $\hat{n}_e$=1.6•10^{20} m^{-3}, I_p= 0.5 MA, B_t= 6T. The fraction of driven current has been estimated [1] from the drop in V_L to be about 60% with an increase in T_e from 1.8 to 3.8 KeV. The neutron yield increase is of a factor of 7 corresponding to a rise in T_i from 1.2 to 1.55 keV. The sawtooth full stabilization is reached but an m=1 activity persists. The launched $N_{||}$ spectrum was again peaked at 1.82. The B_t swing recipe is not adopted in this discharge, so that the impurity influx came earlier as soon the full power phase is reached (2.1 MW) and the discharge disrupted. The Z_{eff} just before the disruption reach the value of 3.5. During the last shutdown the diagnostic supports have been removed and a conditioning procedure of first wall, based on Boron implantation, has been extensively used. The Boron is injected in form of B_2H_6 compound and an Hydrogen retention on the first wall has been observed, imputable to the cryogenic operative temperature of FTU. The data base has been widened at higher B_t to improve the LH accessibility and at higher density in gas and pellet fuelled discharges. The data are preliminary, but some interesting results can be pointed out. In Fig. 4 the behavior of a 0.5MA, 7.2T discharge is shown. The $\bar{n}_e$ is 0.9•10^{20} m^{-3} and $\hat{n}_e$ is 1.5•10^{20} m^{-3}. The T_e increases from 2.1 to 3.8 keV with full stabilization of sawtooth. The neutron yield increases of a factor of 6 and T_i from 1.2 to 1.45 keV (fig. 5). The Z_{eff} reaches 2.0 during LH against a figure of 1.4 in ohmic phase. The fraction of driven current is 75%. In this case the launched $N_{||}$ is 1.52. Taking into account the Hydrogen dilution due to the Boron implantation procedure we obtain better performances, in spite of a lower LH power (1.5 MW). Neglecting the small difference in density this can be explained in terms of improvement in the LH waves accessibility and in the cleanliness of the first wall. Also the lower $N_{||}$ can play a role. An accurate analysis has been made for the discharge at B_t=6T. The comparison between the confinement time and ITER89P scaling (fig. 6) is satisfactory and shows a good efficiency of LH at high density. The confinement can actually be better when the LH power actually accessible is used in computation removing also the small discrepancies observed. An analysis of the LH power deposition profile has been done using a fast electron bremsstrahlung (FEB) camera on loan from the CEA Laboratory of Cadarache. The deposition profile (fig. 7) is well inside one third of the minor radius (0.30 m). The comparison with the result of Bonoli type deposition code [6] shows a good agreement making us confident in the use of the code. The analysis of confinement and deposition profile for discharge at B_t=7.2T is still in progress. Finally a very recent result of LH wave injection experiment in a pellet fuelled discharge at I_p=1.1 MA, B_t= 7.2T is reported. For comparison the behavior of similar ohmic pellet fuelled discharge is shown. In both discharges the pellet injection rise the density at 2.5 10^{20} m^{-3}. In one discharge the LH is injected 30 ms after the pellet injection and gradually reaches the power level of 1.8 MW. The launched $N_{\parallel}$ was 1.52. The T_e, from Thomson Scattering, increases of 0.3 keV. The electron cyclotron emission is optically thick so that the data from polycromator can be used and confirm the figure. Correspondingly the neutron yield increases of a factor of 2 and the ion temperature of 0.1 keV. The drop in loop voltage is of 10% but it not significant. Against all expectations, attempts to use slower $N_{\parallel}$ did not show any effect on plasma. This is the Lower Hybrid injection experiment performed at the highest density to date

Conclusions. The FTU experiment has proved the capability of driving current and heating plasmas by means of lower hybrid waves at average density (10^{20} m^{-3}) and toroidal field (6÷7 T) ranges relevant for reactor regimes. Within the limitation of the “L – mode” confinement scaling ITER89P a good the efficiency of the LH is demonstrated. These experiments show that the expected increase in collisionality leads to a significant transfer of energy from electron to ion. Lower Hybrid waves have been launched to the aim of sustaining the re-heating phase in plasmas after the pellet injection. The preliminary results are unexpected but encouraging. Even if the effects are marginal these experiments deserve an accurate study and further experimental campaign.

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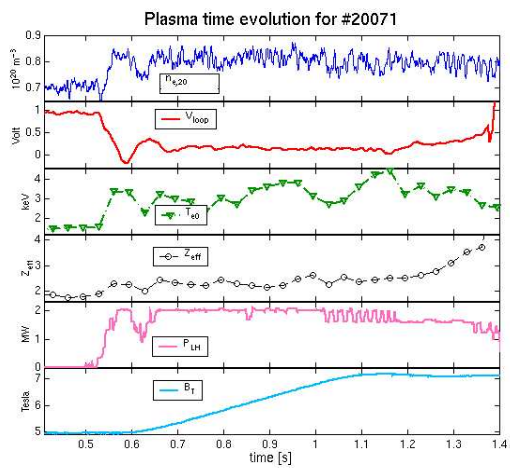

Fig. 1. Discharge #20071, I_p= 0.36 MA, swinging B_t.Temporal evolution of density, loop voltage, electron temperature, Z_{eff}, LH power and toroidal field. .

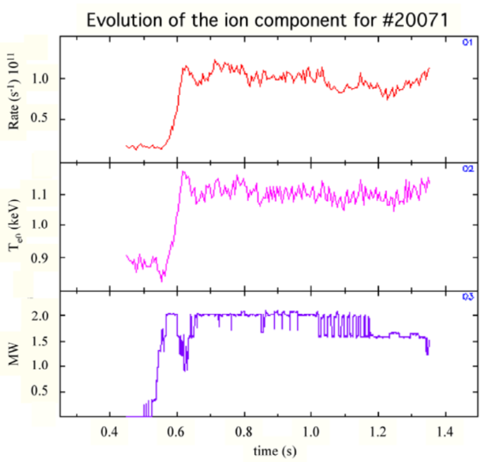

Fig. 2. Discharge #20071, I_p= 0.36 MA, swinging B_t. Temporal evolution of ion component: neutron rate, temperature, LH power

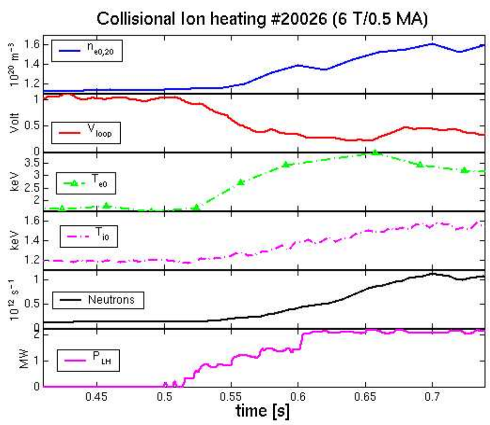

Fig. 3. Discharge #20021, I_p= 0.50 MA, B_t= 6T. Temporal evolution of density, loop voltage, electron temperature, ion temperature, neutron rate and LH power.

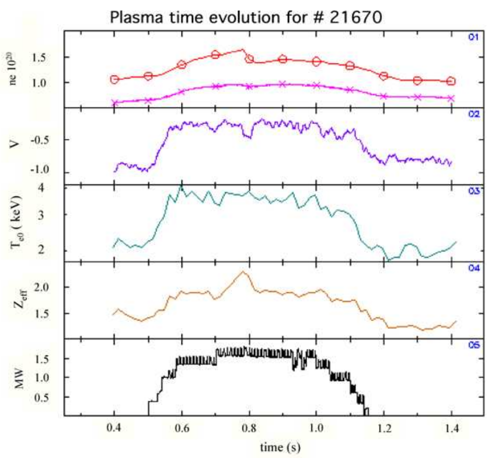

Fig. 4. Discharge #21670, I_p= 0.50 MA, B_t= 7.2T. Temporal evolution of peak and average density, loop voltage, electron temperature, Z_{eff}, and LH power.

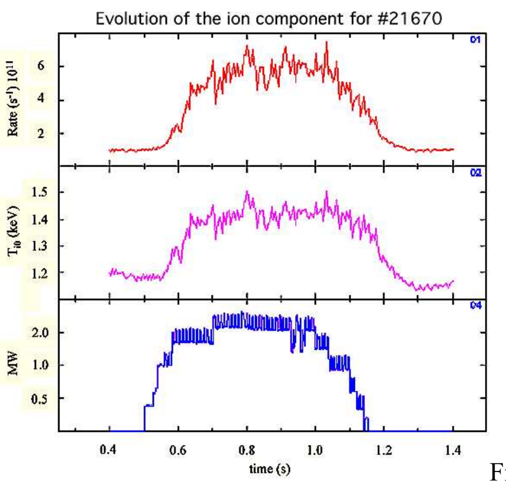

Fig. 5. Discharge #21670, I_p= 0.36MA, B_t= 7.2T. Temporal evolution of ion component: neutron rate, temperature, LH power

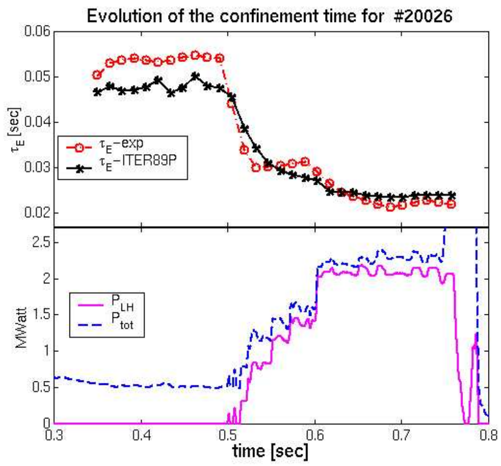

Fig. 6. Comparison between the experimental confinement time and the ITER89P scaling, LH an total power in the second frame

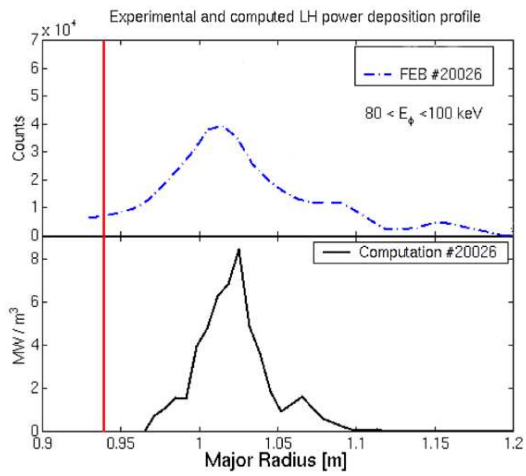

Fig. 7. Experimental deposition profile from FEB camera compared to the theoretical prediction from a Bonoli type code. The vertical line is the plasma centre.

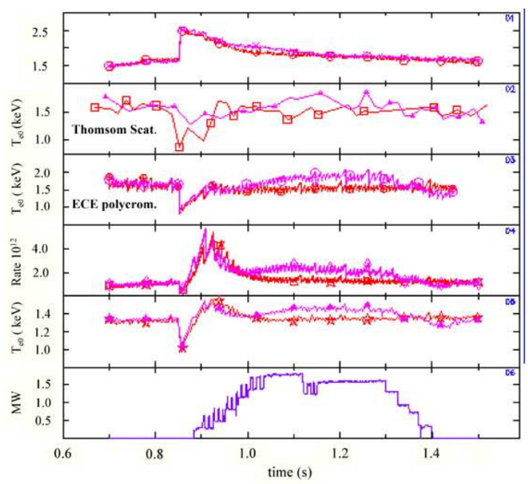

Fig. 8. Discharge #21802 (without LH), 21831 (with LH), I_p= 1.1MA, B_t= 7.2T. Temporal evolution of density, electron temperature from Thomson scattering and ECE polycromator, neutron rate, ion temperature and LH power