Interaction of Lower-Hybrid with Fast Ions in JET

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INTERACTION OF LOWER-HYBRID WITH FAST IONS IN JET

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It is predicted by theory [1] that the fast minority ions in the plasma, generated during minority heating experiments with ion cyclotron waves (ICRH), can interact with Lower-Hybrid waves (LH), through Landau Damping, in the direction perpendicular to the toroidal magnetic field when the resonance condition, $v_\perp=\omega/k_\perp=c/n_\perp$, is fulfilled. $v_\perp$,$k_\perp$ and $n_\perp$ are the perpendicular components of the ion velocity, the wave vector and refractive index of the wave respectively, and ω is its frequency. The LH-fast ion interaction, which simulates the interaction of α particles (~3.5MeV) with LH, is competitive with parallel electron Landau Damping thus reducing the current drive efficiency of an LHCD system. Recent studies, however, have indicated that the energy exchange between α particles and LH waves in a reactor scenario, where very high density and electron temperature occur, might improve the accessibility of the wave to the core of the plasma [2].

A 1-D Fokker-Planck equation [3], including the ICRH and LH quasi-linear diffusion coefficients, describes the interaction between LH and fast ions and their slowing-down over a Maxwellian plasma. This interaction requires both ICRH and LH power deposition profiles on the fast ion population to be superimposed.

The first experimental evidence of the interaction of LH waves with fast ions at JET is presented in this work. LH experiments at JET were performed in low density plasmas with 1 to 2 MW of LH power in 2.6 to 3.3T limiter plasmas and 2 and 3 MA of plasma current. These experiments were carried out in order to optimise LHCD current drive efficiency. Heating of hydrogen minority with minority concentration ranging from 5 to 15% in deuterium plasmas was done using 4 to 6 MW of ICRH power with the cyclotron resonance layer ranging between the plasma centre and r=40cm in relation to the magnetic axis. The central electron density was approximately $n_e(0)=2.5\times10^{19}$ m^{-3} in order to enhance LH wave penetration for current drive studies and central electron temperatures were ranging from 5 to 8 keV. Between 1 to 2 MW of LH power at 3.7GHz were launched with power spectrum centred at a parallel refractive index $n_\parallel=1.8$. LH wave propagation leads to $n_\perp$ values in the range of 10 to 25. In this case, the fast ion resonance energy, ($E_{fi}=0.5m_i(c/n_\perp)^2$), ranges from 0.75 to 4.7 MeV.

Diagnostics: Observations on the absorption of LH waves by the fast minority ions were mainly based on the analysis of the fast ion energy, and on the γ ray and neutron rates.

Fast Ion Energy: The fast ion energy content (W_f), defined as the perpendicular energy in excess of the isotropic component, is related to the anisotropic high energy tail generated during ICRH heating [4], which increases preferably the perpendicular velocity component of the minority ions. There is however a component of their parallel energy above the thermal level due to pitch angle scattering or because of the variation of the magnetic field along the particle orbit. It can be obtained from the diamagnetic energy $W_{DIA}=3/2W_\perp$, measured by the diamagnetic loop, and the MHD energy, $W_{MHD}=3/4(W_\perp+2W_\parallel)$, obtained from MHD equilibrium calculations resulting in $W_f=4/3(W_{DIA}-W_{MHD})$. A possible off-set between W_{DIA} and W_{MHD} is accounted in order to obtain $W_f=0$ for an isotropic distribution in absence of fast ion tails.

γ Rays and Neutron rate: The fast minority ions can interact either with the main ions in the plasma or with impurity ions. The unstable products originated from these reactions emit γ rays whose spectrum and flux rate can be measured to estimate the fast ion minority density as well as their threshold in energy in order to excite such reactions [5]. In this work we present the γ rays count rate in reactions between fast ions with ^{9}Be, one of the main impurities in JET plasmas. These reactions have a threshold in energy of 1 MeV, and the energy of γ rays released during this process is 3.5 MeV. The neutron rate measures the D-D reaction rate in the plasma and in most of the cases this rate increases when LH is coupled to the plasma.

NPA: The new neutral particle analyser at JET which can diagnose minority ions with energy ranging from 286 keV to 1.0 MeV shows that there is an increase in the fast particle flux for all energies when LH is present. Further analysis still has to be carried out since impurity and minority concentrations, which are difficult to be measured accurately, are critical elements in the data analysis.

Experimental results: Time dependence of plasma parameters for a typical JET pulse where LH coupling to the fast ions was observed, is shown in fig1. Approximately 25% of increase in W_f (200 kJ) is observed for #27760 (Fig.1d) when 2MW of LH power is applied in addition to 3.0 MW of ICRH at 48 MHz. This gives an estimate of approximately 10% for the LH power damped on the fast ion population which is in reasonable agreement with the 8% obtained from code simulations carried out for this shot. Time dependent code simulations including the presence of ICRH only [6] for #27760, do not reproduce the fast increase on the fast ion energy content as it is observed experimentally, suggesting that the step on the fast ion energy is related to the presence of LH. An increase, of more than a factor 2, in the γ count rate is observed after 8.5s in #27760, after LH is switched on (Fig.2). The electron temperature measured by the LIDAR diagnostics remains approximately constant and the higher γ rays rate observed cannot be accounted by an increase in Z_{eff} , which remains approximately 3.8. Therefore the possible cause of this increase, is the increase of the fast ion population when LH is launched in the plasma. The neutron rate, which is a measure for the D-D reaction rate, also increases after 8.54s (Fig.1e).

Finally, Figs 3a and 3b show the analysis on the Fourier analysis (FFT) of shots where LH power is modulated with a frequency of 1 Hz. The results are shown for shots #24898 and #24909 where the hydrogen minority cyclotron layer was respectively 40 cm and 10 cm outboard of the magnetic axis. In the first pulse the resonance is outside the q=1 surface and represents the off-axis heating case. In both shots the plasma parameters are similar but the FFT for #24898 of the fast ion energy gives a peak in its spectrum around 1Hz, not evident in #24909. As shown in fig.4, the fast electron profile, as deduced from the FEB camera [7] is hollow and peaked at r~50 cm. This indicates that damping of LH waves on the minority ions takes place when the cyclotron resonance layer is close to the region where the fast electrons are located.

Conclusions: The first experimental evidence at JET on the interaction of fast minority ions with LH is reported in this work. An increase of approximately 20% on the fast ion energy content was observed in the presence of LH, with an estimated LH absorbed power of approximately 10% for 2 MW of LH power and plasma densities of 2.0×10^{19} m^{-3} with central temperatures $T_e(0)$~6 keV. γ ray and neutron rates also show that absorption of LH waves by the fast minority ions is taking place. FFT analysis confirms a better damping of the wave when ICRH heating and maximum of fast electrons population coincides. This condition would be somewhat relaxed when α particles are considered due to large orbit effects. The next JET operational campaign, where 10 MW of LH are expected to be coupled to the plasma, will provide further information on the interaction between α particles and LH waves, as simulated with ICRH minority fast ions.

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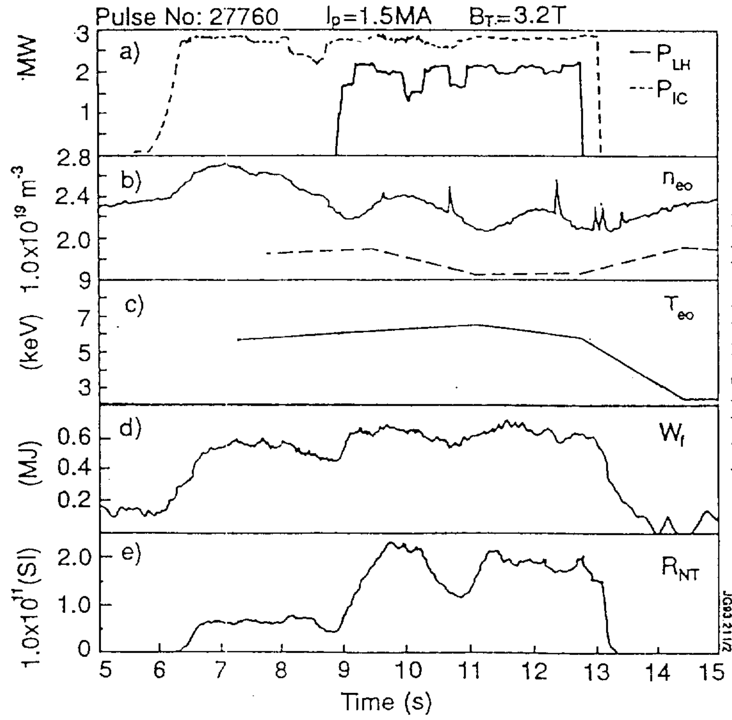

fig.1: Time evolution of the main plasma parameters, fast ion energy W_f and neutron rate (RNT) for #27760. a) — LH power, --- ICRH power, b) — central electron density $n_e(0)$ (interferometer),---$n_e(0)$ from LIDAR, c) central electron temperature $T_e(0)$ from LIDAR, d) increase on the fast ion energy (W_f) after 8.5 s e)increase on the neutron rate when LH is coupled to the plasma.

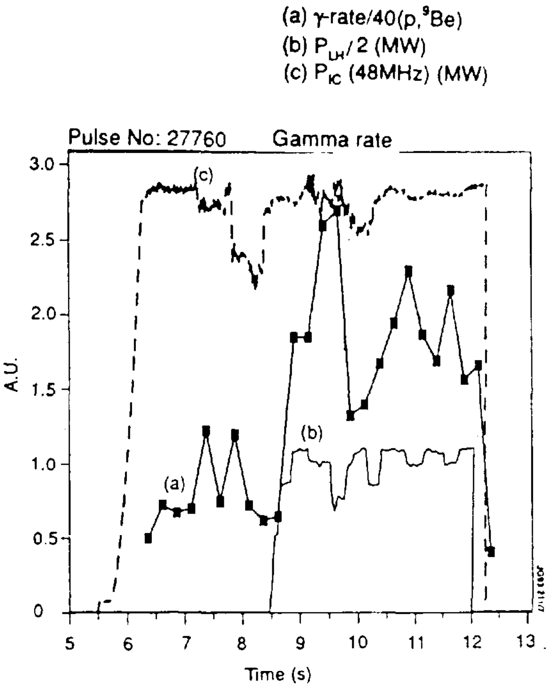

fig.2: Gamma rays rate for #27760. An increase higher than a factor two is observed after LH is launched in the plasma (8.5s).

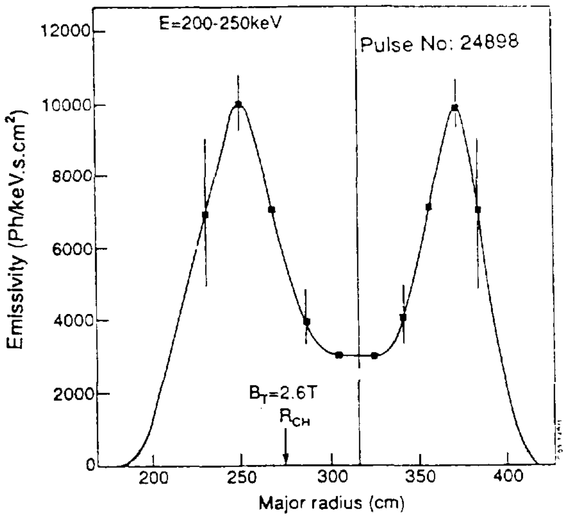

fig.4: Fast electron profile (FEB camera), for #24898 peaked at r~50 cm, close to the ion cyclotron resonance layer (r~40cm)

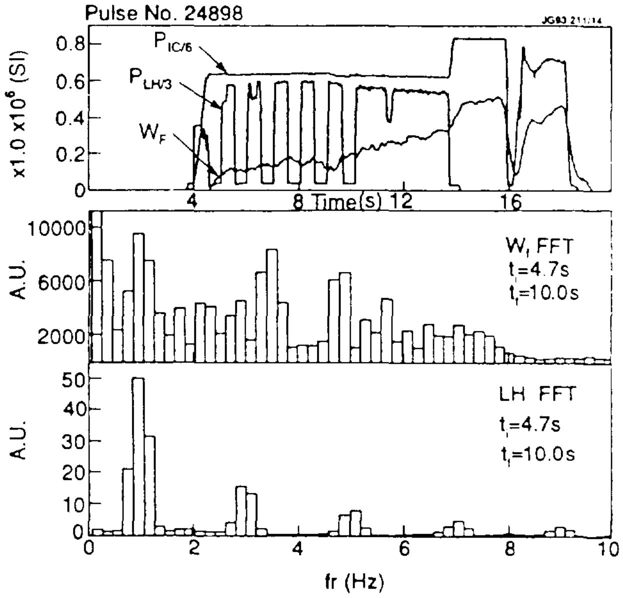

fig.3a: Time evolution of fast ion energy and FFT analysis for W_f and LH for #24898 (off axis) with $n_e(0)\sim2.7\times10^{19}m^{-3}$ and B_T=2.6T. There is a peak on the W_f spectrum around 1 Hz, the frequency of LH power modulation. Peaks in upper frequencies seem still to follow LH Fourier spectrum.

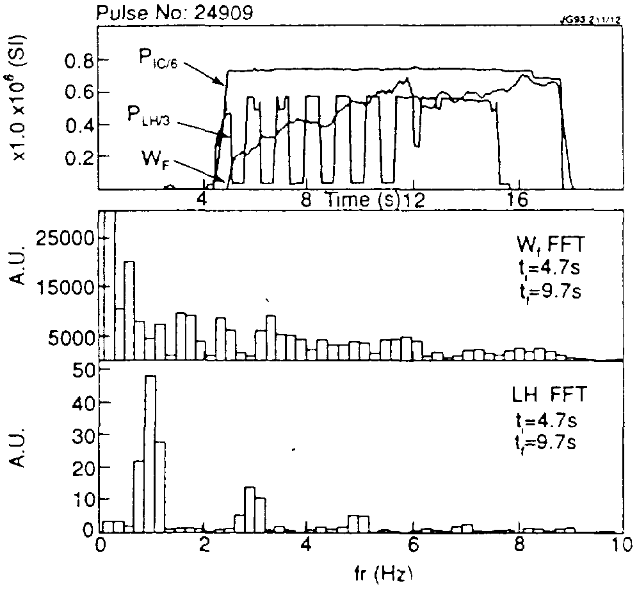

fig.3b: Time evolution of fast ion energy and FFT analysis for W_f and LH power for #24909 (on axis) with $n_e(0)\sim2.7\times10^{19}$ m^{-3} and B_T=2.8T. In this case W_f FFT does not show any evident peak at 1Hz, the frequency of LH power modulation.