# Experiments on FW-IBW mode conversion heating combined with LHCD on Tore Supra

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## 1.Introduction

Recent RF heating and current drive investigations [1] revealed a growing interest in a scheme based on mode conversion (MC) of externally excited fast waves (FW) to ion Bernstein waves (IBW). Full-wave analysis of MC phenomena in bounded plasma shows [2] that high efficiency of mode conversion is attainable with FW excitation from the low field side (LFS) of the tokamak regardless of the parallel wave number $k_\parallel$ of the launched wave. On the other hand, strong $k_\parallel$ variation inherent to IBWs [3] can lead to their strong interaction both with bulk and accelerated plasma particles. Thus, a number of reactor-relevant MC applications can be considered, including localised plasma heating, current profile control [4], synergy with low hybrid current drive (LHCD) [5] and $\alpha$-particles' energy channelling [6].

Suitability of MC scheme for on/off axis electron heating has already been reported on Tore Supra [7]. New results, which were obtained during MC experiments combined with LHCD are presented in this paper. Application of new experimental tools and numerical techniques provided better insight into the problem of MC power deposition (see also [8]). An outcome of active search for synergistic LHCD-IBW current drive effects is also reported.

## 2. Key aspects of the studies

The experiments were conducted in H-$^3$He plasma with the following parameters: $R_0$=2.33m, a=0.75m, $B_0$=3.68T, $I_P$=0.65-1.0MA, $n_e(0)$=3-6 $10^{19}$ m$^{-3}$. The plasma current was partially or totally ($V_{loop}$=0.8-0.0V) sustained by $P_{LH} \leq$3.3MW LHCD. ICRH power $P_{IC} \leq$2.6MW was injected into the plasma by dipole/monopole phased FW LFS antennae, operating at the frequency of f=48MHz. The fundamental cyclotron layer of hydrogen intersected LFS plasma region at r/a$\approx$0.5. Preprogrammed puffing of $^3$He, which was maintained either constant or linearly increasing controlled the MC layer position.

A procedure of reconstruction of direct electron power deposition profiles was invoked to provide more detailed picture of the investigated heating scheme. Both Fourier and "break-in-slope" techniques were applied to analyse the temporal behaviour of electron temperature, measured by 16-channels superheterodyne ECE radiometer ($\Delta$t=1ms, up to 2$\mu$s) during 100% modulation of injected ICRH power ($f_{mod} \approx$10Hz).

A new approach of numerical description of MC phenomena, combining advantages of FW full-wave and IBW ray-tracing treatments was applied during simulations of power deposition profiles [8]. 2D global field patterns produced by the "ALCYON" code [9] were used to extract "incipient" IBW fields and to determine IBW rays' starting parameters. The IBW behaviour was analysed by ray-tracing "RAYS" code [3], which is capable to account for the ray trajectory and wave-vector evolution in 3D tokamak geometry. Up to 50 rays were launched in plasma cross-section for each toroidal harmonic number with subsequent summation over the antenna spectrum.

## 3. Localised electron heating

Experiments on Tore Supra have confirmed reliability of MC scheme for localised electron heating. On/off axis peaked electron power deposition profiles (Fig. 1) with half-maximum width $r/a \leq 0.2$ were registered. The maximum power $P_e$ directly deposited on electrons within the central plasma region ($r/a < 0.5$) was estimated as 70% of the injected ICRH power, providing the MC layer was located at the high field side (HFS) of the magnetic axis. This fraction turned to be 20-25% lower as the layer was shifted to the LFS region. Simultaneously, signs of increased hydrogen cyclotron damping were registered by ion ripple losses diagnostic and CX analysers. As an example, shots #23139 and 23109 can be compared on Fig.1: having the opposite location of the MC layer relative to the magnetic axis due to the different helium content ($n_H/n_{3He} \approx 3$ and $n_H/n_{3He} \approx 1$), they are characterised by $P_e/P_{IC} = 0.68$ and $P_e/P_{IC} = 0.46$ correspondingly. About 30-35% of $P_{IC}$ presumably was deposited in exterior ($r/a > 0.5$) plasma regions and unaccounted by the measurements.

Simulations based on "ALCYON"/"RAYS" codes coupling adequately represented observed peculiarities of power deposition (Fig. 2). They accounted for at least 15% of $P_{IC}$ power deposition to hydrogen ions (shot #23109), in contrast to negligible ion damping, given by purely full-wave modelling. Noticeable power deposition in the outer ($r/a > 0.5$) plasma regions was also predicted, which can explain the registered ICRH power balance deficit.
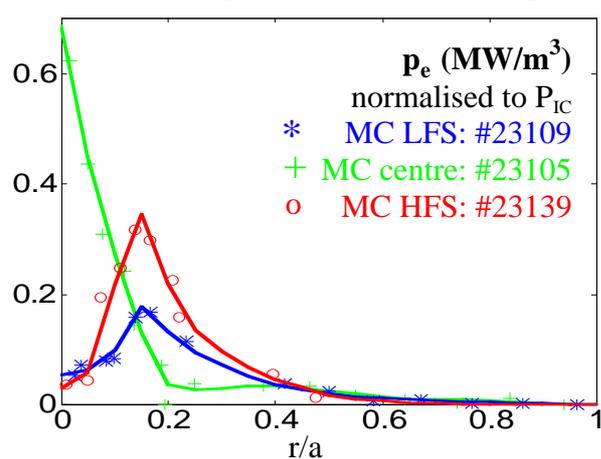


*Fig. 1 Electron power deposition profiles, normalised to the injected ICRH powers: measurements in discharges with different positions of the MC layer.*
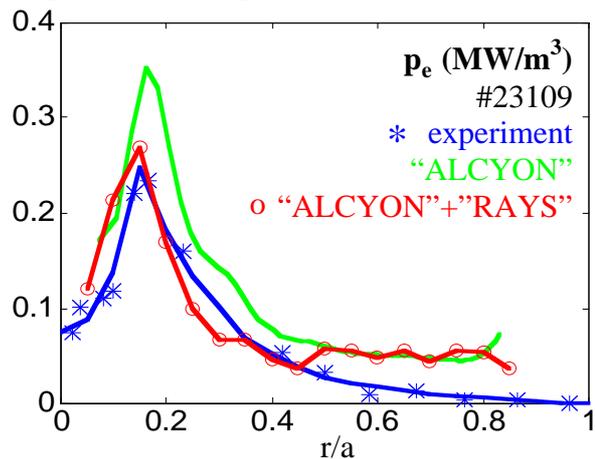
*Fig. 2 Electron power deposition profiles (not normalised), $P_{IC}=1.4MW$, dipole antenna phasing: comparison of measurements and simulations.*

Off-axis HFS localised electron heating was accompanied by transient (~1s) stabilisation of low-level sawtooth activity. The phenomena took place only if electron power deposition profile was peaked somewhat outside the sawtooth inversion radius. The presence of fast ions population was not registered in these discharges, thus, the observed stabilisation can be connected with local modification of the current profile during localised electron heating, as was reported previously during a number of ECRH experiments (e.g. see [10]).

Electron heating efficiency and global plasma performance typical to MC and LH schemes were found comparable (in discharges with L-mode confinement). Consecutive injection of equal RF powers caused similar plasma response (Fig. 3). Efficient electron heating was observed also during MC application in discharges with stationary LH driven current. On-axis electron power deposition resulted in formation of centrally peaked temperature profiles (Fig. 4 a,b). High central temperatures were attained due to improved electron confinement, which characterise LHCD operation on Tore Supra [11]. Low Hybrid Enhanced Performance mode was not disturbed during MC experiments (Fig. 4 c,d).
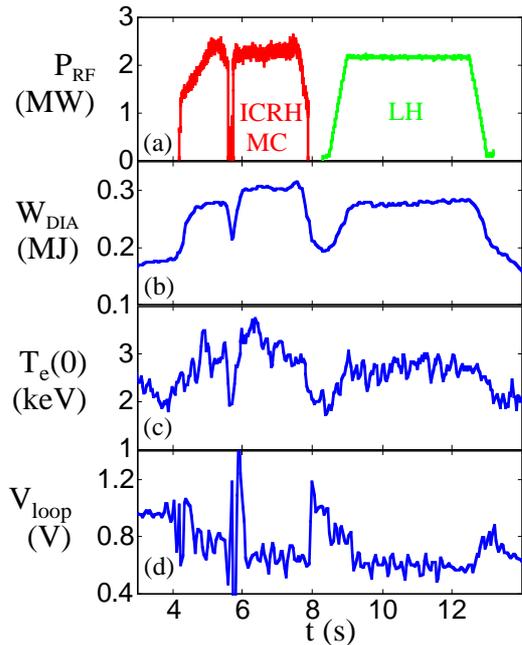
*Fig. 3 Consecutive MC and LH application: temporal behaviour of (a) injected RF powers, (b) plasma diamagnetic energy, (c) central electron temperature, (d) loop voltage.*
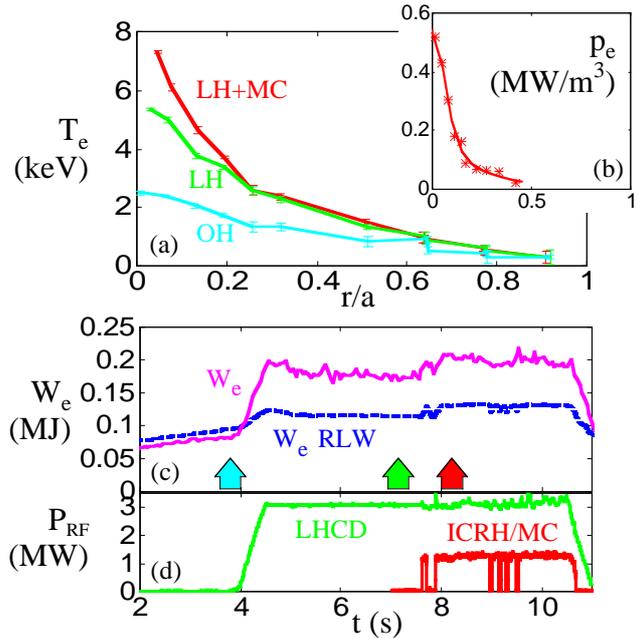
*Fig. 4 Simultaneous MC and LH application: (a) electron temperature profiles, (b) electron power deposition profile during MC, (c) electron energy content (measurement and L-mode scaling), (d) injected RF powers.*

## 4. Search for LHCD/IBW synergy

Synergistic current drive effects were registered some years ago during combined ICRH and LHCD operation on JET [5]. Since then, a question is discussed: can mode converted IBW accelerate LHCD driven fast electrons and increase current drive efficiency?

Experiments, performed on Tore Supra in stationary non-inductive discharges with different ICRF antenna phasing gave negative answer to this question. No sign of synergy was found in more than 25 discharges with constant or linearly increasing injection of $^{3}$He. Comparison of the measured loop voltage with predictions of 0-dimentional discharge scenario simulations, based on known Tore Supra scaling laws has shown that no additional current is generated during ICRH pulse. Hard X-ray measurements [12] have demonstrated unaffected spectra (E=20-200keV, ΔE=20keV) on 59 available chords indicating no detectable variation in the behaviour of the fast electrons.
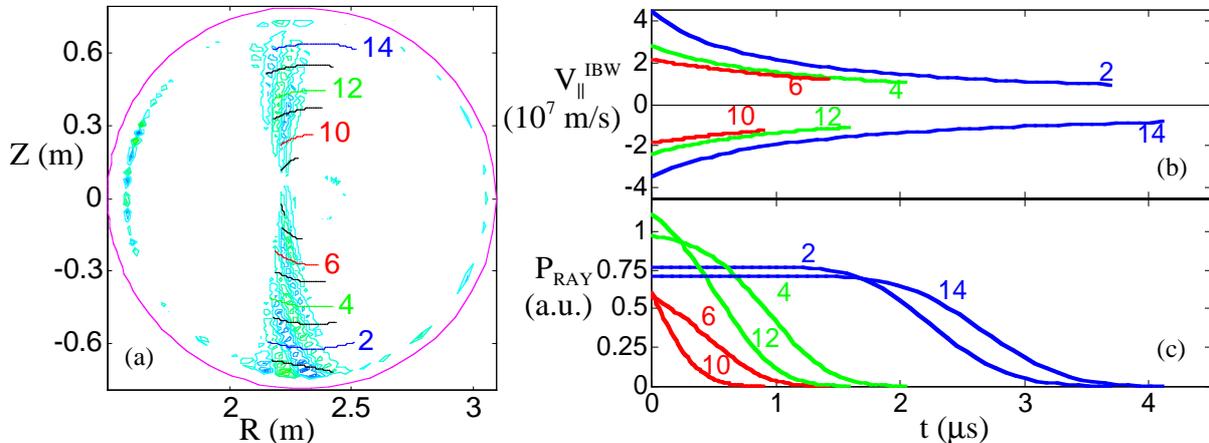


*Fig .5 Coupled "ALCYON"/"RAYS" simulations for $N_{TOR}$=5 ($V_{\parallel}^{FW} \approx 1.4 \cdot 10^{8}$m/s): (a) poloidal cross-section pattern of "incipient" IBW fields Re($E_X$), extracted from the "ALCYON" output and typical IBW ray trajectories, calculated by "RAYS", (b) parallel phase velocity, and (c) power of the rays, predicted by "RAYS"*

Recent numerical simulations, based on full-wave/ray-racing codes coupling have revealed possible reason of the missing synergy. It was shown that very rapid $k_\parallel$ up-shift takes place during mode conversion. Even if initial parallel phase velocity of the launched fast wave is high enough to match the fast electron parallel velocity, it quickly slows down up to thermal electron velocities. More important is that the IBW amplitude, growing generally with $k_\parallel$ remains quite small when the phase velocity is favourable for interactions with fast electrons. Thus, only bulk electron damping could be expected in such situation, which actually was observed in experiments. An example of simulations for $N_{TOR}=5$ ($k_\parallel^{FW}=N_{TOR}/R$) is shown on Fig. 5. When IBW rays were launched from the region with noticeable amplitude of small-scale waves (Fig. 5a), their parallel phase velocities were found to correspond to thermal electron velocities (Fig. 5b) and strong bulk electron damping (Fig. 5c) was predicted.

As IBW evolution is quite sensitive to parameters of MC experiment (and particularly to the nature of used ion mixture), proposed explanation can not exclude feasibility of LHCD/IBW synergy in different conditions.

## 5. Conclusions

Reported experiments have confirmed reliability of MC scheme with LFS fast wave excitation as an efficient tool for localised electron heating. On/off axis peaked electron power deposition profiles were registered during MC experiments combined with LHCD. Up to 70% of the injected ICRH power was directly deposited on electrons in the central plasma regions (r/a<0.5). Off-axis electron heating was accompanied by transient (~1s) stabilisation of sawtooth activity, providing the power was deposited outside the sawtooth inversion radius. Low Hybrid Enhanced Performance mode was not deteriorated during mode conversion. New approach of MC numerical treatment based on full-wave/ray-tracing codes coupling was proposed and demonstrated good agreement with the experimental observations.

Active search for synergistic LHCD-IBW current drive effects has been undertaken in stationary non-inductive discharges with varying ion concentration. No sign of synergy was observed with dipole and monopole ICRF antenna phasing either by the loop voltage analysis or by hard X-ray tomography. Possible explanation was proposed as a result of simulations. Peculiarities of IBW evolution in H-$^3$He plasma of Tore Supra (very rapid $k_\parallel$ up-shift with low $E_\parallel$ values corresponding to $V_\parallel^{wave} \sim V_\parallel^{fast\ el.}$) can be responsible for the missing synergy.

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