Hard X-ray measurements during LHCD experiments with passive active multijunction and fully active multijunction antennas in Tore Supra

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Introduction. This paper presents the first experimental results on the hard X-ray (HXR) emission measurements during lower hybrid waves (LHW), injected by the Passive Active Multijunction (PAM) antenna [1,2] in Tore Supra. In particular, the LHW coupling during edge perturbations, mimicking ELMs, was studied by employing multiple supersonic molecular beam injection (SMBI) and by analyzing the HXR emission, measured by CdTe detectors, with an energy response ≤ 200keV [3,4]. The studies covered a wide range of plasma parameters like LH power (P_{LH} up to 2.7MW), parallel refractive index ($N_{\|}$ from 1.7 to 2.0), plasma current (I_P up to 1.0MA) and volume averaged density ($<n_e>_{vol}$ varying across 1.4 – 3.8 x 10^{19} m^{-3}). During each SMBI, the HXR counts signal falls, but the slow response of the HXR counts suggests that this is rather due to the perturbation of the bulk density, which is also altered during SMBI. The edge perturbation in itself does not seem to cause a redistribution of the fast electron profile (hence the LH power deposition). Furthermore the analysis shows a dependence of the HXR emission on various plasma parameters. A scenario with ICRH heating is also presented to establish enhanced interaction of LHW with electrons in the presence of ICRH heating. A comparison with the results obtained from previous fully active multijunction (FAM) is also presented in this paper.

HXR emission during edge perturbations. During these studies, SMBI (two injections at 2Hz, every 3s for 3 different $N_{\|}$) are injected into the plasma over wide range of plasma parameters. The $\langle n_e \rangle_{vol}$ is varied from 1.5 to 3.8 x 10^{19} m^{-3}, I_P is varied from 0.6 to 1.0MA and $N_\parallel$ is varied from 1.7 to 2.0. A typical temporal evolution of edge and central plasma

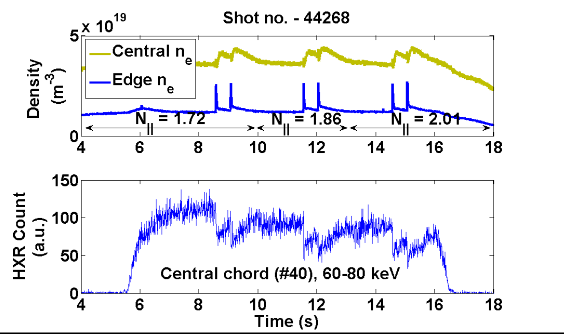

Fig. 1: Response of HXR emission (shown below) during SMBI follows central or bulk density response rather than edge density response (shown above).

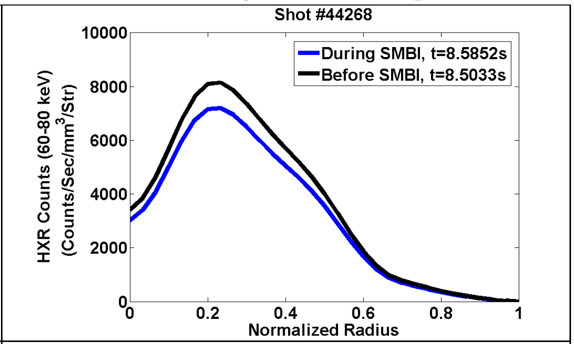

Fig. 2: Radial profile remains insensitive to SMBI and change in count is due to change in density.

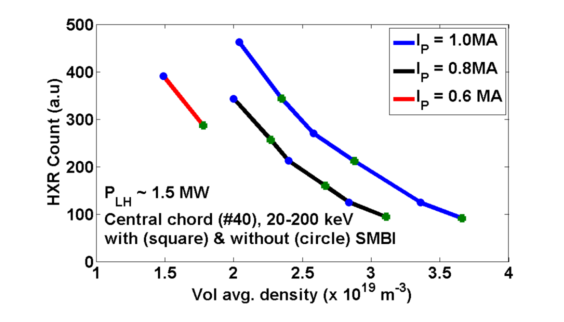

Fig. 3: HXR for different plasma current, keeping other parameters fixed.

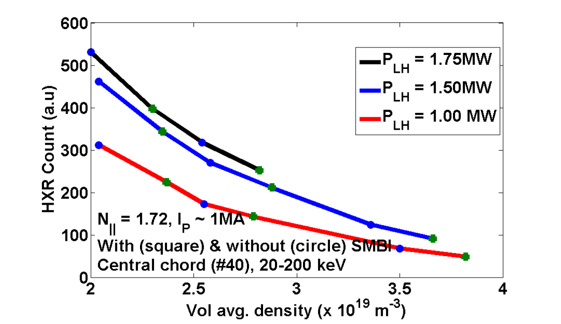

Fig. 4: HXR for different LH power, keeping other parameters fixed.

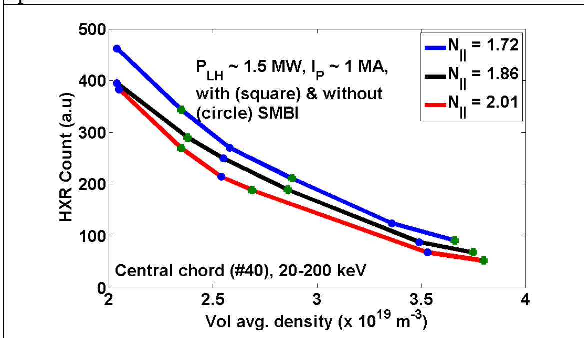

Fig. 5: HXR for different $N_\parallel$, keeping other parameters fixed.

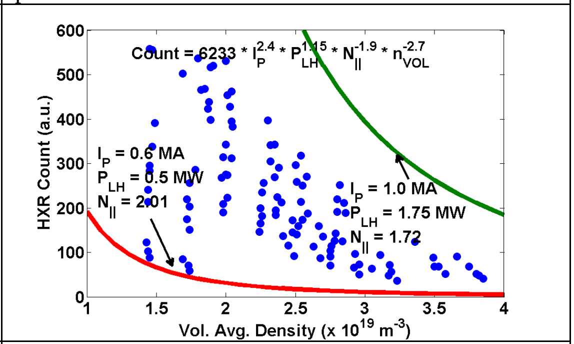

Fig. 6: The extreme parameter regime is plotted using the obtained fitting law along with experimental data.

density with SMBI is shown in fig. 1 for different $N_\parallel$. During SMBI significant bulk perturbation is also observed along with edge perturbation. The temporal evolution of the HXR counts, obtained from the central chord #40, in the 60-80 keV energy range, shows a decrease during SMBI. Though the occurrence of edge perturbation with SMBI is instantaneous, the HXR emission takes finite time to respond. Recovery of the edge density is very fast compared to recovery of central density and it appears that the HXR emission seems to follow the central or bulk density response. The LH power reflection coefficient during SMBI also remained modest [5] indicating good edge coupling of LHW. The edge perturbation in itself does not seem to cause a redistribution of the fast electron profile, hence the LH power deposition, as indicated in fig. 2.

Dependence on plasma parameters. To establish the dependence of HXR emission on plasma parameters, 28 shots data were analyzed and HXR counts (≤ 200keV) were averaged for a central chord. The analysis shows that absorption increases with I_P (fig.3) and P_{LH} (fig.4) and decreases with $N_{\|}$ (fig.5). From all the figs. 3-5, it is obvious that absorption decreases with density. The fitting law obtained from these data, as shown in fig.6, shows that HXR emission decreases with density as $\sim 1/n_e^3$, decreases with $N_{\|}$ as $\sim 1/N_{\|}^2$ in accordance with Fisch theory, increases almost linearly with P_{LH} and with plasma current as $\sim I_P^2$ [6,7].

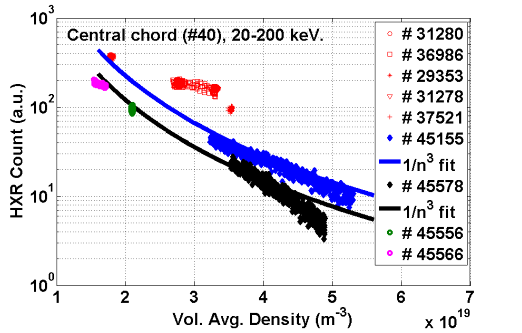

Fig. 7: PAM and FAM results are compared with respect to plasma density. Smaller plasma has higher power density and thus increased HXR counts.

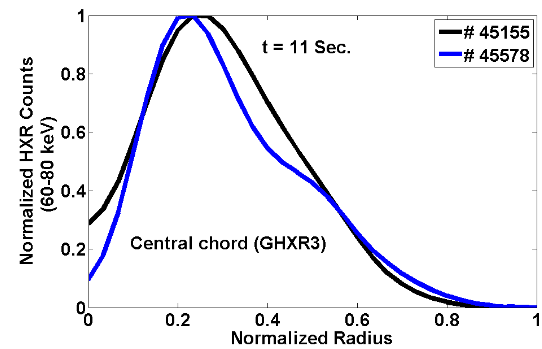

Fig. 8: Radial profile of normalized HXR counts clearly indicates higher power density for smaller plasma (a~0.66m) compared to standard plasma (a~0.72m).

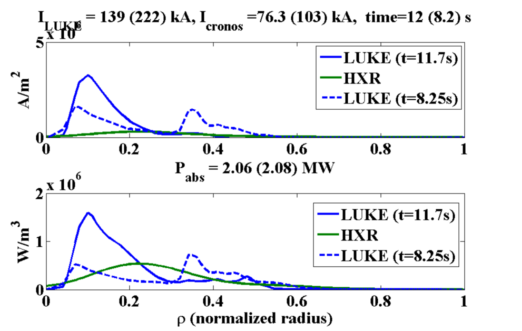

Fig. 9: Radial deposition profile obtained from LUKE/CRONOS code at two densities for shot #45155 shows similar LH efficiencies.

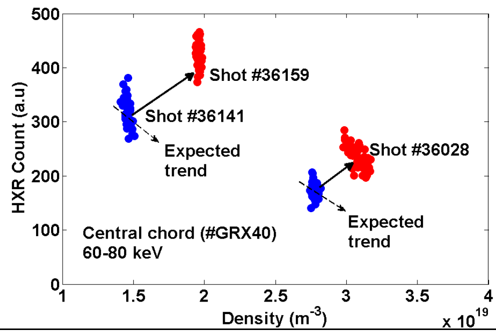

Fig. 10: With ICRH heating, HXR counts increases with density, suggesting improved efficiency and is attributed to higher temperature.

HXR emission with different LHW antennas. The HXR emission versus density has been compared for the PAM and FAM antennas in Tore Supra. The HXR counts are averaged over 20-200keV range for a central viewing chord and the results obtained are shown in fig.7. FAM results obtained from 5 shots, shown by various symbols in red are compared with PAM results (#45578, t=7-12s, #45556 & #45566). Typical plasma parameter during PAM (FAM) operation is I_P ~1.0 (0.9) MA, P_{LH} ~2 (3.0 to 3.5) MW & $N_{\|}$ ~1.7 (1.8). Since plasma parameters were not exactly the same for PAM & FAM operations and since HXR acquisition system was different, an absolute comparison is not possible. However similar behavior with density is observed, i.e. HXR counts decrease with density. When plasma radius is reduced from 0.72m (#45578) to 0.66m (#45155), the HXR counts increase (see fig.7), which is consistent with a higher power density, as confirmed from radial profile of HXR emission, shown in fig.8. In both cases, the dependence on density is the same i.e. $1/n_e^3$ [8]. However CRONOS (deposition based on HXR data) and LUKE (deposition based on Fokker-Plank calculation) simulation (for shot #45155) shows a more radially inward (outward) deposition at higher (lower) density i.e. $<n_e>_{vol}$ ~5.1 (3.6) x 10^{19} m^{-3} (fig. 9) while the current drive efficiency remains nearly same for the two density cases in spite of marginal change in temperature from 1.8 to 2.6 keV.

LHW interaction in the presence of ICRH. Normally on Tore Supra, n_e increases with ICRH power (P_{ICRH}) suggesting lowering of HXR counts in the presence of P_{ICRH}. Two representative cases are studied (one at low I_P ~0.6MA and other at higher I_P ~0.8MA) to verify this effect using FAM antenna. The results obtained are shown in fig. 10 where circles in blue (red) show the HXR counts in the presence of P_{LH} (P_{LH} + P_{ICRH}). It supports enhanced interaction of LHW in presence of ICRH power and could be attributed to the increase in plasma temperature during ICRH phase from ~3keV to ~4 keV. Further investigation for these shots using CRONOS/LUKE code confirms an increase in current drive efficiency of LHW in presence of ICRH heating (shown in fig.11).

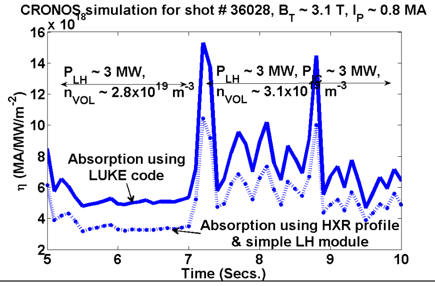

Fig. 11: Results obtained from CRONOS/LUKE confirms the increase in efficiency when LH is assisted with ICRH heating.

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