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Effect of fluctuations on lower hybrid power deposition and hard x-ray detection

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The hard x-ray intensity radial profiles from lower hybrid current drive experiments are interpreted as being correlated with fluctuations in the bulk plasma. This view seems to be dictated by comparing the hard x-ray data for various $n_\parallel$ with the Monte Carlo solutions of the lower hybrid wave energy deposition on plasma electrons. Information on internal magnetic fluctuations may, under certain conditions, be unfolded from a $n_\parallel$ scan of the hard x-ray profiles.

I. INTRODUCTION

In recent years, lower hybrid (LH) waves have been utilized for electron and ion heating, to sustain and rampup the toroidal plasma current, and to stabilize sawteeth instabilities.[1] An accurate prediction of the lower hybrid current drive (LHCD) profile is important in assessing the feasability of each of these applications. Thus, it is of interest to ascertain the effects of wave scattering from both density and magnetic fluctuations on the propagation and absorption of LH waves. Typically, computer models[1] of LH heating and current drive concentrate on the confinement properties of the suprathermal tail electrons produced by LHCD and the transport properties of the background electrons. In these models, a one-dimensional (1D) radial transport code is coupled to a Fokker–Planck toroidal ray tracing code. While it is known that density fluctuations[2] can play a major role on LH wave propagation, it is computationally prohibitive to incorporate these scattering effects into the transport LHCD simulation model.

Here, we explicitly examine the effects of fluctuations on LHCD, and connect these wave scattering results to hard x-ray emission[3] caused by collisions of the suprathermal electrons with the background plasma ions. In particular, the results from a Monte Carlo solution of a wave kinetic equation that now includes both density and magnetic fluctuations are compared with hard x-ray intensity radial profile measurements[4] from JT-60. We then consider Alcator C-Mod parameters and find that an analysis of experimental radial hard x-ray intensity profiles could distinguish between magnetic and density fluctuation scattering provided the fluctuation levels are sufficiently high. Thus, this hard x-ray diagnostic (a standard diagnostic on LHCD experiments) could then be combined with a recently proposed microwave mode-conversion scattering scheme[5] to assess the level of internal magnetic fluctuations in a tokamak. The determination of magnetic fluctuation levels and structure has strong implications on general plasma transport.

II. WAVE KINETIC EQUATION FOR DENSITY AND MAGNETIC FLUCTUATIONS

The theory of Bonoli and Ott[2] for LH wave scattering from density fluctuations is extended to also include the effects of magnetic fluctuations. Using weak turbulence theory, one finds that the wave energy density F is determined by

$$\left(\frac{dF}{dt}\right)_r + 2\gamma(\mathbf{x},\mathbf{k})F(\mathbf{x},\mathbf{k},t)$$
$$= \int_0^\infty d\kappa\,\delta(\kappa-\kappa_\omega)k_\perp' \int_0^{2\pi} d\beta[F(\phi+\beta)-F(\beta)]$$
$$\times[S^n(\kappa)\,|V^n(k_\perp,\kappa,\beta)|^2$$
$$+S^B_{\alpha\beta}(\kappa)\,|V^B_\alpha(k_\perp,\kappa,\beta)V^B_\beta(k_\perp,\kappa,\beta)|^2]. \quad (1)$$

$(dF/dt)_r$ is the time evolution of the wave packet following a ray trajectory in a toroidal tokamak equilibrium and γ is the wave damping due to resonant electron and ion Landau damping as well as collisional damping. The right-hand side of Eq. (1) gives the effect of fluctuations on the ray trajectory. The fluctuations scatter the wave number $\mathbf{k}_\perp$ through an angle β to a new wave number $\mathbf{k}_\perp'$, with $\mathbf{k}_\perp\cdot\mathbf{k}_\perp' = k_\perp k_\perp'\cos\beta$ and $\boldsymbol{\kappa}=|\mathbf{k}_\perp-\mathbf{k}_\perp'|$. V^n and $\mathbf{V}^B$ are the density and magnetic coupling coefficients, while S^n and the tensor $\mathbf{S}^B$ are the corresponding wave number fluctuation spectra. Equation (1) is solved by a Monte Carlo procedure.[2] For the results presented here, each electron radial power deposition profile is averaged over 100 runs. It should be noted that the parallel wave number $k_\parallel$ varies because of magnetic shear, toroidicity as well as by the scattering process itself. These changes to $k_\parallel$ directly effect the accessibility of the LH wave $(n_\parallel = ck_\parallel/\omega > n_a)$ as well as the strength of the electron damping $[n_\parallel < n_{eld} \approx 7.0/T_e^{1/2}(\mathrm{keV})]$ of the LH wave.

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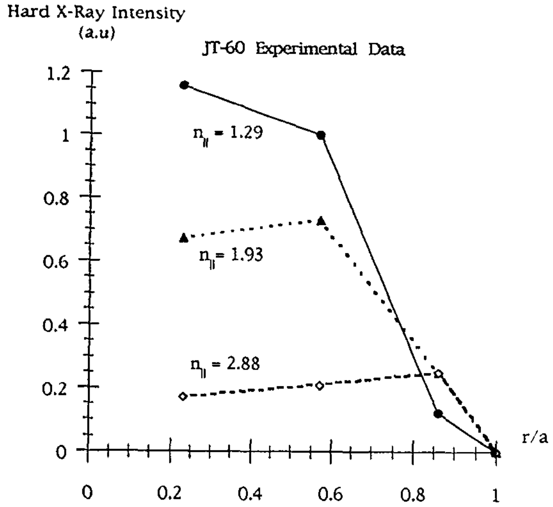

FIG. 1. Radial profile of the hard x-ray diagnostics with four channels on JT-60 (Ref. 4).

III. ELECTRON POWER DEPOSITION AND HARD X RAYS

We first consider the JT-60 tokamak for which the radial profiles for the hard x-ray signals are given for various $n_{\parallel}$ at three radial chord positions,[4] Fig. 1. For these JT-60 parameters ($a=93$ cm, $R_0=300$ cm, $T_{e0}=2$–3 keV, $B_0=4$T, $I_{tor}=1$ MA, $n_{e0}=1.5\times10^{13}$ cm^{-3} and LH wave frequency $f_0=2$ GHz) we show in Fig. 2 the Monte Carlo results for the radial electron power deposition profiles for a density fluctuation level $(\delta n/n_{oe})^2=1\%$, peaked at the plasma edge [the "pe-n" curves]. Two magnetic fluctuation spectra are considered on top of these density fluctuations: the "pe-m" curves for which the magnetic spectrum is also peaked at the plasma edge, and the "pe-mm" curves for which the magnetic spectrum is peaked internally at $r/a=0.6$. The level of magnetic to density fluctuations is assumed to be[5]

$$\left[\frac{\langle \delta B_{\perp}^2 \rangle / B_0^2}{\langle \delta n^2 \rangle / n_{oe}^2}\right]_{\text{peak}} = 10^{-4}. \quad (2)$$

Also shown in Fig. 2 is the electron power deposition if there were no fluctuations (density or magnetic) present ["pe-vac"]. One immediately sees a strong similarity between the structure of the hard x-ray profiles and the electron power deposition profiles provided fluctuations are taken into account. Clearly, if one ignores the effects of fluctuations, the corresponding power deposition profiles are markedly different from those coming from the experimental hard x-ray profiles. Although fast electrons can diffuse spatially before they thermalize (so that the rf power deposition profiles may not exactly track the rf current density profiles), we feel that the hard x-ray profiles are directly correlated to the presence of fluctuations in the plasma. It is apparent from Fig. 2 that for JT-60 it is not expected to be possible to distinguish density from magnetic fluctuations in the hard x-ray diagnostics. Moreover, the Monte Carlo solutions of Eq. (1) indicate that this

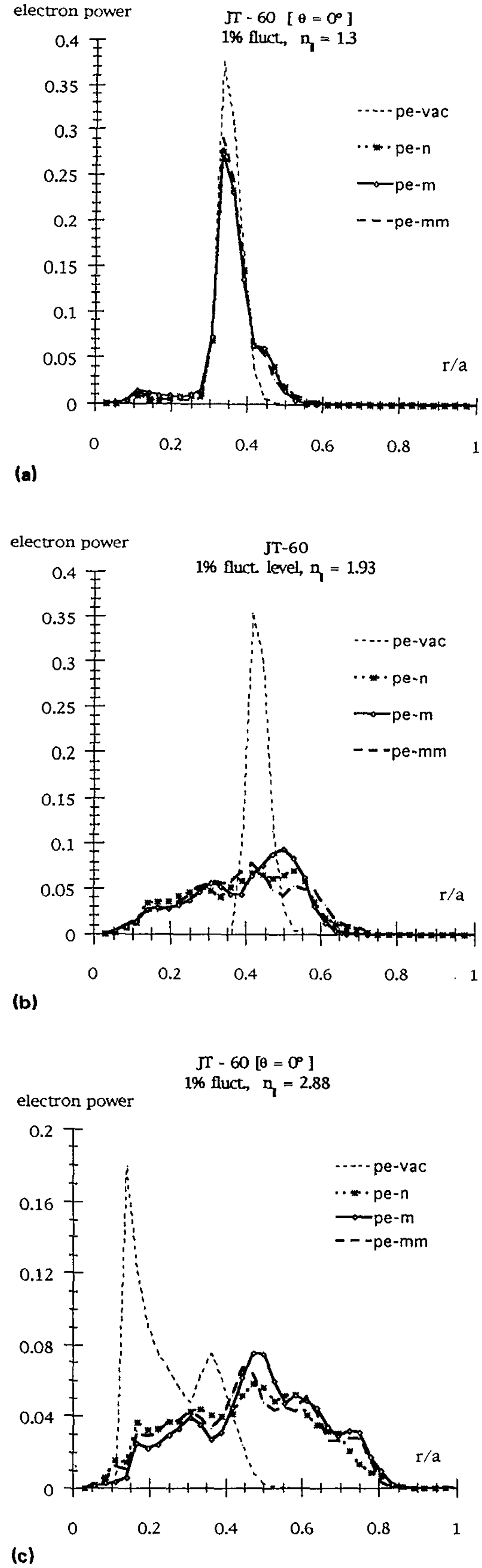

FIG. 2. Electron power deposition profile for JT-60 in the divertor mode [edge density fluctuation level $\approx 1\%$] for various $n_{\parallel}$. pe-vac: no fluctuations, pe-n: only edge density fluctuations, pe-m: edge density and magnetic fluctuations, pe-mm: edge density fluctuations and internal magnetic fluctuations. (a) $n_{\parallel}=1.3$, (b) $n_{\parallel}=1.93$, (c) $n_{\parallel}=2.88$. The fluctuation deposition profiles seem to track the experimental hard x-ray data of Fig. 1.

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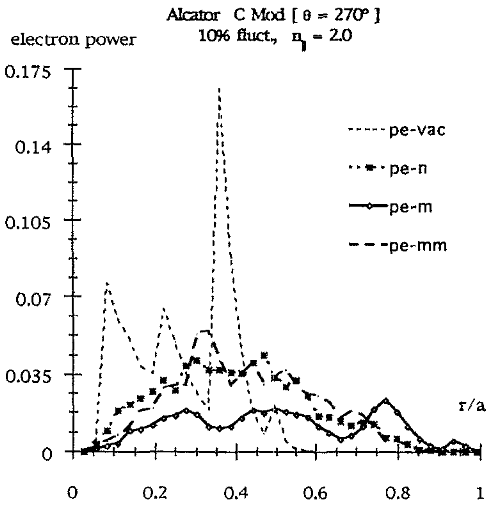
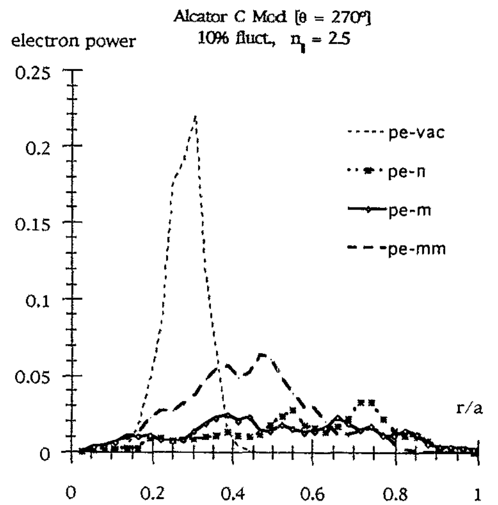
statistical similarity in the three fluctuation spectra (pe-n, pe-m, pe-mm) persists even if JT-60 is run in a limiter mode with a resultant edge density fluctuation levels of 10%.

In Fig. 3, the electron power deposition profiles are shown for Alcator C-Mod [$a=21$ cm, $R_0=67$ cm, $T_{e0}=5$ keV, $B_0=9$ T, $I_{tor}=3$ MA, $n_{eo}=3.5\times10^{14}$ cm^{-3}, and $f_0=4.6$ GHz] run in a limiter mode, with a peak edge density fluctuation level of 10%. For $n_{\parallel}=2.0$, Fig. 2(a), there is substantial statistical difference between the power deposition curves for pe-n and pe-mm over that for pe-m, the case of both density and magnetic fluctuations peaked at the edge. For $n_{\parallel}=2.5$, there is now a substantial difference between electron power deposition for magnetic fluctuations peaked internally (pe-mm) over magnetic fluctuations peaked at the plasma edge (pe-m), or the case of only density fluctuations (pe-n), Fig. 2(b).

LH waves drive suprathermal electrons, and it is the prompt collisions of these suprathermal electrons with the background plasma that gives rise to the hard x rays.[3] We thus expect that these power deposition differences should be reflected in a hard x-ray intensity radial $n_{\parallel}$ scan and so give important information on the fluctuations within the plasma. If so, then hard x-ray data, together with the diagnostic results from the proposed microwave scattering for the detection of internal magnetic fluctuations for Alcator C-Mod, should give more insight into the correlation between internal magnetic fluctuations and bulk plasma transport.



(a)



(b)

FIG. 3. Electron power deposition profile for Alcator C-Mod parameters in the limiter mode [edge density fluctuations $\approx 10\%$] for (a) $n_{\parallel}=2.0$, and (b) $n_{\parallel}=2.5$. Since it seems that the fluctuation power depositions determine the hard x-ray diagnostics, then it should be able to decern internal magnetic fluctuations from hard x-ray intensity profile scans in $n_{\parallel}$.

ACKNOWLEDGMENTS

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