1995

Effects of Large Aspect Ratios and Fluctuations on Hard X-Ray-Detection in Lower Hybrid Driven Divertor Tokamaks

Linda L. Vahala
Old Dominion University, lvahala@odu.edu

George Vahala

Paul Bonoli

Original Publication Citation

Vahala, L., Vahala, G., & Bonoli, P. (1995). Effects of large aspect ratios and fluctuations on hard x-ray-detection in lower-hybrid driven divertor tokamaks. *Review of Scientific Instruments, 66*(1), 838-840. doi: 10.1063/1.1146241

Effects of large aspect ratios and fluctuations on hard x-ray detection in lower hybrid driven divertor tokamaks

Linda Vahala
Department of Electrical and Computer Engineering, Old Dominion University, Norfolk, Virginia 23509

George Vahala
Department of Physics, College of William and Mary, Williamsburg, Virginia 23187

Paul Bonoli
Plasma Fusion Center, M. I. T., Cambridge, Massachusetts 02139

(Presented on 11 May 1994)

It is shown that lower hybrid wave scattering from fluctuations plays a critical role in large aspect ratio divertor plasmas even though the edge density fluctuation levels are only at 1%. This is seen in the theoretically calculated electron power-density profiles which can be directly correlated to the standard experimental chordal hard x-ray profiles. It thus seems that fluctuation effects must be included in determining rf current-density profiles. © *1995 American Institute of Physics.*

I. INTRODUCTION

Lower hybrid (LH) waves have been used for electron and ion heating, to sustain and ramp up the toriodal plasma current, and to stabilize sawteeth instabilities.[1] Recently, experiments on JET have indicated that LH current drive efficiency can be significantly enhanced in the presence of ICRF waves. This enhancement may be due to an interaction of the suprathermal electrons generated by the LH waves with a mode converted ion-Bernstein wave.[2] The collision of these suprathermal electrons with the background plasma gives rise to hard x rays that are readily detected.

Now, it has been shown[3,4] that chordal experimental hard x-ray profiles can be directly correlated to theoretically calculated LH electron power-density deposition profiles. Moreover, to obtain this excellent correlation to experimental data, it was critical to incorporate the effects of LH ray scattering from fluctuations in determining the power-density profiles. These results were drawn from JT-60 chordal hard x-ray profiles[5] for three different initial values of parallel refractive index $n_{\|0}=ck_{\|0}/\omega=1.29$, 1.93, and 2.88. Hence, a theoretical determination of the LH electron power-density deposition can be translated into experimentally observable chordal hard x-ray profiles.

Here we examine the effects of large aspect ratio and fluctuations on hard x-ray profiles for a divertor plasma, in which the edge fluctuation levels can be as low as 1%. There is currently a tendency towards larger aspect ratio tokamaks and this plays a profound role on the accessibility of LH waves towards the plasma center. This is because in cylindrical geometry there is no upshift in $k_\|$ as the LH wave propagates[6,7] (neglecting LH wave scattering from fluctuations). Hence there is a minimum inverse aspect ratio ϵ_{cr}, such that the nonstochasticity of LH rays persists for sufficiently small inverse aspect ratios: $\epsilon<\epsilon_{cr}$.

II. WAVE KINETIC EQUATION FOR LH RAY SCATTERING FROM FLUCTUATIONS

Using weak turbulence theory, the propagation of the wave energy density F can be determined from the wave kinetic equation[4,5]

$$\left(\frac{dF}{dt}\right)_{\text{ray}}+2\gamma(\mathbf{x},\mathbf{k})F(\mathbf{x},\mathbf{k},t)$$
$$=\sum\int_0^{2\pi}d\beta[F(\phi+\beta)-F(\phi)]$$
$$\times[S^n(\kappa)K^n+\mathbf{S}^B(\kappa):\mathbf{K}^B]. \qquad (1)$$

$(dF/dt)_{\text{ray}}$ is the time evolution of the wave packet following a ray trajectory in a given toroidal tokamak equilibrium, while γ is the resonant electron and ion Landau damping as well as collisional damping of the wave packet. The right-hand side of Eq. (1) gives the effect of ray scattering from fluctuations. In particular, during fluctuation scattering, the perpendicular wave number $\mathbf{k}_\perp\to\mathbf{k}'_\perp$ while $\mathbf{k}_\|=\mathbf{k}'_\|$. $\kappa=|\mathbf{k}_\perp-\mathbf{k}'_\perp|$ and $\mathbf{k}_\perp$. $\mathbf{k}'_\perp=k_\perp k'_\perp\cos\beta$ where the scattering angle β is such that $\phi\to\phi+\beta$. The scattering kernels K^n and

TABLE I. Some tokamak parameters.

	JT-60	TPX
Inverse aspect ratio ϵ	0.31	0.22
$B_0(T)$	4	4
Current (MA)	1	2
LH $\omega/2\pi$ (GHz)	2.0	3.7
n_{e0} (10^{13} cm^{-3})	1.5	10
T_{e0} (keV)	3	10
Fluctuation rms κ_0 (cm^{-1})	15	15
Density fluctuation levels	1%	1%
$n_{\|0}=ck_{\|0}/\omega$	1.29,1.93,2.88	2.0,2.5,3.0

 0034-6748/95/66(1)/838/3/$6.00

K^B are complicated expressions,[4,5] while the perpendicular density-fluctuation spectrum is assumed to have the form[4,5]

$$S^n(\kappa)=\left\langle\left(\frac{\delta n}{N_0}\right)^2\right\rangle\frac{1}{\pi\kappa_0^2}\exp\left(-\frac{\kappa^2}{\kappa_0^2}\right), \tag{2}$$

where the spatial intensity variation $\langle(\delta n/N_0)^2\rangle$ is peaked at the plasma edge. A similar Gaussian distribution is assumed for magnetic fluctuations. The wave kinetic equation is solved in toroidal geometry with the scattering integral evaluated by Monte Carlo methods. In particular, for the results reported here, we have used 100 Monte Carlo iterations for each initial $n_{\parallel 0}$. The correlation length κ_0^{-1}, and other relevant tokamak parameters are given in Table I.

III. EFFECT OF FLUCTUATIONS ON ELECTRON POWER-DENSITY DEPOSITION IN TPX

For TPX parameters listed in Table I, we consider the effect of 1% edge density fluctuations on electron power-density deposition profiles (and thus on what one should expect to find from experimental chordal hard x-ray data). At a central electron temperature of 10 keV, and for a LH launched wave packet with initial Gaussian distribution of mean $\langle n_{\parallel 0}\rangle=2.5$, one sees from Fig. 1 that even in divertor plasmas with only 1% edge fluctuations there is a substantial reduction in the power deposition profiles: as expected, the deposition profiles are more radially diffuse but because of the high temperature (10 keV), there is little increase in the penetration of the LH wave bundle into the plasma center. In Fig. 2, we compare effects of the 1% edge fluctuations for the planned range of LH wave launch $n_{\parallel 0}$. We see that power-density deposition profiles become much less sensitive to the initial $\langle n_{\parallel 0}\rangle$ once fluctuation effects are taken into account.

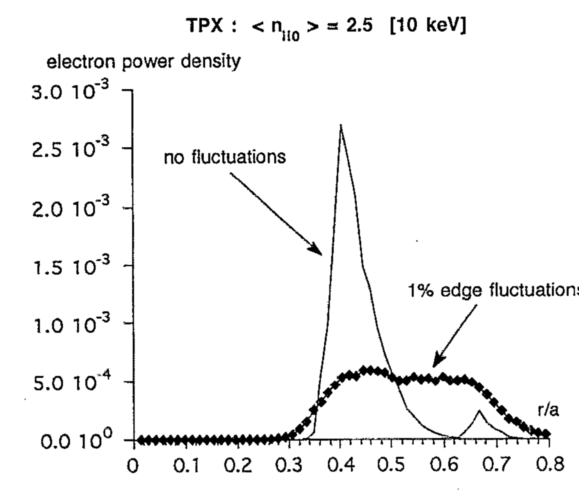

FIG. 1. Electron power-density deposition profiles for TPX parameters, with central temperatures of 10 keV and LH Gaussian initial $n_{\parallel 0}$ distribution of mean $\langle n_{\parallel 0}\rangle=2.5$ and standard deviation=0.1 [notation: $G(2.5,0.1)$]. Note the strong effect of fluctuations on the power-density profiles—even low fluctuation levels of 1%.

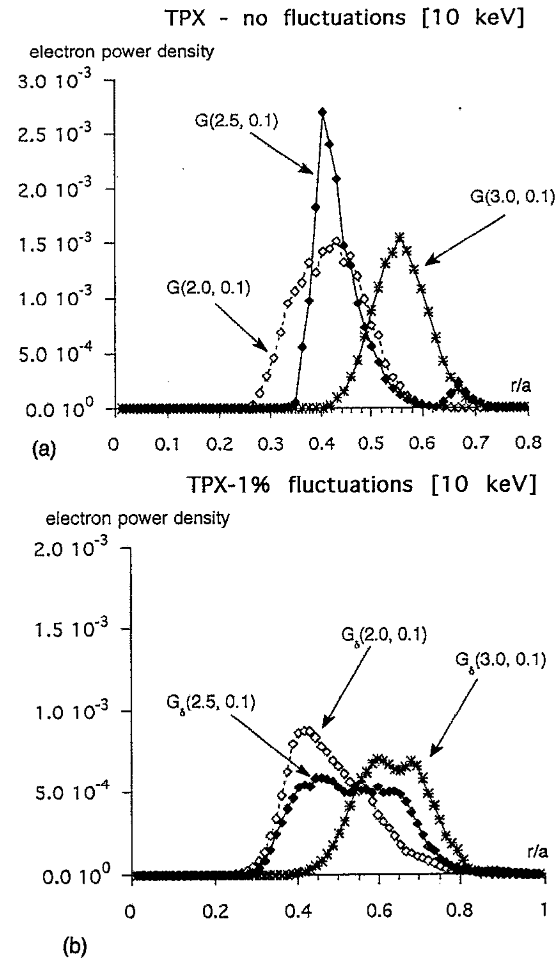

FIG. 2. Electron power-density deposition profiles for TPX parameters, with $T_{e0}=10$ keV and various LH Gaussian $n_{\parallel 0}$ for (a) no fluctuations and (b) 1% edge fluctuations characteristic of divertor plasmas. Chordal hard x-ray profiles are sensitive to the LH wave scattering from fluctuations.

For lower central temperatures (4 keV) and incorporating 1% edge fluctuation scattering, however, one finds that the absorption profiles become much more independent of the initial $\langle n_{\parallel 0}\rangle$, as seen in Fig. 3. Note that fluctuations now

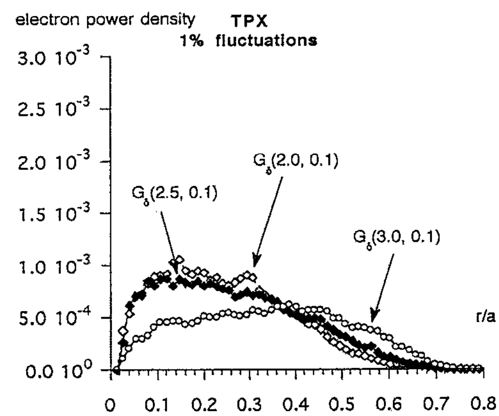

FIG. 3. Effect of decreasing the central temperatures from 10 to 4 keV for TPX parameters on the power-density profiles with scattering from 1% edge fluctuations.

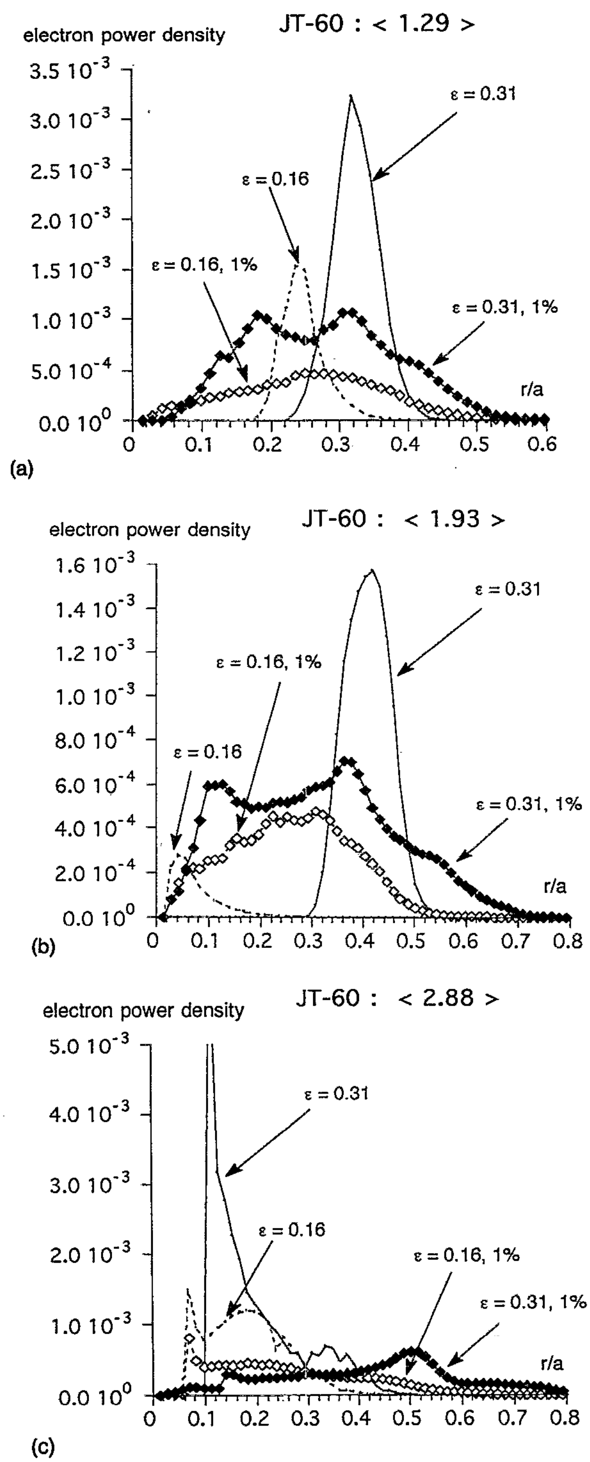

FIG. 4. Effect of aspect ratio and 1% fluctuation levels on the power-density profiles based on JT-60 plasmas. The inverse aspect ratio is decreased from ϵ=0.31 to ϵ=0.16. (a) Initial LH $n_{\|0}$ spectrum is $G(1.29, 0.05)$; (b) initial LH $n_{\|0}$ spectrum is $G(1.93,0.1)$; (c) initial LH $n_{\|0}$ spectrum is $G(2.88,0.1)$. If LH wave scattering from fluctuations is considered, it is denoted by "1%:" e.g., ϵ=0.16,1%.

play an important role in aiding the LH rays to penetrate further towards the plasma center. (If fluctuation scattering is neglected, then the electron power-density peak for $\langle n_{\|0}\rangle=2.0$ is 5.3×10^{-3} at $r/a=0.06$, a peak of 2.0×10^{-3} at $r/a=0.2$ and at $r/0.28$ for $\langle n_{\|0}\rangle=2.5$, and a peak of 3.5×10^{-3} at $r/a=0.2$ for $\langle n_{\|0}\rangle=3.0$.)

IV. EFFECT OF ASPECT RATIO AND FLUCTUATION ON HARD X-RAY EMISSION

As the inverse aspect ratio of future tokamaks is decreased, the LH ray trajectory itself become less stochastic.[6,7] Under these circumstances, the role of fluctuation scattering should become more important. We have investigated this by considering typical JT-60 parameters (with inverse aspect ratio ϵ=0.31; see Table I) and then decreasing the inverse aspect ratio to ϵ=0.16 while holding the other plasma parameters fixed. In Fig. 4, we compare the power-density profiles for a divertor plasma with 1% edge fluctuations (plots labelled "ϵ=0.31, 1%" and "ϵ=0.16, 1%") with those profiles obtained if scattering from fluctuations is ignored (plots labelled "ϵ=0.31" and "ϵ=0.16"). As expected,[6] there is a very strong dependence of the power-density profiles on the inverse aspect ratio if fluctuation scattering of LH waves is ignored. This is extremely evident for both $\langle n_{\|0}\rangle=1.93$: there is little absorption of LH waves for ϵ=0.16. From Fig. 4, it is evident that fluctuation scattering effects will significantly counteract the effect of decreasing inverse aspect ratio. The electron power-density absorption profiles, when fluctuation scattering is included, are only weakly dependent on ϵ.

V. DISCUSSION

It is shown that for large aspect ratio divertor plasmas, LH scattering from fluctuations plays a critical role in the power-density absorption profiles and hence, in the experimental chordal hard x-ray profiles—even for 1% fluctuation levels. Magnetic fluctuation effects are observable for high toroidal magnetic fields and at lower plasma temperatures.[4] Based on these results, it also indicates the importance of including wave scattering from fluctuations in the determination of rf current-density profiles. Within the LH frequency range, it does not seem possible to avoid the detailed Monte Carlo iterations by using a larger sampling of the $n_{\|0}$ distribution.

ACKNOWLEDGMENTS

This work was supported by the Department of Energy in grants to O.D.U, W&M, and M.I.T. (No. DE-AC02-78ET51013).

[1] P. T. Bonoli, Am. Inst. Phys. Conf. Proc. **159**, 85 (1987).
[2] A. K. Ram, A. Bers, V. Fuchs, and S. D. Schults, Am. Inst. Phys. Conf. Proc. **289**, 293 (1994).
[3] G. Vahala, L. Vahala, and P. T. Bonoli, Rev. Sci. Instrum. **63**, 4682 (1992).
[4] G. Vahala, L. Vahala, and P. T. Bonoli, Phys. Fluids B **4**, 4033 (1992).
[5] K. Uehara, H. Kimura, and JT-60 Team, Am. Inst. Phys. Conf. Proc. **190**, 106 (1989).
[6] P. T. Bonoli and E. Ott, Phys. Fluids **25**, 389 (1982).
[7] K. Kupfer, D. Moreau, and X. Litaudon, Phys. Fluids B **5**, 4391 (1993).