Modelling of LHCD and Comparison with Experimental Results in JET

Y F Baranov, M Brusati, A Ekedahl, P Froissard,
C Gormezano, M Lennholm, F Rimini.

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.

"This document is intended for publication in the open literature. It is made available on the understanding that it may not be further circulated and extracts may not be published prior to publication of the original, without the consent of the Publications Officer, JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK".

"Enquiries about Copyright and reproduction should be addressed to the Publications Officer, JET Joint Undertaking, Abingdon, Oxon, OX14 3EA".

MODELLING OF LHCD AND COMPARISON WITH EXPERIMENTAL RESULTS IN JET

Y.F. Baranov, M. Brusati, A. Ekedahl, P. Froissard,
C. Gormezano, M. Lennholm, F. Rimini
JET Joint Undertaking, Abingdon, UK, OX14 3EA

ABSTRACT. A new code has been developed for the simulation of LHCD in JET. The model which includes stochastic radial diffusion of electrons and scattering of Lower Hybrid waves is validated by comparing its results with the current drive efficiency derived from the LHCD experiments in JET, and by simulating the hard X-ray bremsstrahlung emission from fast electrons and comparing it with the experimentally measured emission. Good agreement has been found for both LH only cases and LH plus electric field.

LH WAVE PROPAGATION

The ray-trajectory method is used to simulate propagation and absorption of Lower Hybrid waves. The equations describing the ray trajectory of a wave are presented in /1/. The dispersion relation for LH waves includes electromagnetic part and thermal corrections. Collisional and Landau damping by electrons is taken into account. The calculations are carried out for the equilibrium magnetic field topology.

SCATTERING OF LOWER HYBRID WAVES BY DENSITY FLUCTUATIONS

Scattering of the slow LH waves by low frequency density fluctuations is taken into account using a theory proposed by Ott /2/. The spectrum of the fluctuations is approximated by a Gaussian function $S(k)=(1/\pi k_0^2)<\delta n/n>^2\exp(-k^2/k_0^2)$ where k is a wave vector of the fluctuations, which is perpendicular to the magnetic field. The characteristic wave scalelength k_0^{-1} is assumed to be of the order of the ion Larmor radius ρ_i (all calculations were carried out for $k_0^{-1}=3\rho_i$). The amplitude of the fluctuations is distributed in space according to: $<\delta n/n>^2=\Delta r\rho_i/a^2$, where r is the radial coordinate and a the minor radius. The parameter Δ is introduced to investigate the influence of the fluctuation amplitude on the distribution of the driven current. The best agreement between the experimental data and results of calculations is observed for $0.25\leq\Delta\leq 1$. The scattering of the waves is modelled in the framework of the ray-trajectory approach using Monte Carlo method. The scattering length l_s for a slow wave with a given $k_\perp$ can be calculated according to /3/. It is assumed that, during each small step $\Delta s \ll l_s$ along the trajectory, $\vec{k}_\perp$ is deflected by an angle $\Delta\Theta=\pi/2(\Delta s/l_s)^{1/2}$ with the average value $<\Delta\Theta>=0$.

The FEB signal is calculated using the simulated electron distribution function. The local suprathermal emissivity for a photon of energy ε at an angle ϕ' with respect to the local magnetic field direction, is given by:

$$\frac{dN}{d\varepsilon dV dt d\Omega}(\varepsilon,\phi',r) = \iiint v_s f_s(\mathbf{p},r)\left[\sum_i Z_i^2 n_i(r)\frac{d\sigma_{ei}}{d\varepsilon d\Omega}(\mathbf{p},\varepsilon,\phi',Z_i)+n_e(r)\frac{d\sigma_{ee}}{dk d\Omega}(\mathbf{p},\varepsilon,\phi')\right]d^3\mathbf{p}$$

where $f_s(\mathbf{p},r) = F(p_{||};r)(1/2\pi m T_\perp(p_{||},r))\exp(-p_\perp^2/(2\pi m T_\perp(p_{||},r))$, $n_i(r)$ ion density, v_s-suprathermal electron velocity, $d\sigma_{ei}$ is the electron-ion Bremsstrahlung cross-section calculated according to the Bethe-Heitler-Elwert formula, and $d\sigma_{ee}$ is the electron-electron Bremsstrahlung cross-section calculated with the Haug-Elwert formula (both are in the Born approximation) /7/.

The line averaged emissivity along the FEB sightline is deduced from local emissivity. The photon temperature is obtained by fitting the line averaged emissivity spectrum.

RESULTS OF THE CALCULATIONS AND COMPARISON WITH THE EXPERIMENTAL DATA

The results of modelling of LHCD with LH only for three shots (#27745,#24955,#24918) with different densities and temperatures are chosen for the comparison with experimental data. The main parameters of the shots are listed below:

	1(MA)	B_T(T)	n_{eo}($10^{19}m^{-3}$)	T_{eo}(keV)	P_{LH}(MW)	Z_{ef}	V_{res}(V)
#27745	3.1	3.3	1.4	7.8	1.8	3.8	0.38
#24955	1.5	3.1	3.0	2.3	2.3	1.7	0.2
#24918	0.37	2.5	1.8	1.4	1.8	1.6	0.

All calculations are done for fixed values D_m=0.5m^2/s and Δ=0.25, unless indicated. Fig. 1 shows the calculated LH driven current density $J_{RF}(r)$ and dissipated RF power density $P_{RF}(r)$ for a high temperature, low density plasma in a residual electric field (shot #27745). Profiles for the calculated and experimentally observed brightness and temperature of hard X-ray emission are shown in Fig. 2 and Fig. 3, respectively. For all three shots reasonable agreement between measured and simulated data is observed. For some cases, where LHCD is combined with ICRH, the calculated photon temperature is significantly lower than the measured one. The discrepancy in these cases can be attributed to synergistic effects between IC waves and the fast electron tail, produced by LH waves /8/.

In conclusion the comparison between the experimental data and the numerical simulations shows that the code describes well LHCD in JET. This comparison stands well for large excursions in electron temperature: 1.4 to 7.8 keV and in electron density: 1.4 to 3 $10^{19}m^{-3}$. The code is based on the model, which incorporates the stochastic diffusion of fast electrons with D_{rr}~v, scattering of the LH waves by low frequency fluctuations and analytical approximation for $T_\perp$.

Authors are grateful to Dr.V.Parail for very fruitful discussions.

FOKKER-PLANCK EQUATION

The electron distribution function $F(p_{||},r)$ is calculated via numerical solution of the relativistic 2-D (in $p_{||}$ and r) Fokker Planck (FP) equation:

$$\frac{\partial F}{\partial t}=\frac{\partial}{\partial p_{||}}D_{q1}\,(p_{||},r)\,\frac{\partial F}{\partial p_{||}}+\upsilon_o\frac{\partial}{\partial p_{||}}\,\frac{P_e^3}{P_{||}^3}\left(p_{||}F+mT(p_{||},r)\frac{\partial F}{\partial p_{||}}\right)+\frac{1}{r}\frac{\partial}{\partial r}rD_{rr}(p_{||},r)\,\frac{\partial F}{\partial r}+\frac{eE(r)}{m}\,\frac{\partial F}{\partial p_{||}}\text{ where}$$

$p_{||}$ is a parallel momentum, p_e the momentum of thermal electrons, E(r) the toroidal electric field, $\upsilon_o= C(5+Z_{ef})\omega_{pe}^4\,\log\Lambda/(8\pi n_e v_e^3)$, n_e the electron density, Z_{eff} the effective charge of the plasma, $D_{q1}(p_{||},r)$ the coefficient of the quasilinear diffusion and $D_{rr}(p_{||},r)$ the coefficient of the radial diffusion. It is assumed that fast electron diffusion is connected with the stochasticity of the magnetic field. In the framework of this model $D_{rr}=D_m v/v_e$, where v and v_e are the parallel velocity of fast electrons and velocity of thermal electrons, respectively. A factor C=0.55 is introduced into the expression for υ_o to reproduce the current drive efficiency derived from experimental results as well as observed hard X-ray emission. It should be noted that the comparison between 2-D (in $v_{||}$ and $v_\perp$) and 1-D nonrelativistic calculations gives $C\approx 0.4$ /4/. It is assumed that the electron distribution function is spread in the perpendicular direction due to pitch angle scattering. In the plateau region i.e. for $v_1(r) < v < v_2(r)$ (v_1, v_2 are lower and upper boundary of parallel phase velocity of LH waves, respectively), the characteristic temperature $T_\perp=2T_b((v-v1)/(v2-v1))^2$, and for $v>v2$, $T_\perp=2T_b$, where T_b is defined in /5/ (formula(37)). Parameter $T(p_{||},r)$ in FP equation is chosen to be $T(p_{||},r)=T_e(r)$ for $v < v_2(r)$, and $T(p_{||},r) = T_\perp(r)$ for $v>v_2(r)$.

CALCULATION OF THE LHCD

The ray tracing and Fokker-Planck equations are solved iteratively to get the stationary solution. All relevant parameters are taken from experimental data. The magnetic field topology calculated by three moments equilibrium code is adjusted to match the JET reconstructed equilibrium.

The wave spectrum $P(n_{||})$ for Lower Hybrid waves launched by the antenna is divided into 89 equal intervals. To simulate the height of the grill, the ray trajectories are launched from K different poloidal positions (25< K <40) for each fixed $n_{||}$ with initial power $P(n_{||})$.

FEB DATA SIMULATION

The Fast Electron Bremsstrahlung (FEB) diagnostic is a multichord system designed to detect hard X-ray emission in the range 100 keV upwards /6/. The X-ray emission spectrum is analyzed on 4 equal energy windows between 100 and 300 keV to produce 4 line integrated emissivity profiles.

REFERENCES

/1/ Yu.F.Baranov, A.R.Esterkin, Sov.J.Plasma Phys. 16, 665 (1990).
/2/ E.Ott, Phys. Fluids 22, 1732 (1979).
/3/ P.T.Bonoli, E.Ott, Phys. Fluids 25, 359 (1982).
/4/ C.F.F.Karney, N.J.Fisch, Phys. Fluids 22, 1817 (1979).
/5/ V.Fuchs, et al., Phys. Fluids 28, 3619 (1985).
/6/ P.Froissard, et al., 18th EPS Conf. Proc., Berlin 1991, part 3, p 389.
/7/ H.W.Koch, F.W.Motz, Rev. Mod. Phys. 31, 920 (1959).
/8/ C.Gormezano, 10th Topical Conf. on RF Power in Plasmas. Boston 1993.

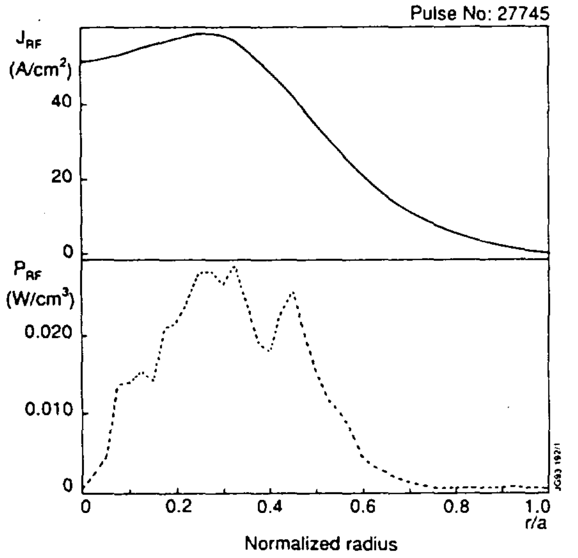

Fig. 1. Current density (a) and dissipated power density (b) profiles (shot #27745).

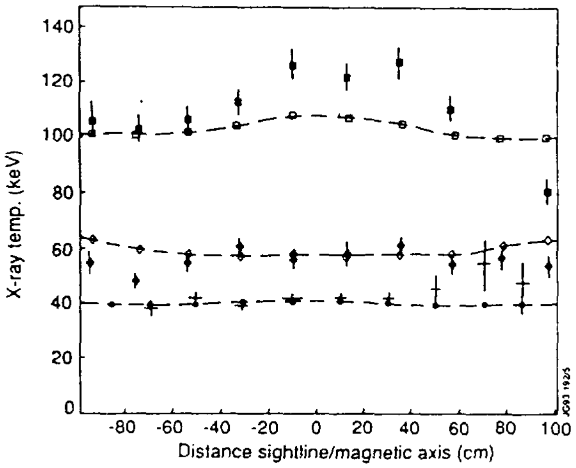

Fig. 3. Photon temperature profiles
■-measured, □-calculated (shot #27745)
◆-measured, ◇-calculated (shot #24955)
†-measured, •-calculated (shot #24918)

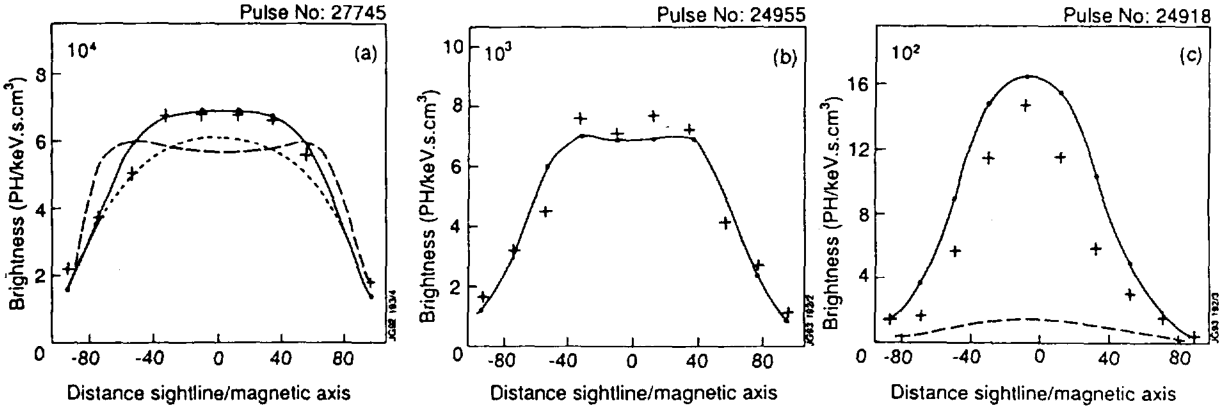

Fig. 2. Brightness profiles for the photon energy window 200÷250KeV. Crosses-experimental data. Solid lines-$\Delta=.25$, $D_m=.5m^2/s$, a) dashed line-$\Delta=0$, $D_m=0$, dotted line -$\Delta=0$, $D_m=.5m^2/s$, c) $T_\perp=T_b\,((v-v1)/(v2-v1))^2$ for v>v1.