Analysis of JET LCHD/ICRH Synergy Experiments in Terms of Relativistic Current Drive Theory

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INTRODUCTION. Synergetic effects between lower hybrid current drive (LHCD) and ion cyclotron resonance heating (ICRH) have led to substantially improved current drive efficiencies. Values of the usual figure of merit ($\gamma = IP^{-1}Rn_e$) as high as 0.4 x $10^{20}AW^{-1}m^{-2}$ have been achieved in JET experiments [1]. So far the mechanism underlying the synergy has not been ascertained. Experimentally, it is clear from fast electron bremsstrahlung (FEB) data that the improved efficiency in full current drive cases (zero remanent electric field) is due to acceleration of the electron tail to MeV energies, well beyond the 200keV achieved by the LHCD alone. The tail temperature increases rapidly as γ increases and reaches 0.8MeV for $\gamma = 0.4 \times 10^{20}AW^{-1}m^{-2}$. In the light of these observations, a question which arises naturally is whether the improved figure of merit agrees quantitatively with the relativistic efficiencies derived from classical theory by Karney and Fisch [2]. In the present paper we give an analysis which demonstrates that this is indeed the case, regardless of the nature of the mechanism responsible for the synergy.

METHOD OF ANALYSIS. The radial profile of the photon temperature obtained from Abel inversion of the FEB data is shown in fig. 1 for pulse 24966 into which was injected 2.4MW of LHCD power and 3.2MW of ICRH power. At the position of the ICRH resonance the photon temperature reaches 120keV. The photon distribution is modelled assuming a fast electron distribution of the form:

$$f_{fast} = C(r).\exp(-p_{//}^2 / 2T_{//} - p_{\perp}^2 / 2T_{\perp}) \text{for } p_{//} > 0.$$

This fit gives combinations of $T_{//}$ and $T_{\perp}$ but is most sensitive to $T_{//}$ [3]. The average value of the perpendicular temperature is obtained by fitting the non-thermal, downshifted second harmonic peak in the electron cyclotron emission (ECE) spectrum [3]. In the case of shot 24966, $<T_{\perp}>$ was found to be 80keV and $T_{//}$ varied from a peak value of 1.3MeV to 600keV near the plasma boundary. The above distribution is used to calculate the current density profile, J(r), which, when normalised to the experimental J(r) profile yields the function C(r). In this way the radial profile of the distribution function of the current carrying fast electrons is determined and is used in conjunction with the narrow spectrum current drive efficiencies of Karney and Fisch to calculate the absorbed power density profile. This profile is integrated to give the total power absorbed and hence a value γ for comparison with experiment. In addition, by integrating over the electron distribution above the LHCD maximum energy the power required of the fast wave to produce the synergy is estimated. A flow chart of the analysis is given in fig.2.

RESULTS. Comparison with experiment is made using the figure of merit γ, the predicted value of which is obtained from the ratio of the plasma current (full current drive) and the calculated total power absorbed. The comparison is shown in fig.3 where experimental and calculated values of γ are plotted against $<T_{//}>$. The efficiencies are normalised to $Z_{eff}=1$ using the factor (Z+5)/6. Two theoretical curves are presented, one with no fast electrons flowing in the backward direction and the other with a distribution having $T_{//B}$=20keV and a normalisation constant C(r) equal to that of the forward flowing distribution. This latter effect reduces the predicted efficiency by about 10%. The experimental values are all taken from shots which have full current drive, so that electric field acceleration can be neglected, and are in good agreement with classical collision theory.

The power absorbed by all electrons above a specified minimum energy has also been obtained and is shown in fig.4 for pulse 24966. The calculated total power absorption of 2.7MW by the fast electrons agrees well with that derived from modulation experiments, namely 1.9MW of LHCD power (80% of the input of 2.4MW, see ref 4) plus 0.6MW directly damped on the high energy electrons from the fast wave. With $T_{//B}$=20keV the predicted power increases to 2.9MW. Taking account of an approximate estimate of the bootstrap current for shot 24966 reduces the calculated power to 2.5MW. The power required to sustain the tail beyond the maximum energy (~230 keV, ref.4) created by LHCD alone is found to be 083MW which is 30% higher than the measured 0.6MW absorbed directly from the fast wave.

The efficiency tends to saturate (fig.3) at a value of γ around 0.5 x $10^{20}AW^{-1}m^{-2}$ as the electron mass increases. This is less than the limit of the narrow spectrum efficiency which reaches $\gamma=1\times10^{20}AW^{-1}m^{-2}$ at 700keV energy. The difference arises from the fact that most of the power is absorbed by electrons with energy below the tail temperature due to their greater numbers and higher collision frequency. Experimentally an improvement in γ requires either higher T_e or a flatter electron distribution function, akin to that developed by LHCD, which might be attained with a narrower spectrum and more power coupled from the ICRF.

Note also that the fast wave power with $N_{//}$ between 1 and 1.5 (resonant with electrons above 200 keV) is only 6% of the total power. This is much less than the predicted 0.8 MW absorbed by electrons above the LHCD maximum energy which constitutes 26% of the ICRH power. A resolution of this difficulty might lie in the poloidal field effect on $N_{//}$. A change in the field angle of only 3° can give rise to $\Delta N_{//} = \pm1$ and within this range there is 23% of the fast wave power.

PROFILE CONTROL WITH SYNERGY. The JET experiments have shown that the minority resonance, or the ion-ion hybrid resonance, needs to be close to the source of fast electrons. If the fast electrons diffuse significantly whilst slowing down, it might be possible to move the current density profile away from the LH power deposition by employing more than one minority resonance. To show this effect we have used a 3D Fokker-Planck code (BANDIT) with two velocity variables a radial space coordinate. The lower hybrid power deposition was obtained using a model operator resonating with electrons between 50 keV and 250keV. The fast wave absorption was modelled using a Landau damping operator accelerating electrons between 100keV and 400keV. The fast wave operator was located at the cyclotron resonance layer with a radial width of 0.1m. The value of the RF diffusion coefficient was chosen to give typical synergy parameters, namely a γ of $0.4AW^{-1}m^{-2}$ and about equal LHCD and fast wave power absorption as shown in fig.5. The fast electrons with energies above twice the thermal velocity υ_e were assumed to spatially diffuse with a coefficient varying as $D(m^2/s) = 0.5\upsilon_{//}/\upsilon_e$. For a single ICRF resonance close to the LHCD absorption peak, the current density peaks at the power density maximum and the fast electron diffusion creates $0.2MA/m^2$ central current density (fig.5). Adding two additional ICRF resonances on the inside, to accelerate the diffused electron tail , produces a two fold increase of the central current density relative to the maximum (fig.6). Thus depending on the degree of fast electron diffusion there is some scope for changing the current density profile, and especially the central current density, using multiple minority resonances.

SUMMARY. The present analysis shows that the observed efficiency of current drive with synergy between LHCD and ICRH is in good agreement with the relativistic theory of Karney and Fisch for Landau damped waves. The predicted power absorption from the fast wave by the electron tail is within 30% of the measured value. In the presence of significant fast electron diffusion within a slowing down time it would be possible to produce central current drive using multiple ICRF resonances even when the LHCD deposition is at half radius, as in an ITER type device.

REFERENCES

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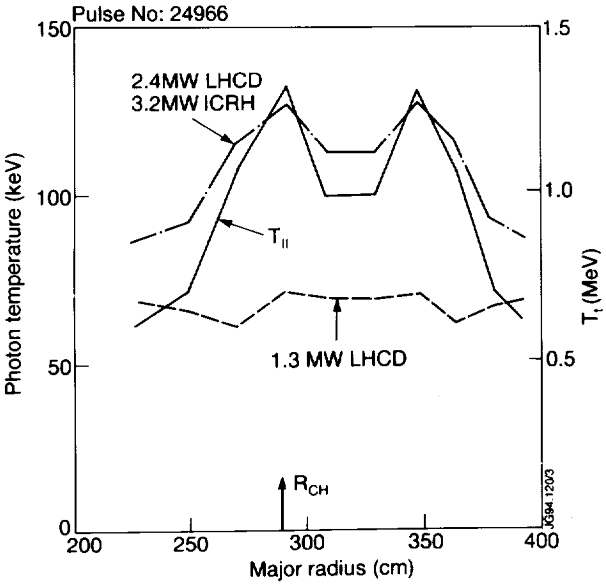


Fig.1: Photon and fast electron temperatures.

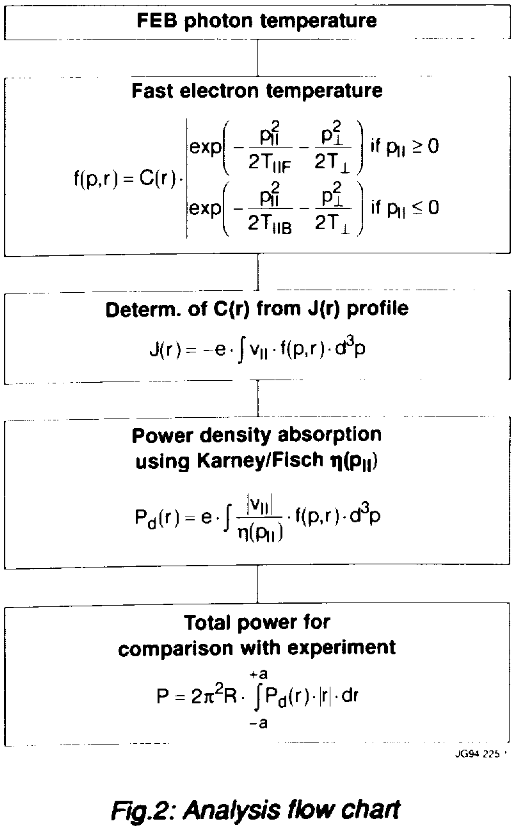
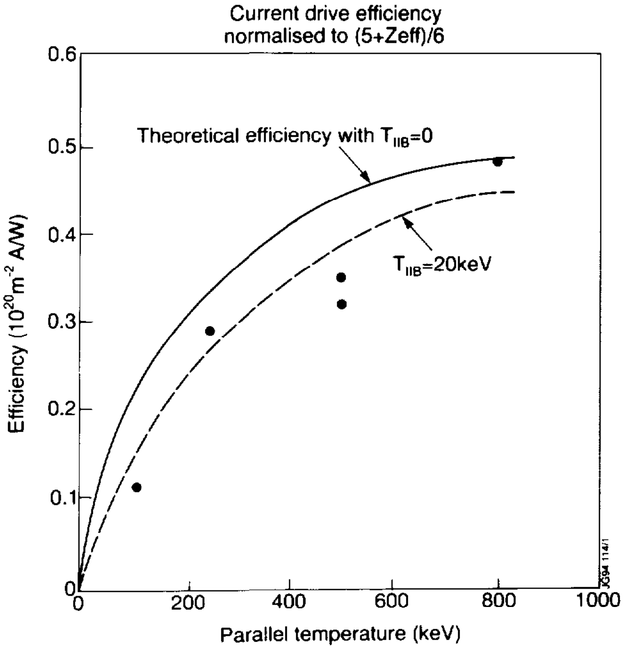


Fig.2: Analysis flow chart



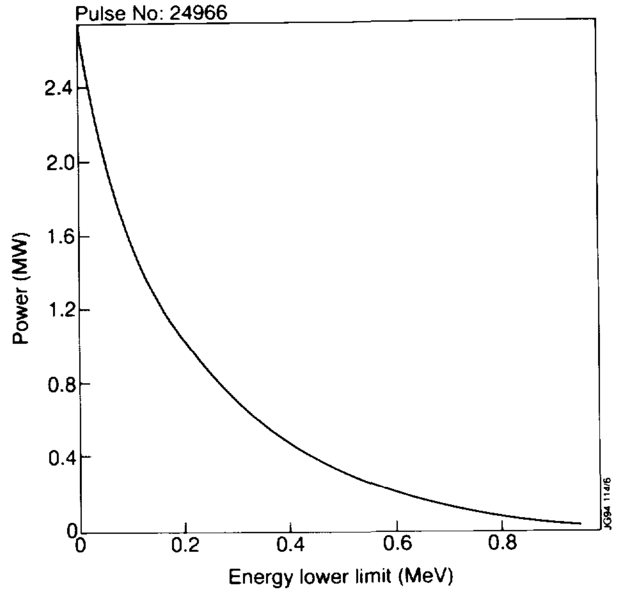
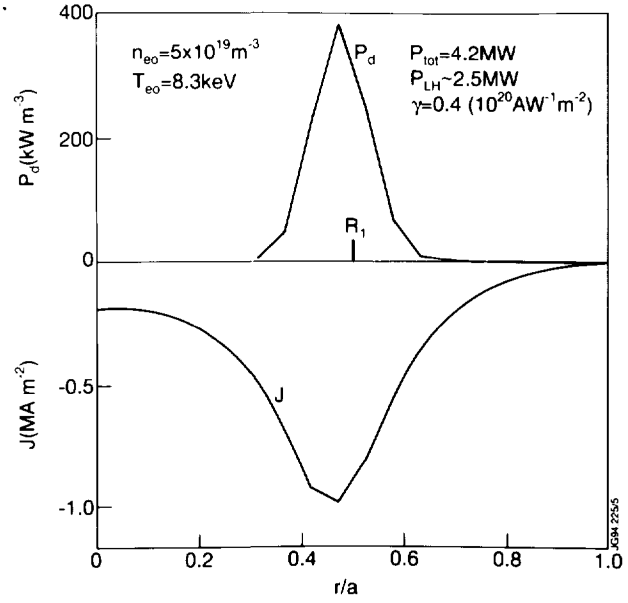


Fig.3: ***Comparison of experimental and predicted efficiencies for given full current drive experiments and for average tail temperatures up to 800 keV.***

Fig.4: ***Power damped on electrons above a minimum energy***



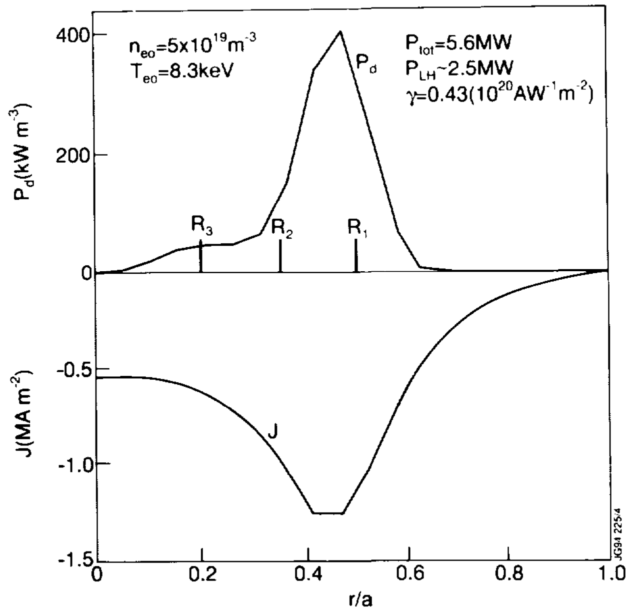


Fig.5: ***Simulations of synergism with electron diffusion present***

Fig.6: Enhancement of the central current density using three minority resonances.