Power Deposition and Driven Current Profiles in Lower Hybrid Current Drive Experiments on JET

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JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA, UK.

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SUMMARY.

High performance and reliability of the new Lower Hybrid Current Drive (LHCD) system has been demonstrated in the recent experiments on JET in divertor discharges. The system operates at a frequency 3.7GHz with the maximum power of 12MW (20s). Up to 6MW of LH power was launched into the plasma through a single multiple waveguide grill type antenna. Nearly full current drive of Ip=2MA was achieved in the plasma with $n_e(0) \cong 2.3\ 10^{19} m^{-3}$ by launching about 4MW of LH power during 3.5s. The electron temperature increased from 3keV up to about 5keV during current drive phase. The LHCD experiments have been modelled by means of code [1]. It includes ray-tracing in the toroidal geometry with the real divertor configuration and 2-D Fokker Planck calculations. Scattering of the lower hybrid waves on density fluctuations and spatial diffusion of the fast electrons with the diffusion coefficient $D=D_0 v_{//}/v_e$ ($D_0=0.5m^2/s$, $v_{//}$ and v_e, parallel and thermal electron velocities) are taken into account. Results of the modelling are in good agreement with the experimentally observed LHCD efficiency [2]. Simulated fast electron bremstrahlung (FEB) emission is compared with the measured FEB profiles [3] for a number of shots. The deposition profile varies with plasma density, temperature, and plasma current.

2MA CURRENT DRIVE EXPERIMENTS.

Discharge with nearly full plasma current driven by LH waves. Calculated by LHCD code $I_{LH}=1.86MA$ and efficiency $\eta=0.22*10^{20}(A*m^{-2}W^{-1})$. It is very close to the estimation from the change of the loop voltage and plasma resistance.

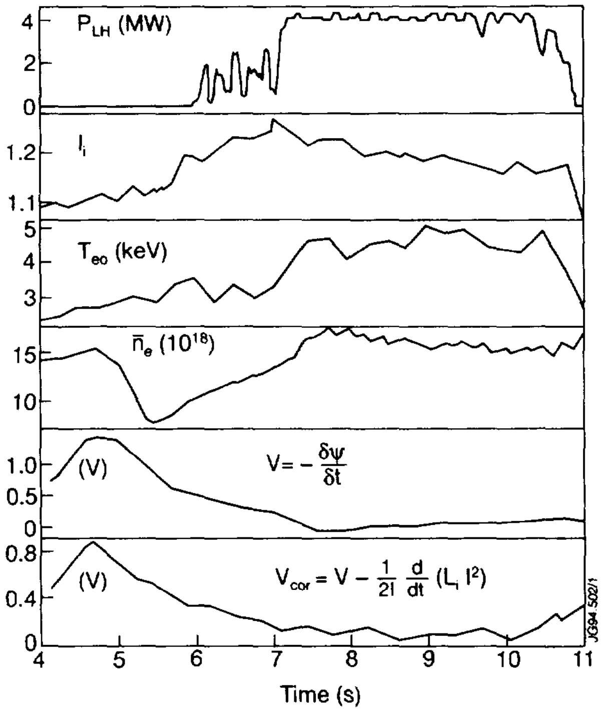


Fig. 1. Shot #29711. with I_p=2MA, n(0)≅2.3 $10^{19}m^{-3}$, at B_t=2.8T. Evolution of LH power (a), internal inductance (b), central electron temperature (c), line averaged density (d), flux consumption (e), smoothed over 0.5s measured and corrected loop voltages (f).

BROADENING OF LH DRIVEN CURRENT PROFILE WITH DENSITY INCREASE.

Current and power deposition profiles broaden when density increases while electron temperature does not change significantly in a greater part of the plasma volume.

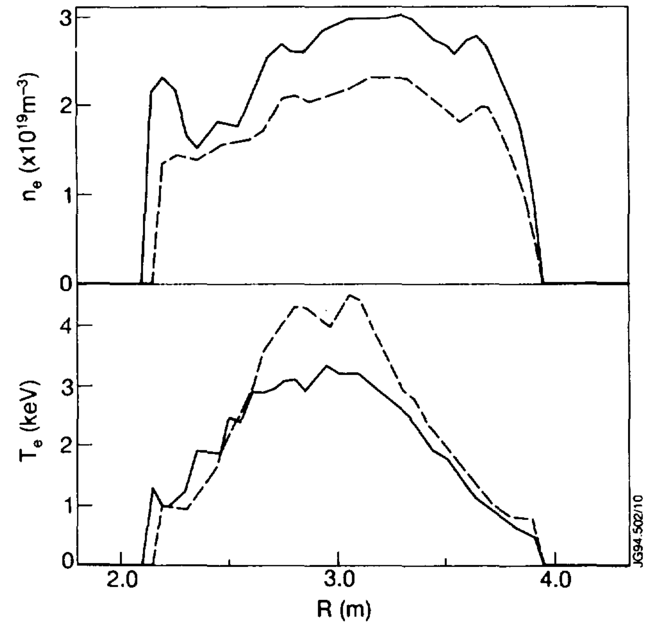


Fig. 2 Electron density (a) and temperature profiles (b) for shots #29711 and #29639. I_p=2MA, B_t=2.8T.

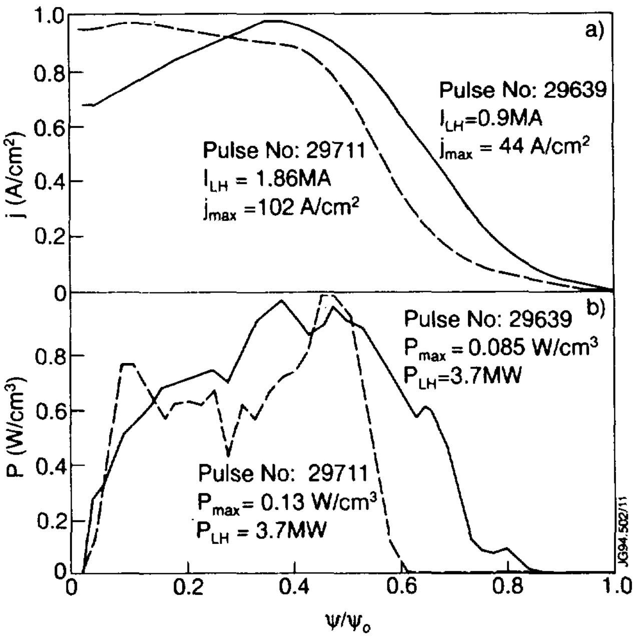


Fig. 3. Calculated driven current (a) and power deposition (b) profiles. Solid line-#29639, dashed line- shot #29711

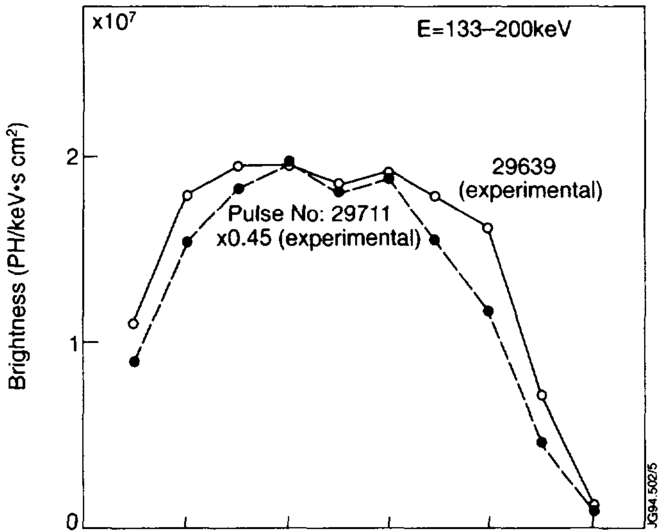


Fig. 4. Comparison of measured FEB profiles for shot #29639 (solid line) and #29711 (dashed line, this profile normalised by a factor 0.45).

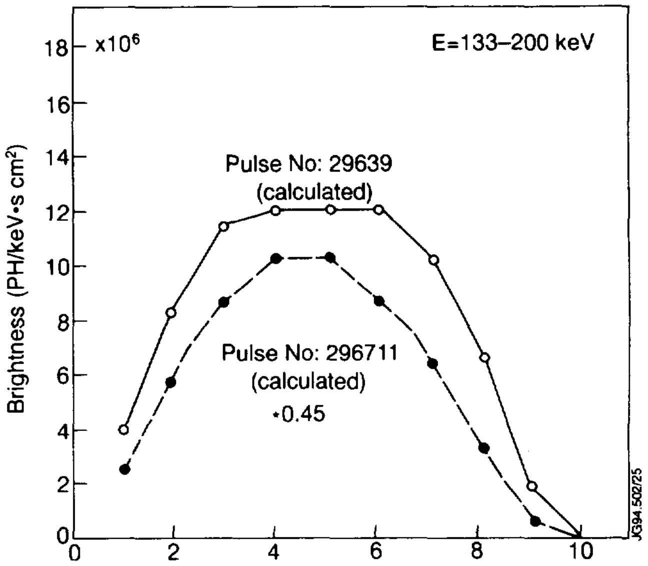


Fig.5. Comparison of calculated FEB profiles for shot #29711 (dashed line, this profile is normalised by a factor 0.45). The discrepancy in the calculated and measured brightness may be caused by uncertainty in $Z_{eff}(r)$ and error in the estimation of the average perpendicular electron energy of the tail $E_{\perp}(v)$ [1].

In the framework of the model the broadening of the profile is explained in the following way: at high density plasma the LH waves propagate closer to the periphery, where RF energy density (quasi linear diffusion coefficient $D_{ql)}$ increases. Ray trajectories experience greater number of reflections.

When reflection occurs in the top sector of the plasma boundary, the wave is strongly slowed down. This is the major mechanism for the 'spectral gap' filling. Higher power is absorbed and greater current is driven further out from the centre, (due to the higher value of D_{ql}) than in lower density plasma (under the condition that electron temperatures are not too different).

BROADENING OF THE LH CURRENT PROFILE WITH PLASMA CURRENT INCREASE

Comparison of experimental data shows that the LH driven current profile is systematically broader in discharges with higher plasma current. Calculation of ray trajectories (Fig.14) indicates that waves experience a greater number of reflections and spend more time in the peripheral region in the case of higher plasma current. Result is similar to the increase of plasma density (see above).

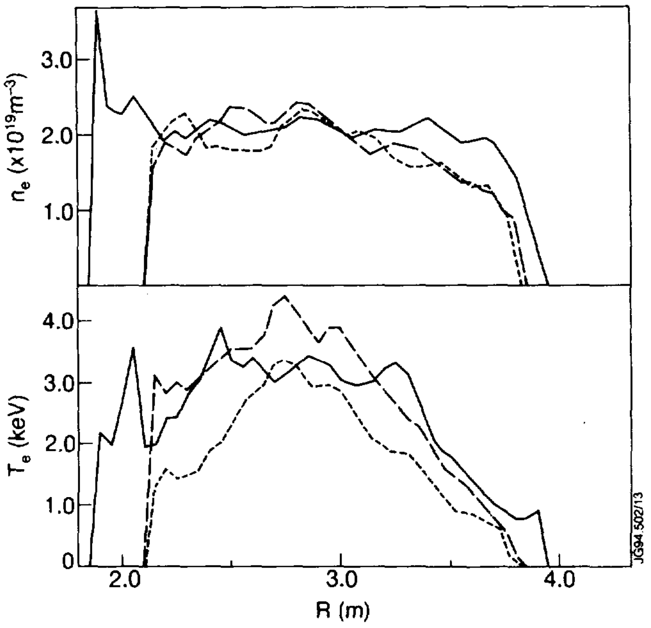


Fig. 6. Density and temperature profile for shots #30505 (solid line), #30542 (dashed line) and #30649 (dotted line)

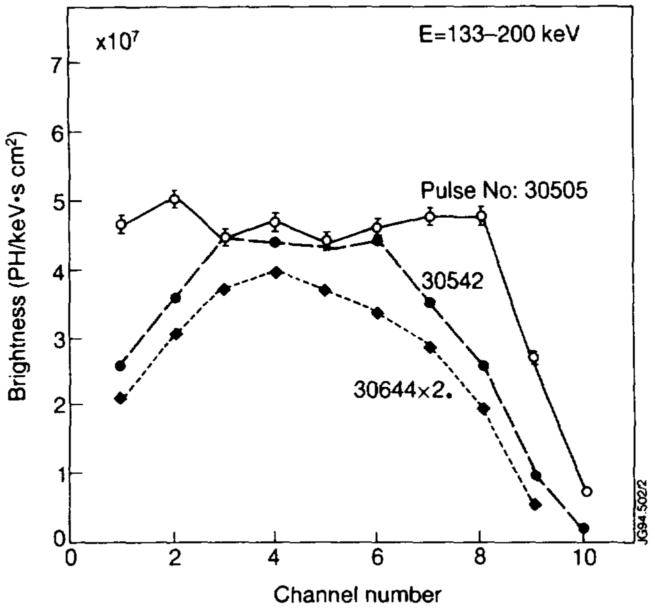


Fig. 7 Comparison of measured FEB profiles for pulses with different plasma current: -shot #30505, Ip=3MA, P_{LH}=4.6MW-(dashed line), and shot #30644, Ip=1.5MA, P_{LH}=1.9MW-(dotted line)

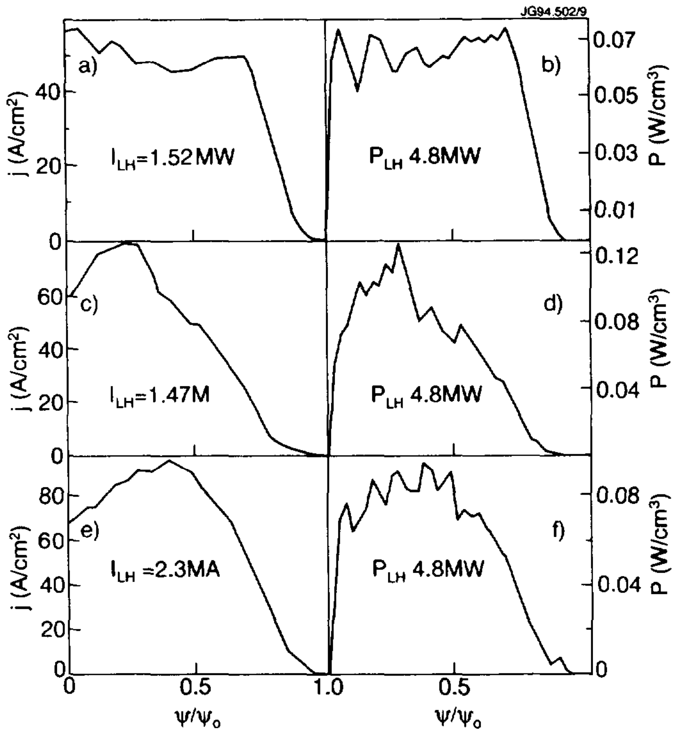


Fig. 8 Calculated LH current (a) and power deposition (b) profiles for shot #30505. Calculated LH current (c) and power deposition (d) profiles with equilibrium from shot #30542, and plasma parameters from shot #30505. Calculated LH current (d) and power deposition (f) profiles with equilibrium from shot #30505 and plasma parameters from shot #30542.

TRANSPORT CODE MODELLING OF LHCD

Evolution of the full current and l_i was simulated with the transport code JETTO taking into account the driven current, calculated by the LHCD code. In most shots with high LH power internal inductance l_i decreases and current profile broadens. This indicates off axis power deposition. Simulations reproduce the broadening of current profile and the decrease of l_i.

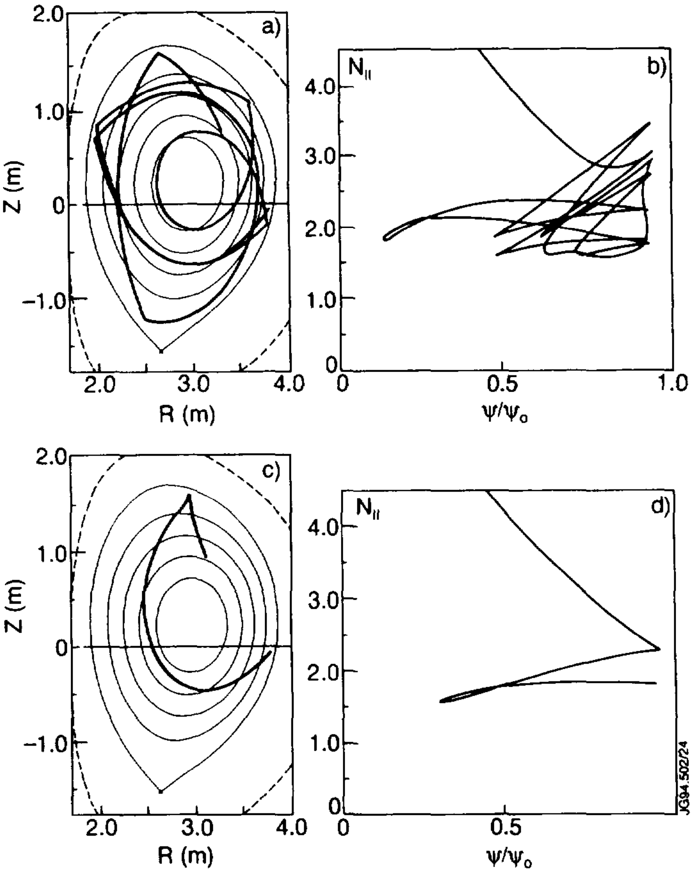


Fig. 9. Ray trajectories (a),(c) and behaviour of $N_{//}$ along trajectories as a function of poloidal magnetic flux (b),(d) for shots #30505 and #30542, respectively. Initial $N_{//}$=1.85

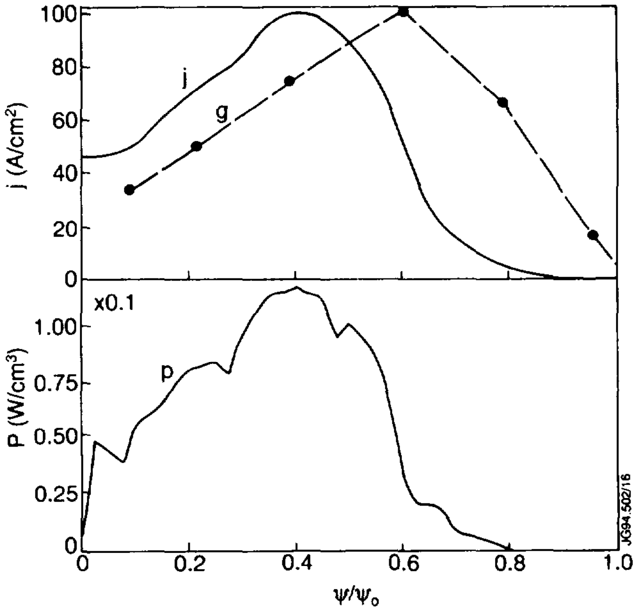
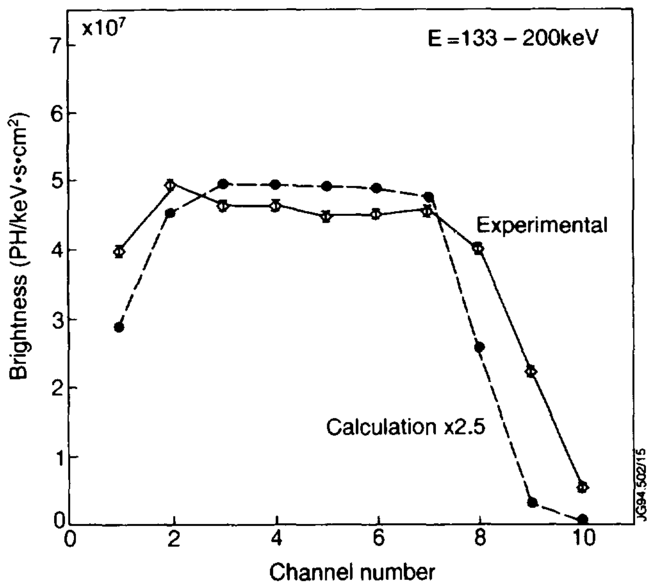


Fig. 10. Calculated LH driven current j and power deposition profiles p and ratio g of the local FEB emissivity and electron density for shot #30517, t=57s, P_{LH}=4.5MW, $\bar{n}_e=1.6*10^{19}\ m^{-3}$, $n_{e0}=1.9*10^{19}m^{-3}$, T_{e0}=3.5keV, $N_{//max}$=1.85, I_p=3MA, B_t=2.8T. Function g is calculated by Abel inversion of the measured chord integrated FEB profile (see Fig. 11). In our simple model g should be proportional to the number of suprathermal electrons.



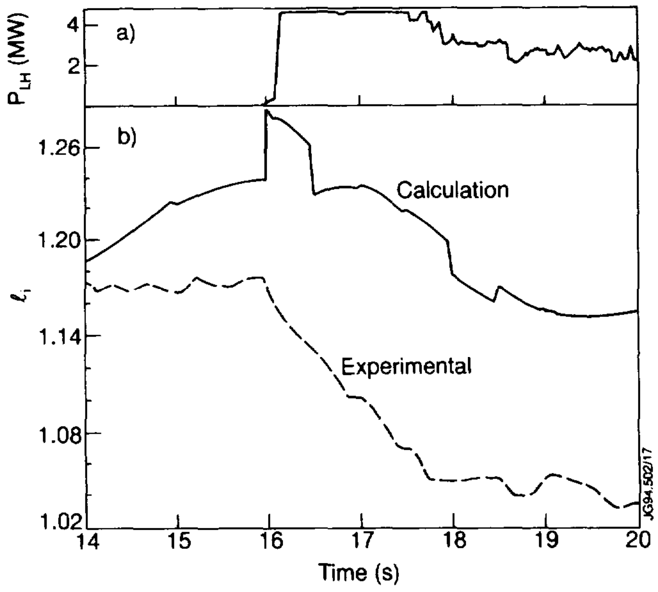


Fig. 11. Comparison of measured and calculated FEB profiles for shot #30517 (calculated signal multiplied by factor 2.5). Discrepancy in the amplitude and form of the profiles may be attributed to the same factors as in Fig.4 and Fig.5..

Fig. 12 Comparison of measured and calculated FEB profiles for shot #31753 at t=41.5s

VARIATION OF LH POWER SPECTRUM

Two spectra with different $N_{//\max}$= 1.4 and 2.3 and equal full width $\Delta N_{//FW}$=0.46 were launched into plasmas with similar parameters. The FEB profiles for both spectra have a similar shape. Simulation roughly reproduces the similarity of LH drive current and power deposition profiles. Calculations show that in the case of relatively high density $n_{eo}=2.9*10^{19}m^{-3}$ and moderate temperature $T_{eo}<2.5$keV multiple pass absorption takes place. Initial spectra are modified considerably in the plasma in both cases.

Comparison of shots with different antenna phasing (parameters change with time in the indicated range):

#29548,

$$P_{LH} = 2.7 - 3.1MW,\ \overline{n_e} = 2.3^*10^{19}m^{-3}, n_{eo} = 2.9^*10^{19}m^{-3},$$
$$T_{eo} = 2.2 - 2.6keV, N_{//\max} = 1.4,\ I_p = 2MA, B_t = 2.8T$$

#29549,

$$P_{LH} = 1.8 - 3.2MW,\ \bar{n}_e = 2.3 * 10^{19}m^{-2},\ n_{eo} = 2.9 * 10^{19}m^{-3},$$
$$T_{eo} = 2.2 - 2.6keV, .N_{II\,\max} = 2.3,\ I_p = 2MA$$

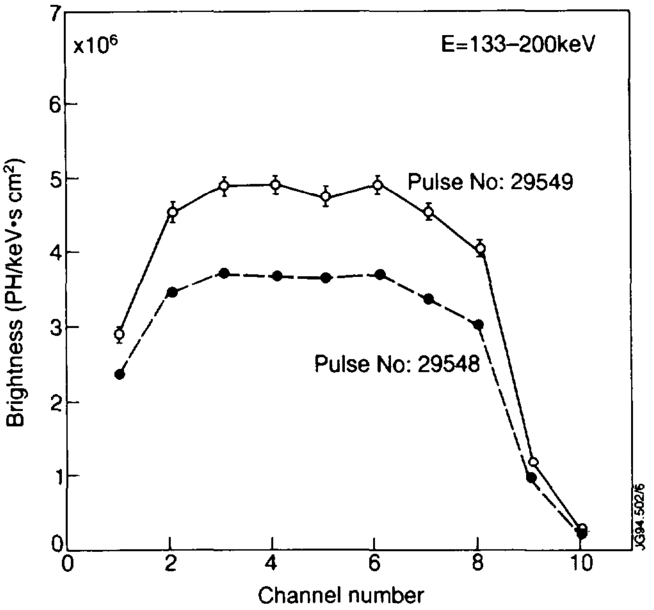


Fig. 13. Measured FEB profiles: crosses-shot #29548, bars-shot #29549.

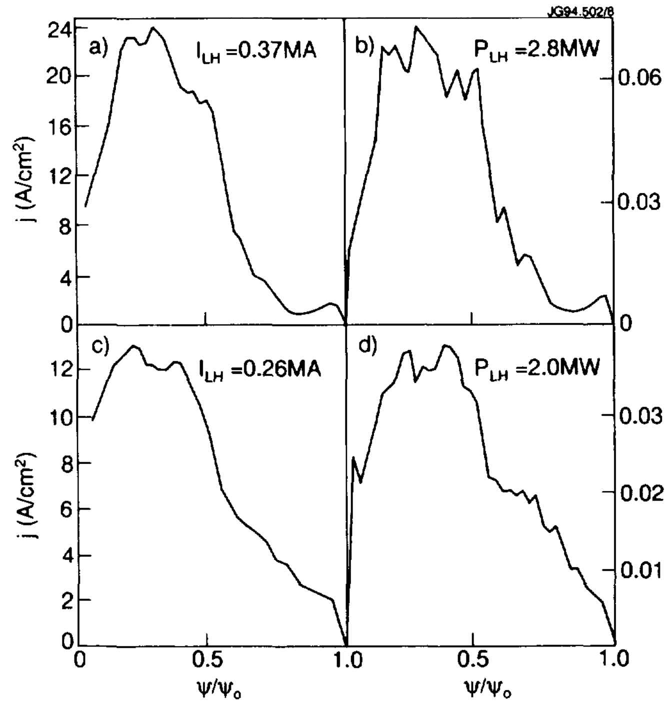


Fig. 14. Calculated current (a), (c) and power deposition (b), (d) profiles for shots #29548, #29549, respectively. Calculated $\eta=0.085*10^{20}(A*m^{-2}/W$ for both shots

CONCLUSION.

High versatility of LHCD was demonstrated in experiments on JET. Full current drive as well as considerable modification of plasma current shape for the purpose of profile control have been achieved. Experiments were carried out in a wide range of plasma parameters; $n_{e0}=(0.9-4.0)*10^{19}m^{-3}$, $T_{e0}=1.5-6.keV$, $I_p=0.5-3MA$, $B_t=2.4-2.8T$ with maximum available LH power of 6MW and different power spectra $N_{//max}=1.4,1.85,2.3$ with LH alone and in combination with NBI and ICRH. Results of modelling by LHCD and transport (JETTO) code are in qualitative agreement with experimental data. Calculations show that in most analysed cases multiple pass absorption of LH waves takes place. Reflection of the waves as well as the process of the wave scattering requires additional investigation. When plasma temperature increases the number of reflections decreases. Extrapolation to high temperature plasma of ITER shows that LH waves should be absorbed during the first pass. Under such conditions predictions of the LHCD code are more reliable.

REFERENCES

1. Y.F.Baranov et al, 20th EPS Conf.Proc., Lisbon 1993, part 3, p.881
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