JOINT EUROPEAN TORUS

JET–P(91)42

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* *See Appendix 1*

Preprint of an Invited Paper presented to RF Topical Conference, Charleston, USA.,
19th-21st August 1991

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Abstract

The JET Lower Hybrid Current Drive (LHCD) prototype system has been in operation in the early part of the 1991 experimental campaign with generated power up to 2.7 MW at 3.7 GHz and coupled power to the plasma up to 2.4 MW. Experiments have focussed so far on the determination of the performance limits of the system, both in terms of long pulse operation and of replacement of the ohmically driven plasma current. Further experiments have also been carried out to confirm early findings of central electron heating induced by LH when applied in combination with Ion Cyclotron Resonance Heating (ICRH).

Long pulse operation has been obtained on JET with 2 MA, 1.9 T limiter plasmas with 1 minute current flat top where 40 % of the required flux is provided by the combined application of the LH and ICRF systems. Full replacement of the inductive current has been observed in 1 MA, 3.4 T ohmic plasmas with 1.9 MW of LH power, with current drive efficiencies up to $\langle n_e \rangle I_{CD}/P_{LH} \sim 0.35\ 10^{20}\ m^{-2}$ A/W with volume averaged electron temperature $\langle T_e \rangle = 1.2$ keV. Combined application of LH and ICRH leads to full sustainment of the plasma current at 1.5 MA, 3.2 T with indications of transformer recharging.

Early findings /1/ obtained during the 1990 campaign of LH induced central electron heating and synergism with the ICRF fast wave have been confirmed with electron heating rates of 1 keV/MW at $\langle n_e \rangle \sim 2\ 10^{19}\ m^{-3}$ and enhanced high energy fast electron bremmstrahlung emissivity leading to a factor 2 increase in the energy content of the perpendicular photon distribution.

Coupling of the LH power to the plasma has proven successful, with reflection coefficient down to 2 % average, but it is found that the LH launcher conditioning is strongly affected by the details of the operation.

The JET Lower Hybrid Prototype System

Results so far have been obtained with an LHCD prototype launcher consisting of 16 multijunctions resulting in 128 narrow waveguides facing the plasma, fig. 1 /2/. The launcher is powered by two modules of 4 klystrons each, with the overall capability of delivering up to 3.2 MW for 20 sec or 4 MW for 10 sec, via a low loss waveguide trasmission line pressurized at 1 bar overpressure SF_6. The vacuum transition is made by means of a circular double quarter wavelength Be window. Longer pulse length operation has been achieved at the expense of the total generated power, by employing only three klystrons per module and lowering the required klystron

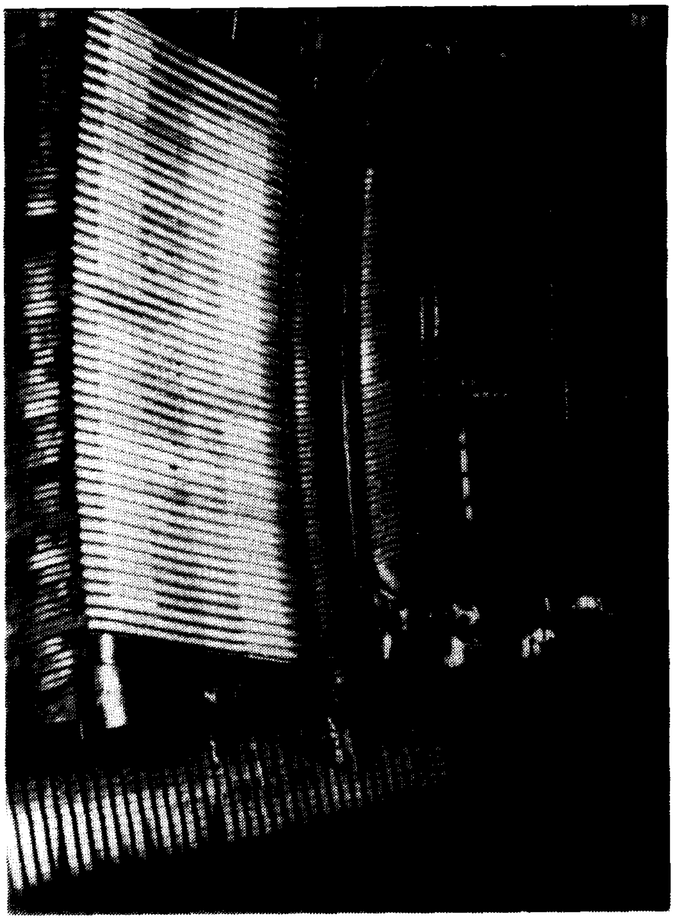

Fig. 1 - The LHCD launcher viewed from inside the vacuum vessel. One of the 8 ICRH antennae is on the left. The toroidal belt limiters are also visible.

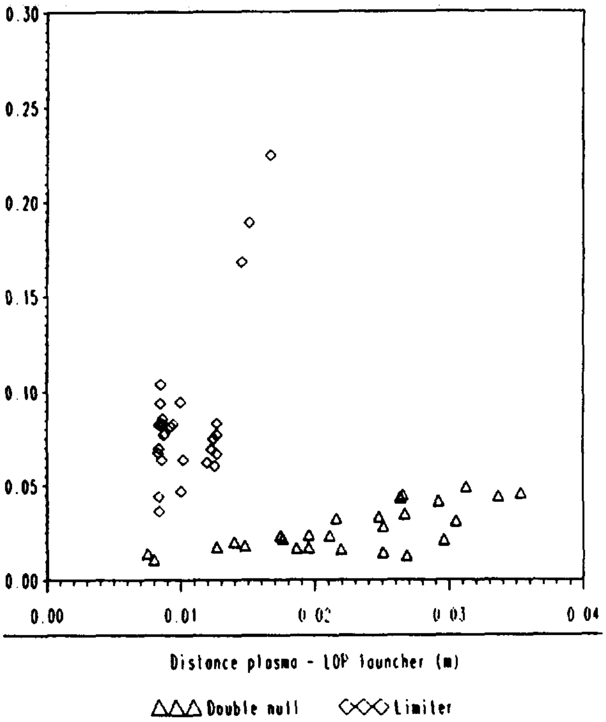

Fig. 2 - The LH reflection coefficient (%) vs. the plasma launcher distance in limiter and double null configurations. Most of the operation so far was performed with a distance of 8 mm.

beam current.

The upper half of the multijunction (module B) is made in C coated CuZr with a short circuit in the fourth multijunction port, following a similar design of the Tore Supra LH system. The lower half (module D) consists of 8 C coated Cu coated SS multijunctions packed together without gaps at the grill mouth, following a JET design. Each horizontal row of multijunctions consists of 16 waveguides. Built-in phase shifters give a $\pi/2$ phasing between adjacent waveguides of a given multijunction. The resulting wave spectrum is centred at $n_{\parallel} = 1.8$ with 70 % directivity. The peak $n_{\parallel}$ value can vary between 1.3 and 2.4 by varying the klystron relative phasing from $-\pi/2$ to $+\pi/2$, at the expense of reduced directivity.

The launcher is assembled onto a main radial equatorial port of the JET vacuum vessel. A position control system, allowing radial displacements up to 210 mm via a bellow assembly, has been in operation during the early part of the LH campaign.

An improved baking system has been installed, which allows to maintain the multijunctions above 350° C, higher than the JET operating temperature of 300° C. This has led to better launcher conditioning and partly explains the 25 % step in generated power compared to the 1990 campaign.

Operational range of the Lower Hybrid experimental campaign

The Lower Hybrid plant has been operated constantly at the maximum achievable power level. The highest generated power obtained so far has been 2.7 MW and 2.4 MW coupled to the plasma, corresponding to ~ 3 kW/cm^2 at the grill mouth. This has been achieved in limiter plasmas where the plasma launcher distance, computed from the magnetic probe signals, was ~ 8 mm.

The Lower Hybrid experiments carried out on JET so far this year were performed on Deuterium plasmas in limiter and double null X-point configuration, with plasma current ranging from 1 MA to 3 MA and toroidal field varying between 1.9 T and 3.4 T. The central electron temperature was varied between 1.5 keV in ohmic plasmas and 8 keV with 3 MW of ICRF Hydrogen minority central heating. The plasma density was controlled by gas feedback in the range $1\ 10^{19}\ m^{-3}$ to $3\ 10^{19}\ m^{-3}$ volume average. The lower density operation was in general characterized by high Z_{eff} values ~ 4, when the plasma was limited by the lower C toroidal belt limiter. Operation at lower Z_{eff} values, ~ 1.3, could be achieved by increasing the plasma interaction with the top Be belt limiter and by continuously feeding gas during the current flat top, thus increasing wall pumping.

Experimental results

The coupling of the LH power to the plasma was monitored by measuring the total reflected power back to high power loads installed in the fourth port of the hybrid junctions in the Splitting Network. A strong dependence is found in limiter plasmas of the reflection coefficient on the launcher plasma distance, as indicated in fig. 2. This dependence is far weaker in double null

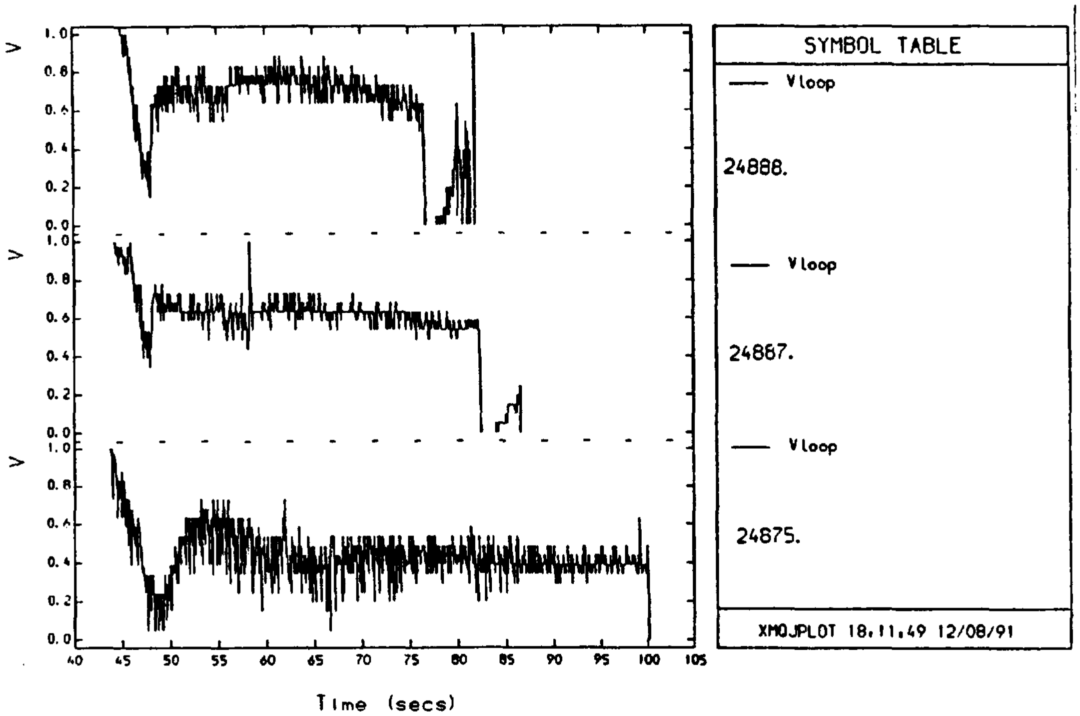

Fig. 3 - Time behaviour of the loop voltage in the long pulse operation, for Ohmic (top), OH+LH (centre) and OH+LH+ICRH (bottom) pulses.

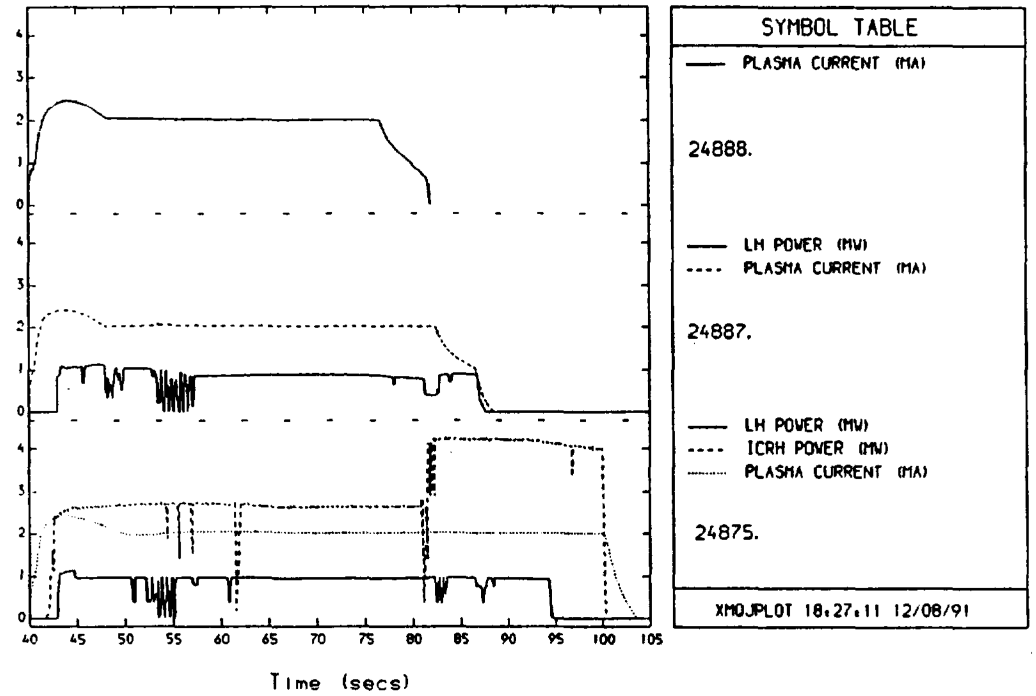

Fig. 4 - Current and power waveforms for the same pulses as in fig. 3. The LH power is modulated at 54 s.

X-point plasmas, where a reflection coefficient below 5 % is found when the plasma launcher distance is up to 30 mm. In both cases it was necessary to shape the plasma boundary to match the launcher poloidal shape. When operating the LH system without a real time position control, the optimum configuration is achieved by preprogramming shaping and vertical fields. Most of the experimental campaign has been conducted with the LH launcher at the same major radius location of the ICRF antennae.

One of the main aims of the JET 1991 experimental programme was to produce plasmas with 1 minute current flat top duration, in order to assess steady state conditions and investigate recycling mechanisms which could provide important informations for the Divertor phase of JET.

Both Radio Frequency Systems have been instrumental in achieving this goal, by providing a high temperature, low resistivity plasma to limit resistive flux consumption from the ohmic transformer (ICRH), and by direct current drive (LH). One minute long pulse operation has been achieved at 2 MA, 1.9 T, with 50 sec LH pulse at 1 MW and 3 successive 20 sec 3 MW pulses of ICRF at 28 MHz H minority, using 2 generators in monopole phasing at each step. This has provided a 4.5 keV central electron temperature plasma target for LHCD at $\langle n_e \rangle \sim 2\ 10^{19}\ m^{-3}$. The density was kept high by gas feedback and edge recycling was controlled by continuous gas feed. 40 % of the required flux was thus provided by the combined action of the RF systems (fig. 3), thus allowing to extend the flat-top duration from 75 sec in the ohmic case to 100 sec (fig. 4), where the plasma termination is caused by the toroidal field system reaching a limiting I^2t value of $10^{11}\ A^2s$. In these conditions steady state is achieved ~ 18 sec in the flat-top in the ohmic case (fig. 5), extended to ~ 21 sec when 1 MW of LH is applied to drive ~ 400 kA at $\langle T_e \rangle = 0.7$ keV with an efficiency $\gamma = .15\ 10^{20}\ m^{-2}A/W$. The current diffusion time rises to 35 sec and CD efficiency to $\gamma = .35\ 10^{20}\ m^{-2}A/W$ at $\langle T_e \rangle = 1.9$ keV, including residual electric field corrections, when ICRH is applied. The LH central electron heating efficiency is estimated to be 0.2 keV/MW in these conditions.

Full sustainment of the plasma current has been achieved in JET during limiter operation. In fig. 6 the case is shown where 1.9 MW of LH were applied during the current decay of a 1 MA, 3.4 T plasma after termination of the discharge caused by a locked mode arising from high density limit. The toroidal field when LH was applied had decayed to 2.5 T and the plasma internal inductance was $l_i \sim 2$, corresponding to a highly peaked current density profile, at $\langle n_e \rangle = 10^{19}\ m^{-3}$ and $\langle T_e \rangle = 0.4$ keV. The LH power was able to sustain ~ 400 kA, corresponding to an efficiency $\gamma = 0.06\ 10^{20} m^{-2}A/W$. The Fast Electron Bremmstrahlung measured by the FEB vertical and horizontal cameras /3/ is shown in fig. 7 to have peaked emissivity profiles extending up to 200 keV fast electron energy, compatible with a population sustained by LH only with a power spectrum given by $n_{\parallel} = 1.8 \pm 0.2$. The corresponding "photon temperature" is 40 - 60 keV. The same LH power was found to sustain 1 MA of plasma current in similar conditions, when applied in combination with 3 MW ICRH at

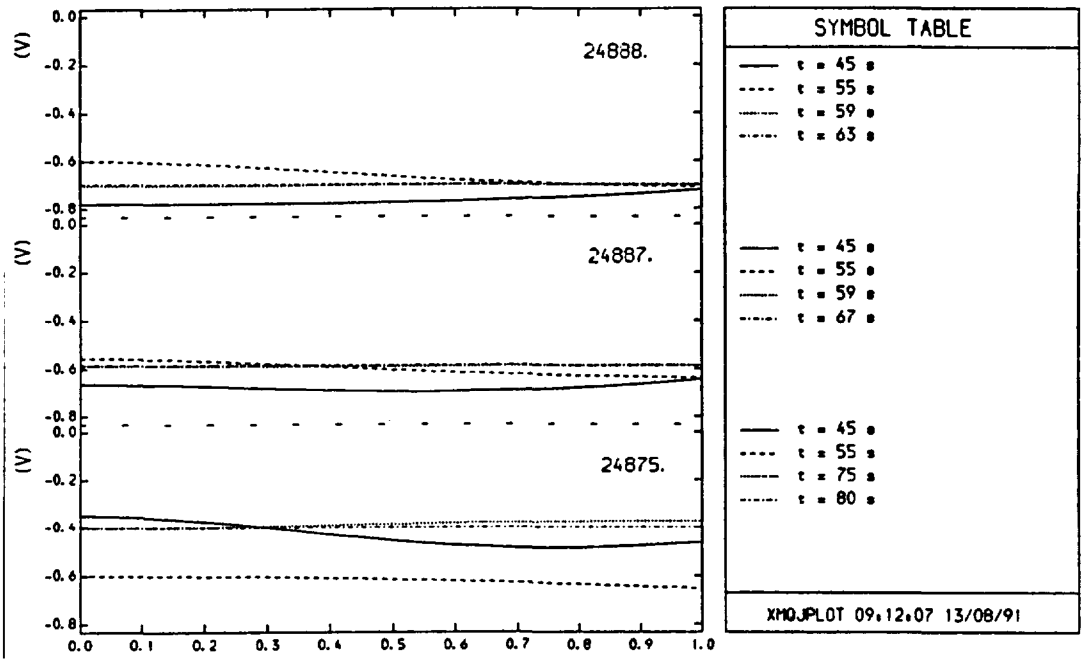

Fig.5 - Time evolution of the radial profile of the loop voltage, as computed by the equilibrium analysis code IDENTC, for the same pulses as in figg. 3 and 4.

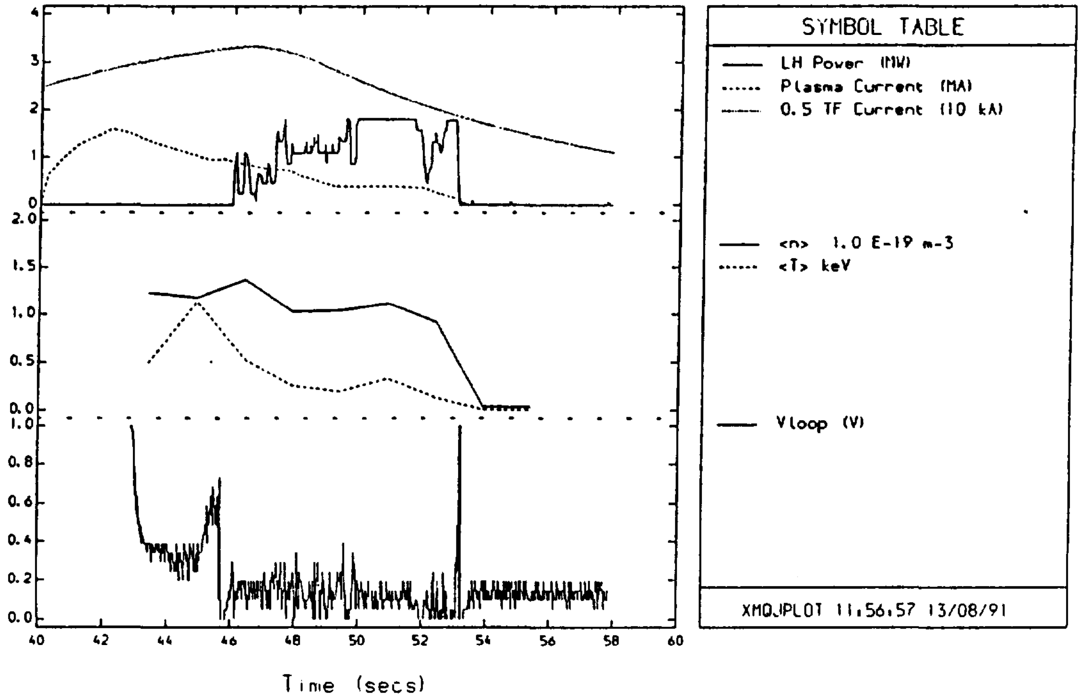

Fig.6 - LH applied during the current and TF decay. 400 kA are sustained from 49 to 52 s. The loop voltage value in this period corresponds to the signal off set.

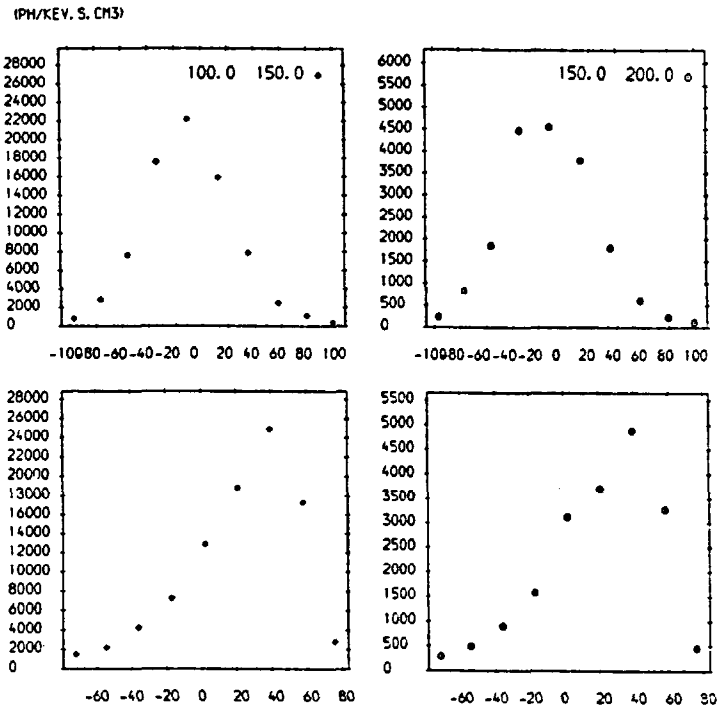

Fig.7 -FEB profiles for pulse 24918 from the (top) horizontal and (bottom) vertical cameras, in the (left) first and (right) second energy window. The radial coordinate refers to the machine axis.

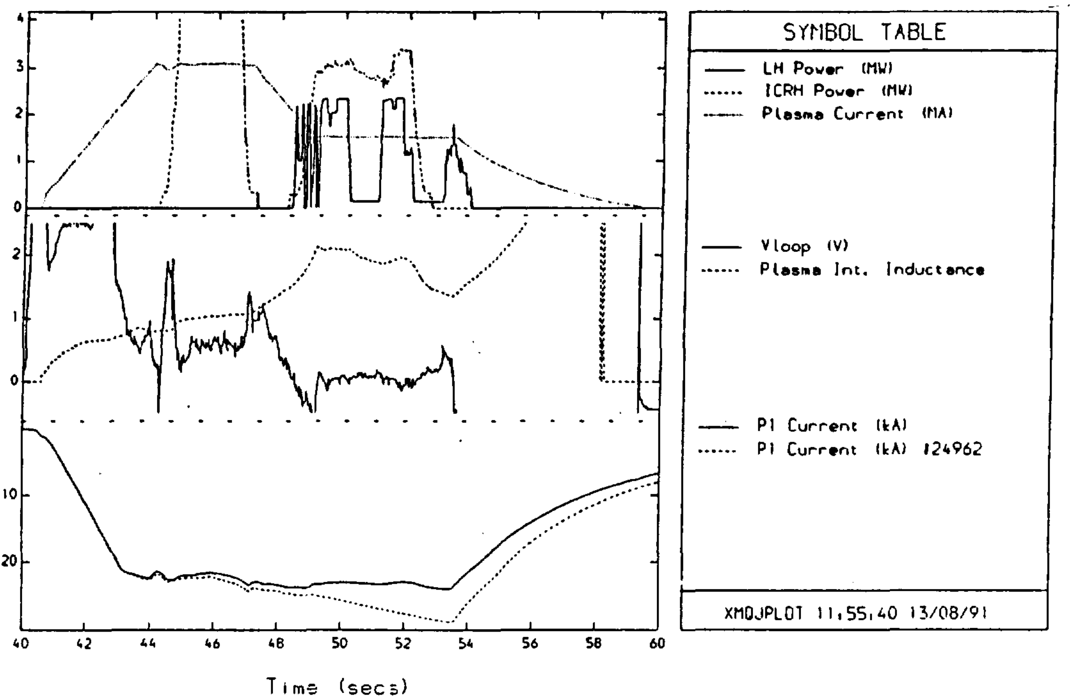

Fig.8 - Full LHCD at 1.5 MA, 3.2 T (JET pulse 24966). High efficiency is well correlated with peaked profiles. The LH modulation footprint in the primary current shows the transformer recharging effect.

$<T_e>$ = 1.2 keV.

Further experiments were performed in 1.5 MA, 3.2 T limiter plasmas, where the current was ramped down from 3 MA with a preprogrammed waveform, thus obtaining an l_i = 2 plasma target at $<n_e>$ = 1.3 10^{19} m^{-3}, and central electron temperature T_{e0} = 7 keV by using 3 MW of H minority ICRF monopole heating. Application of 2.3 MW LH power, 100 % modulated at 0.5 Hz leads to full current sustainment, corresponding to 0.4 10^{20} m^{-2}A/W efficiency (fig.9), as shown by the loop voltage signal in fig. 8. In these conditions the LH power affects the current decay in the main primary windings. It is estimated that ~ 0.1 V-s were provided to the transformer, with a 20 % uncertainty due to reactions arising in the outer poloidal coils.

Central electron heating at a rate of 1 keV/MW is observed (fig. 10) during LH modulation, with broad FEB profiles. Respect to LH only cases at comparable plasma density, high energy regions of the photon spectrum are more populated, doubling the "photon temperature" and extending the fast electron tail to ~ 400 keV (fig. 11), indicating synergistic acceleration of fast electrons by ICRF fast wave induced $\mu \nabla_{\parallel}\tilde{B}$, where μ is the electron magnetic moment and $\tilde{B}$ the RF magnetic field, and LH induced Electron Landau damping. In this case the role of LH is to create an asimmetric parallel electron distribution, allowing Transit Time Magnetic Pumping (TTMP) current drive even without phasing the ICRF antennae.

Conclusions

A number of very promising results have been obtained in the first part of the 1991 JET experimental campaign with the combined application of up to 2.4 MW of Lower Hybrid power and up to 5 MW of ICRH.

Up to 1 minute current flat-top has been obtained at 2 MA, 1.9 T with the aid of 1 min, 3 MW pulse of H minority ICRF monopole heating and 50 s, 1 MW pulse of LH, for a total of 230 MJ generated by the RF systems, which provided 40 % of the required flux.

Full sustainment of the plasma current was achieved at 1 MA, 3.4 T and 1.5 MA, 3.2 T by the combined application of up to 4 MW ICRH and up to 2.4 MW LH. At the highest LH powers it is estimated that ~ 0.1 V-s are induced in the transformer primary, indicating that the current drive efficiency could be higher than the reported values of ~ 0.4 10^{20} m^{-2} A/W .

Electron heating is observed at the plasma centre at a rate of 1 keV/MW of coupled LH power, in conjunction with FEB camera measurements of hollow fast electron profiles at $<n_e> \geq 1.5$ 10^{19} m^{-3}. This observation, and the observed doubling of the "photon temperature", suggests that a synergistic mechanism exists between LH and ICRF fast wave, which allows TTMP current drive in absence of ICRH antenna phasing, thus increasing the current drive efficiency of the individual systems.

The coupling of LH power to the plasma is found to be a strong function of launcher plasma distance in limiter plasmas, the dependence decreasing in double null X-point plasmas. In all

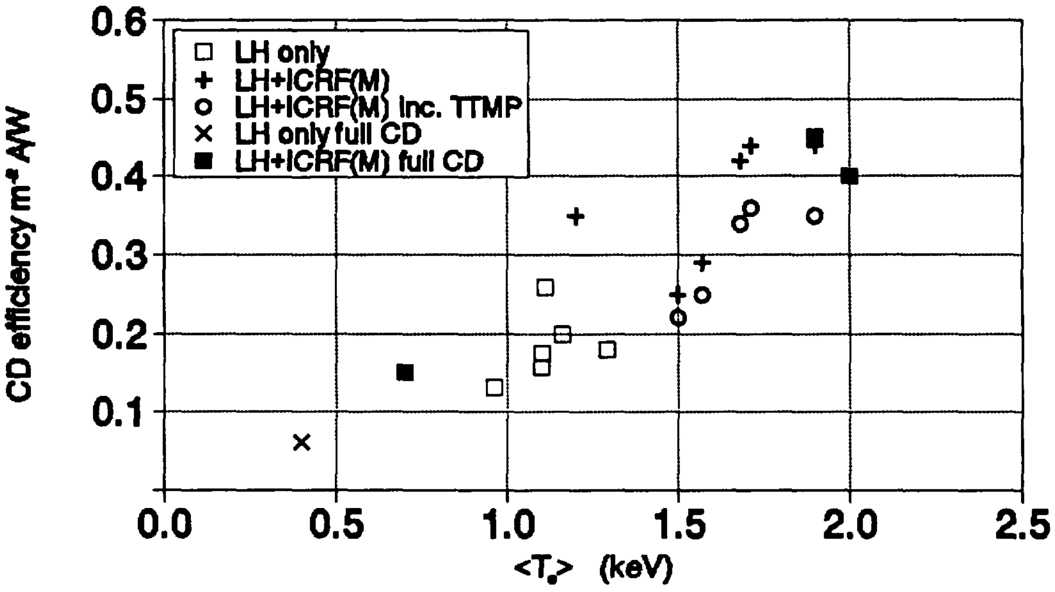

Fig. 9 - **Current Drive efficiency vs <Te>**

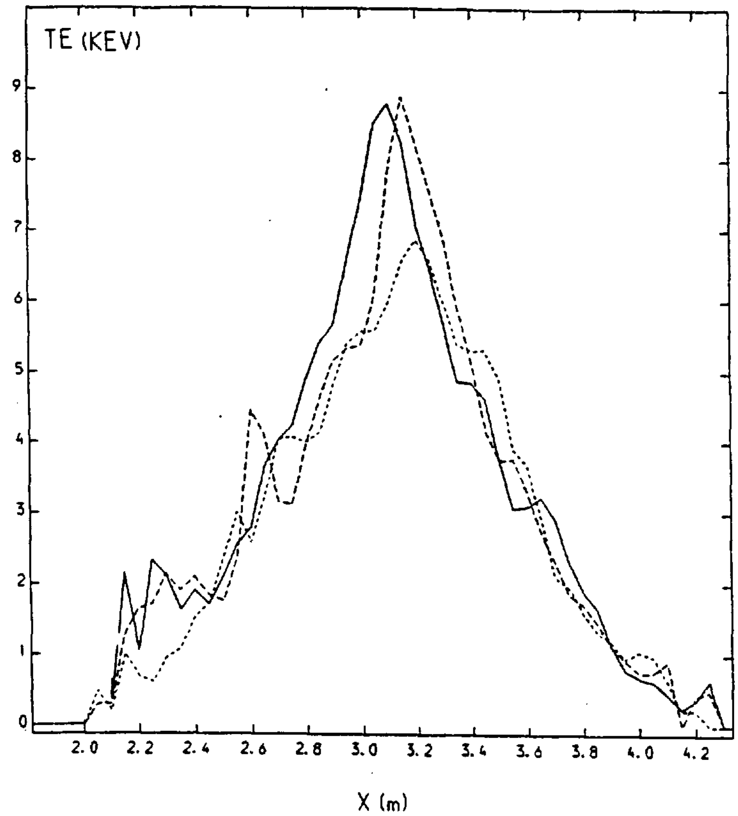

Fig. 10 - T_e profiles as measured by LIDAR, during LH (- , --) and in the ICRH only phase (——) for pulse 24966.

conditions, arcing at the grill mouth and in the multijunctions arise more and more often as machine conditions deteriorate, in particular as the base pressure increases and in consequence of disruptions. This suggests that alternative schemes to the multijunction concept must be developed in view of applying LH systems to the Next Step. In JET an "hyperguide" concept is under development, where the required spectrum is transported to the end part of the grill by high order mode propagation in highly oversized vacuum waveguides. Further quasi-optical systems are under consideration as a further step in the direction of optimizing the plasma launcher interaction.

References

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Acknowledgements

The contribution of Profile Control and RF Physics Groups, RF Division and the whole of the JET team is gratefully acknowledged.

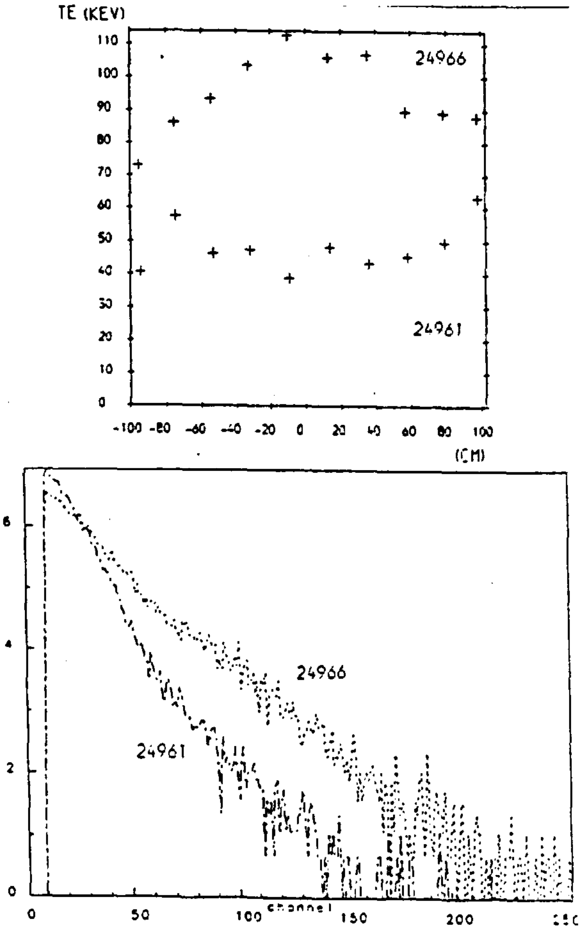

Fig. 11 - Radial profile of the "photon temperature" (top) and photon spectrum for LH only (# 24961) and LH+ICRH (# 24966). The x axis extends to 500 keV.

Appendix I

THE JET TEAM

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