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JET has successfully developed high power auxiliary systems: the Neutral Beam Injectors (NBI), the Ion Cyclotron Resonance Frequency (ICRF) waves and the Lower Hybrid Current Drive (LHCD) system [1]. The LHCD system has been the latest system developed and only a prototype system has been tested. This method is aimed at the control of the plasma current profile by driving a significant part of the plasma current alone or in combination with the other two additional heating methods.

The frequency of the LHCD system has been chosen to be 3.7 GHz both for technical and scientific reasons. Such a frequency belongs to the so called "microwave" domain. This paper will concentrate mainly on the description of the achieved results and on the prospects of LHCD on JET in accordance with the main topic of the workshop.

The paper will be organised as follows:

- description of the technical features of the JET prototype system;
- achieved results and main physics output. In particular the "synergistic" effects between Lower Hybrid waves and Ion Cyclotron waves will be summarised;
- description and status of the full LHCD system;
- prospects for the use of LHCD on JET for the next campaign and some considerations on the long-term aspects of Lower Hybrid Current Drive on a reactor.

1. THE JET LHCD PROTOTYPE SYSTEM

The characteristics of the prototype system have been described elsewhere [2] and are summarised in Table 1. The choice of the frequency (3.7 GHz) takes advantage of the technical developments made previously for Tore Supra [3] and

TABLE 1: LHCD Prototype (full system in brackets)

Frequency	3.7 GHz
Number of klystrons	8, (24)
Power (generator)	
10s pulse	4.8 MW
20s pulse	4 MW (12 MW)
Duty cycle	1/30
Efficiency	42%
Phase control	10 degrees accuracy
Maximum VSWR	1.8
Length of transmission line	40 m
Estimated insertion losses	1 dB
Number of waveguides	128, (384)
Waveguide material	stainless steel and ZiCo (stainless steel)
Coating	copper + carbon, (copper)
Maximum temperature	350°C
Total weight	12 tons (15)
Stroke	210 mm
Response	12 mm/15 ms
Maximum coupled power	2.4 MW

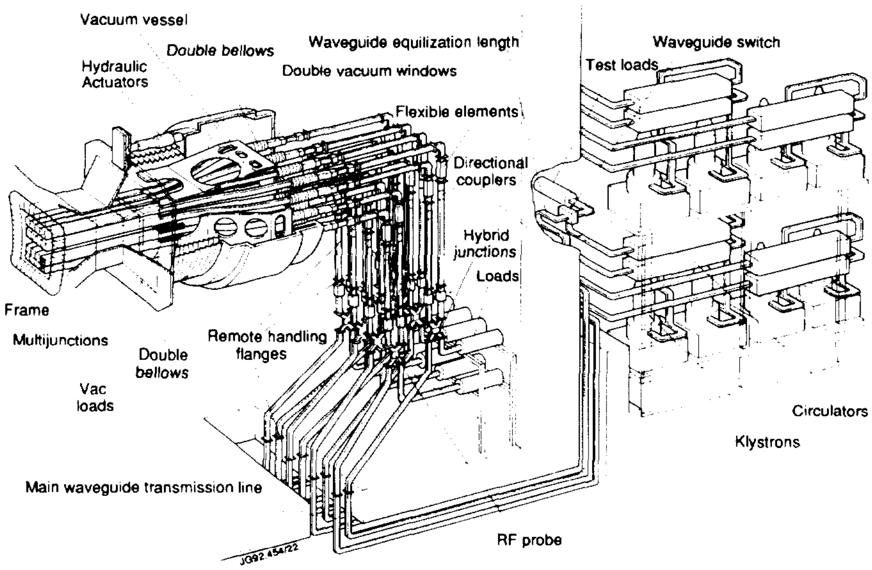

Fig.1 Schematic diagram of the LHCD prototype system

allows the wave to penetrate to the plasma centre for central densities up to $3\ 10^{19}\ m^{-3}$. The prototype system consists of 8 klystrons. The power generated by each klystron is split via one hybrid junction and 2 multi-junctions into 16 waveguides at the grill mouth as sketched in fig 1. The generation of a well defined and well controlled wave spectrum with a high directivity is essential for current drive applications. Therefore particular emphasis has been put on the control of the phase in each waveguide. The whole design of the JET LHCD system has been dictated by the constraints imposed by JET:

- no electronics in the torus hall;
- double tritium barrier;
- remote handling of sensitive parts;
- high degree of reliability;
- maximum automation of the control.

For instance the control of phase and amplitude has to be made far away from the torus (50m). Consequently, an accuracy of 10° in the phase control has only been achieved via a very tight control of mechanical dimensions of the splitting network and a sophisticated feedback control of the phase at the output of each klystron [4].

The resulting wave spectrum, as shown in fig 2, is centred at $N_{//} = 1.8$ with a width of $\Delta N_{//} = \pm\ 0.23$. The central value of the wave spectrum can be varied from 1.4 to 2.3 by varying the phasing between the multi-junctions from -90° to +90 °.

Eight of the multi-junctions were designed specifically for JET and are known as LOP (Launcher Zero, Physics) while the others were provided by CEN Cadarache using the same design as TORE SUPRA and are known as LOC (Launcher Zero, Cadarache). LOP is made of copper plated stainless steel, whereas LOC is made of zirconium copper. Both sets of multi-junctions were coated with a carbon anti-multipactor layer. They were also coated with a beryllium layer from the JET torus evaporators situated next to the launcher.

Operation with the JET machine started in June 1990 for an initial campaign of five months followed by a seven month machine shutdown to change a toroidal field coil. Operation resumed in June 1991. The second campaign ended in February 1992 with a shutdown to install the JET divertor coils. A total of 1700 pulses were achieved with JET plasmas during the two campaigns. Between campaigns the multi-junctions were inspected and found to be in generally good condition except for some flaking of the carbon anti-multipactor layer. The LHCD system operated on about 50% of all available plasma pulses. Where operation was not possible it was usually due to the plasma conditions being unsuitable rather than equipment failure.

During the first campaign power levels were mostly below 200 kW per klystron. The multi-junctions did not loose conditioning during the seven month shutdown between campaigns. At the start of the second campaign power levels increased slowly but steadily as the multi-junctions conditioned. During the second campaign two uncontrolled air leaks occurred on the torus while it was at its operating temperature of 350°C. These had a serious effect on LOC which was unable to recover its output power level. LOP on the other hand recovered with only minor reconditioning and went on to reach the maximum klystron power (650 KW) on some multi-junctions at the end of the campaign. This long conditioning time is attributed to the lack of proper baking, which is the only way for proper conditioning of the vacuum waveguides.

The achieved generator power on LOP was 2.05 MW compared with an installed capability of 2.4 MW with 1.75MW coupled to the plasma. LOC managed 1.5 MW generator power with 1.2 MW coupled to the plasma prior to the air leaks but only achieved 600 KW generator power after the air leaks.
Coupling of the launcher has been studied in a variety of plasma configurations including limiter and double null X-point plasmas (L-mode and H-mode) with different launcher positions. Coupling of Lower Hybrid Waves is a direct function of the density at the grill mouth. This density in turn depends upon the connection length of the magnetic field line, L//, near the launcher. The relevant coupling parameter is $d/L_{//}^{\frac{1}{2}}$ where d is the radial distance between the last close magnetic surface and the grill mouth. As shown in fig 3 there is a very good agreement with a detailed coupling theory [5].

In order to maintain a good coupling, which was required to achieve good power handling, the LH launcher is moveable by means of hydraulic actuators and flexible waveguides. The launcher can be moved during shots, following a preset position waveform or via a feedback control system, which adjusts the launcher position in order to maintain a requested power reflection coefficient for LOP. The position control with a preset position waveform was used during the 7MA shots in JET, where LH power was applied during the ramp up of the plasma current in order to save flux from the ohmic transformer. As the plasma elongation increased, the plasma edge moved inwards and the launcher was requested to follow the plasma movement by moving from 3mm behind the ICRH antennae to 25mm in front of the antennae with a speed of 10mm/s (fig 4).

The use of the feedback control system for the launcher position is exemplified in fig 5. The requested reflection coefficient for LOP was set to 10% in order to avoid trips due to the proximity to the plasma, especially for LOC. The feedback system was allowed to adjust the position within ±3mm from the preset position waveform, which in this case was constant, 4mm behind the ICRH antennae. The position of the plasma was constant, but as the electron density increased the reflection coefficient tends to decrease and as a result the launcher moved outwards.[6,7].

2. PHYSICS RESULTS

Although limited to 2.4 MW of coupled power, operation of the prototype launcher has brought a large amount of physics data reported in several conferences. In particular, the LHCD system has been used as a tool for several applications such as

- obtaining a one minute pulse duration discharge at 2MA where the application of 1MW of LH power for 50 sec has been instrumental in achieving these long pulses [8].

- Flux saving of 2V/s from the application of 1.5 MW of LH power during the low density current ramp-up phase of 7 MA limiter plasmas [9], allowing extension of the current flat top by 2 sec to a total duration of 9 sec.

Full current drive data and synergystic effects between Lower Hybrid and Ion cyclotron waves have been specifically studied [10,11,12]. Full non inductive sustainment of the current has been achieved up to:

- 0.4 MA with LH only;
- 1.5 MA for 6 sec and 2 MA for 1.5 sec in ICRF heated limiter plasmas.

Full current drive has been achieved in conditions where the LH waves can propagate to the plasma centre i.e. with the highest magnetic field (3.4 T) and central density lower than 3 $10^{19}m^{-3}$, as anticipated from theoretical considerations.

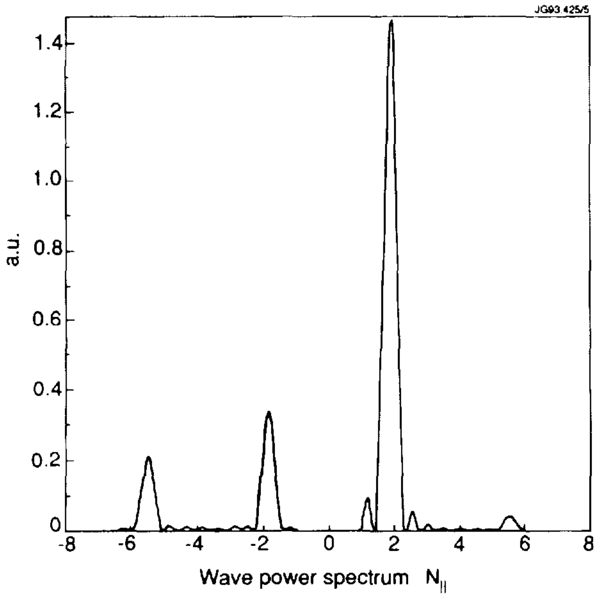

Fig. 2: Wave spectrum of the Prototype Launcher

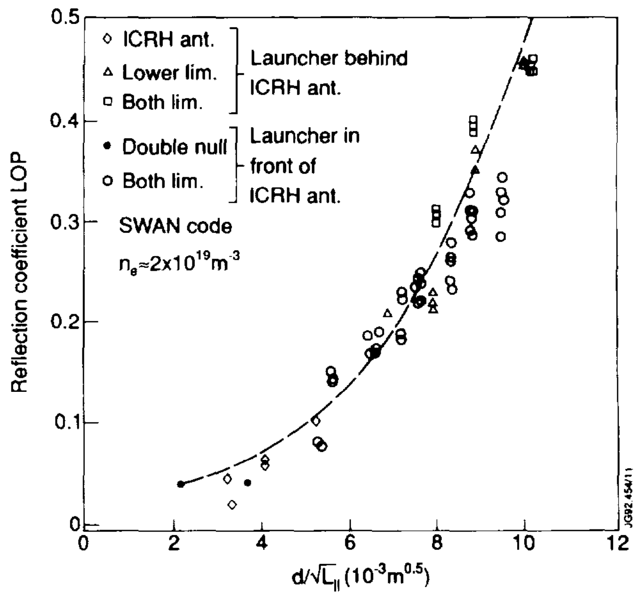

Fig. 3: Reflection coefficient versus $dL_{//}^{-0.5}$ and comparison with the SWAN coupling code

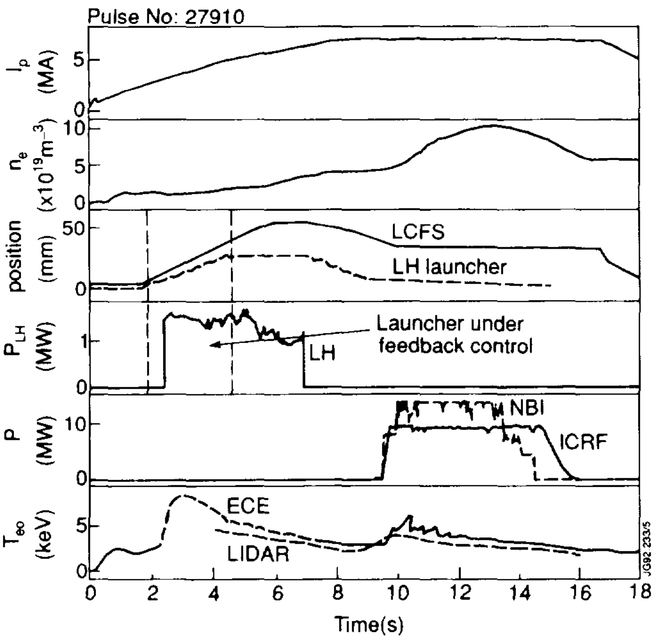

Fig.4: Combined operations of LHCD, ICRH and NBI during the long 7MA discharge.

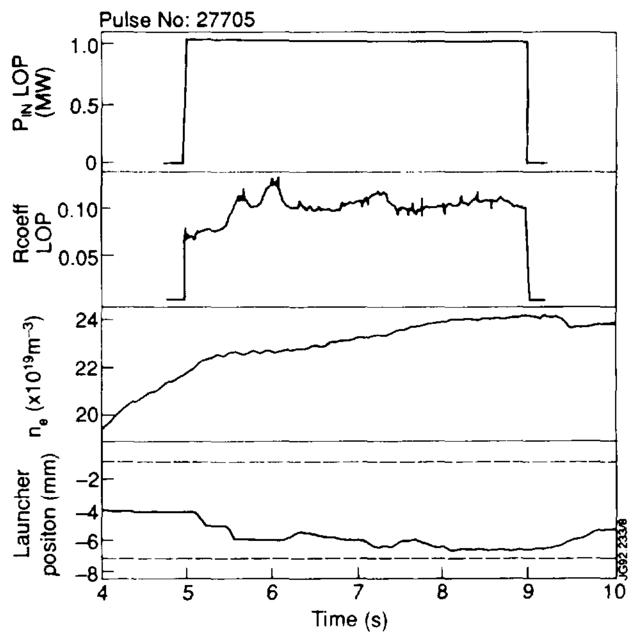

Fig. 5: Feedback control system for the launcher position - the reflection coefficient was set at 10%

In fig 6, LHCD power is applied after ramping down the plasma current from 3 to 1.5 MA in order to achieve a target plasma with higher internal inductance, ℓ_i, and more peaked electron temperature. During LHCD, the loop voltage is negative and ℓ_i is roughly constant or even increases. In addition, a reversal of the sign of the derivative of the primary current is observed indicating that some magnetic energy is supplied both to the plasma and to the transformer. The radial profile of the X-ray emissivity induced by fast electrons is very similar to the plasma current profile as determined from a combination of magnetic analysis and polarimetry measurements and no transients in loop voltage are observed.

In similar conditions, a 2 MA plasma is sustained with zero resistive loop voltage, no driving flux from the primary and constant plasma energy with 2 MW of LH power for about 1.5 second. This time duration is limited by density increase and by trips in the LHCD system.

The time duration of full LHCD current drive is limited by the toroidal field plateau available on JET at high magnetic field (8s). A maximum time of 6s at 1.5 MA with zero resistive loop voltage has been achieved [8]. This limited duration prevents the study of current diffusion.

An example of full current drive in combined LHCD and ICRF heated plasma in an X-point configuration is shown in fig. 7. Throughout all the ELMY phase of the H-mode, the loop voltage is zero, ℓ_i is constant and no primary flux is consumed. The central density reaches 3.6 10^{19} m^{-3} and the poloidal beta a value of 0.74 with a corresponding bootstrap current estimated to be about 40% of the total current. Quasi-stationary conditions are maintained up to the onset of the ELM-free H-mode phase where the density increases.

In some combined ICRF LHCD discharges, synergy between the two waves was quite apparent. The "signature" for such synergy is an acceleration of fast electrons in excess of the 1 MeV range, well above the expected range of acceleration in conditions where the full current was driven by the LH wave field in the absence of ohmic electric field. In these conditions, the total amount of driven current was above the values anticipated from theoretical considerations.

A 19 channel hard X-ray camera is the main tool for estimating the radial electron distribution. As shown in fig 8, photon energy distributions are given for two shots with full current drive with and without ICRF. This acceleration of electrons, in the presence of ICRF, beyond the domain of velocities corresponding to the LHCD parallel wave spectrum (100 keV), in the absence of electric field is

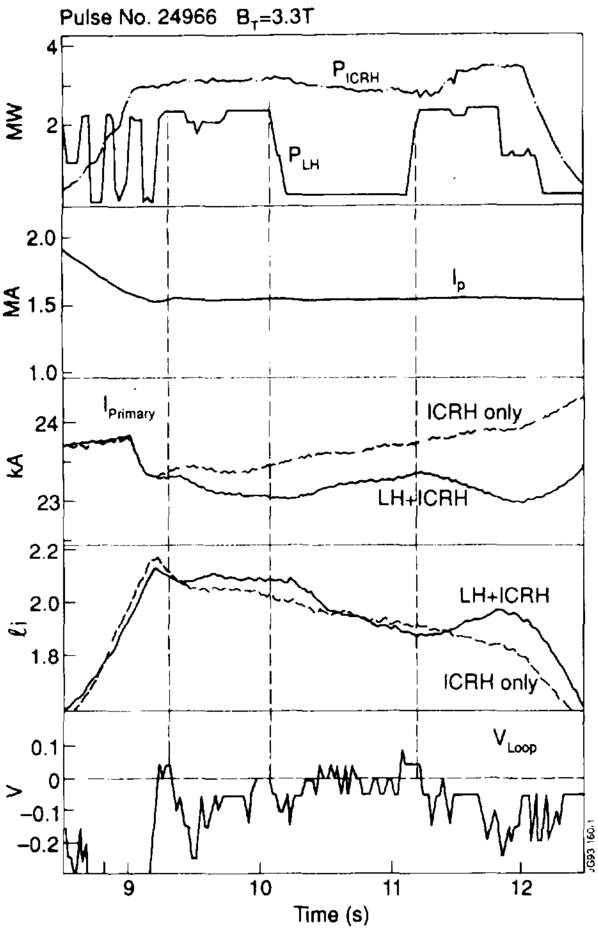

Fig.6: Full Current Drive in 1.5MA limiter plasma

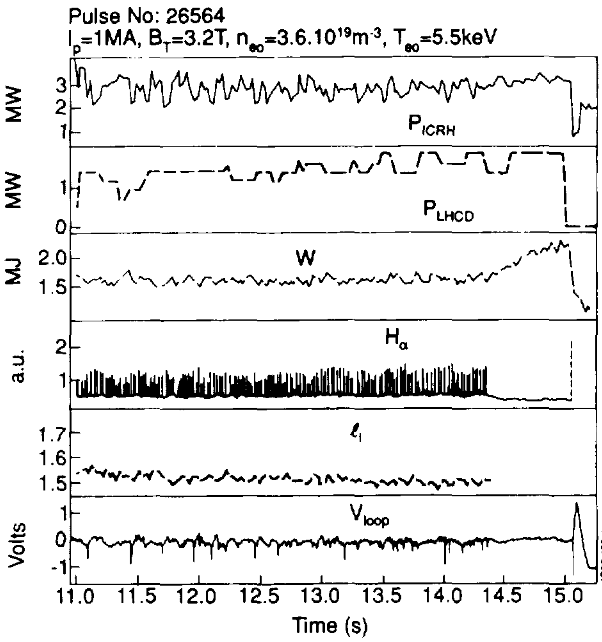

Fig.7: Full Current Drive in 1MA H-mode plasma

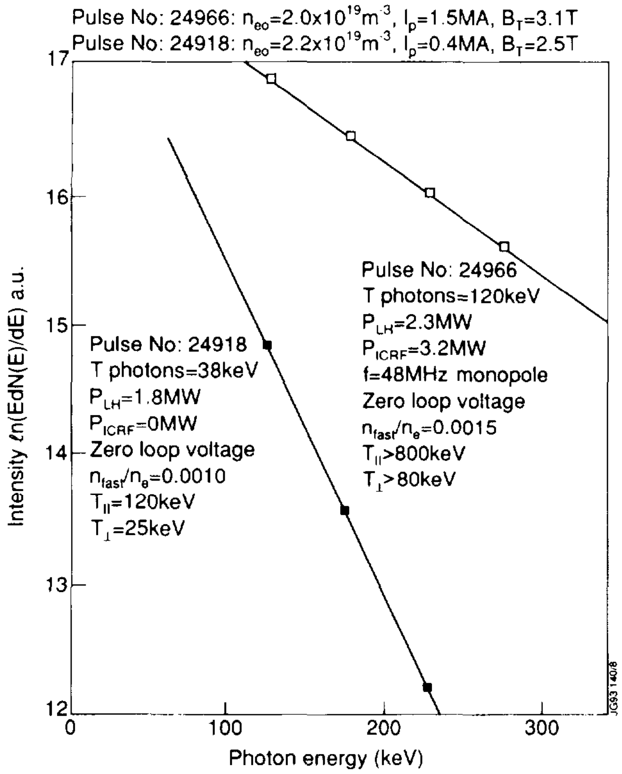

Fig.8: Photon temperature at zero loop voltage with and without ICRF

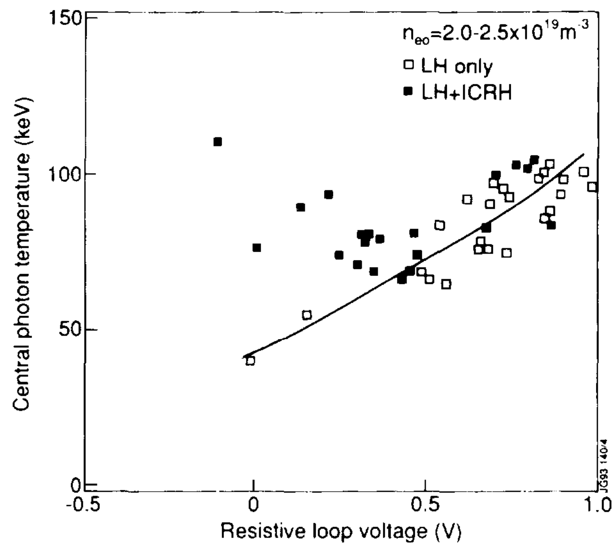

Fig.9: Central photon temperature versus resistive loop voltage

the "signature" of the synergism which is described in this paper. As shown in fig 9, high photon temperatures can be achieved when the loop voltage is not zero, as anticipated from electric field acceleration.

This synergism is further confirmed by calculations carried out with an LHCD numerical simulation code [13]. The physics of Lower Hybrid waves is modelled via a ray-trajectory method, with the dispersion relation including both the electromagnetic part and thermal corrections. The electron distribution function is calculated by the two-dimensional relativistic Fokker-Planck equation, taking into account effects due to spatial fast electron diffusion and the residual toroidal electric field. In this model, the diffusion of fast electrons is due to the stochasticity of the magnetic field. Typical values of the diffusion coefficient are 0.5 m^2/s for thermal electrons and 1.5 m^2/s for 100 keV electrons. The output of the code is then used to simulate the hard X-ray spectrum emitted by the suprathermal population and compared with the output of the FEB camera. In fig 10a the results are shown for 4 different pulses: LHCD only at zero loop voltage, LHCD only at moderate power with residual electric field, LHCD only at high electron temperature (8 keV) and residual electric field, and finally (fig 10b) a combined LHCD-ICRF pulse at zero loop voltage. All cases with LHCD only are very well simulated, with only a small discrepancy at the plasma centre in the high electron temperature case: the large discrepancy between computation and experimental data in the LHCD-ICRF combined pulse is attributed to the synergism.

This synergism can also be substantiated from the estimation of the power coupled to the bulk electrons from electron power balance during LH power modulation with and without ICRF [14]. About 80% of the LH power is estimated to be coupled to the bulk electrons in pulses with LHCD alone. The power coupled to the electrons can slightly exceed the launched LH power in ICRF heated discharges in some specific conditions, as discussed later. Although error bars are large (±20%), there is a systematic difference between coupled power when synergism is present.

When synergism is observed, current drive efficiencies can be high. When the plasma current is fully non-inductively driven, the non-inductive current drive efficiency has been calculated in two ways [1]:

- an engineering efficiency $\gamma_{eng} = \frac{\bar{n}_e R I_p}{P_{LHCD} + P_{ICRF}}$

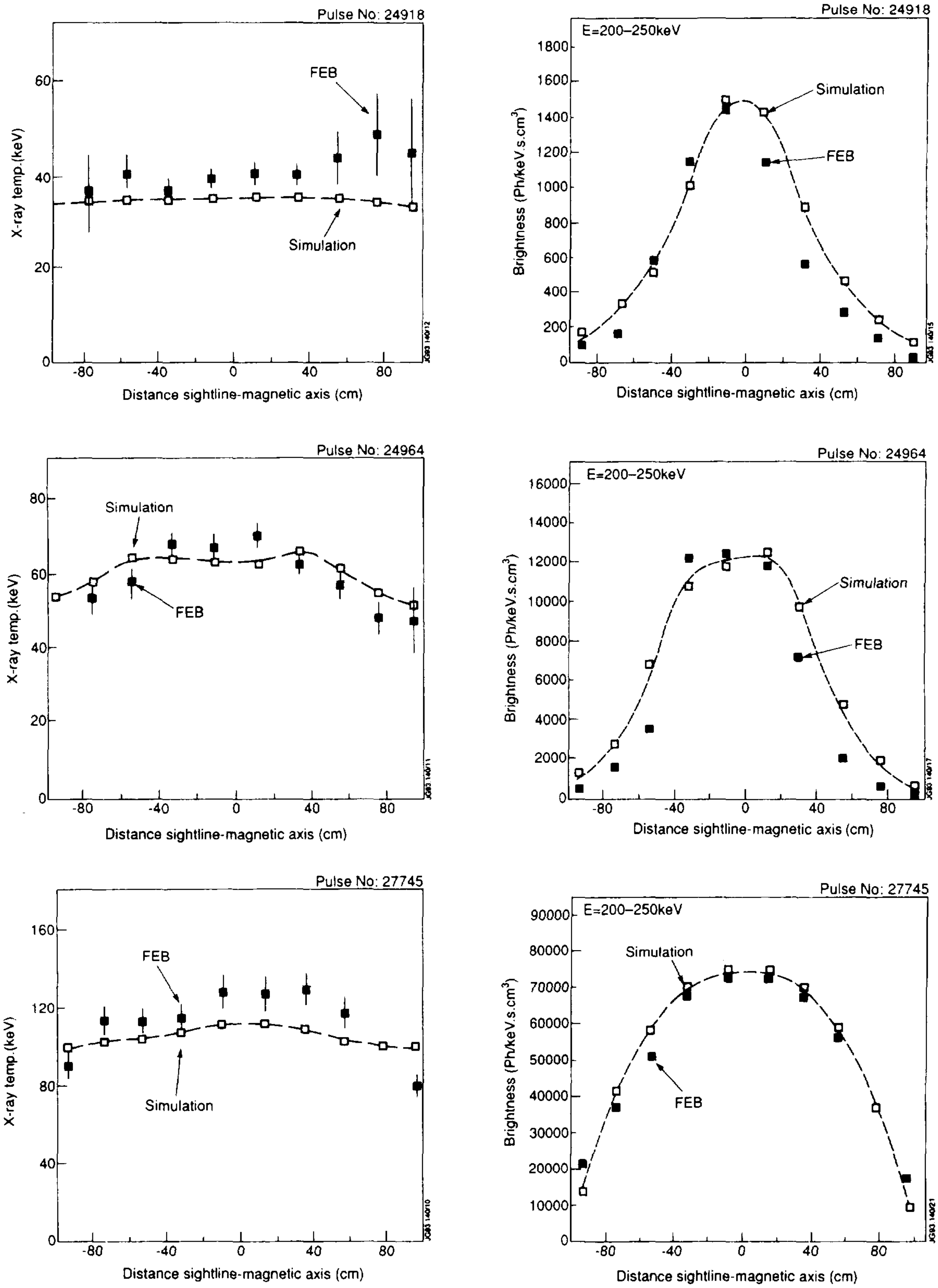

Fig. 10a Comparison between FEB chord integrated signals and ray tracing simulation code.

I_p(MA)	B_T(T)	n_{eo}($10^{19}m^{-3}$)	T_{eo}(keV)	P_{LH}(MW)	P_{ICRF}(MW)	V_{Res}(V)
#24918 0.4	2.5	2.2	1	1.8	0	0
#24964 1.5	3.3	2.2	3	1.1	0	0.1
#27745 3.1	3.3	1.3	8	1.3	0	0.3

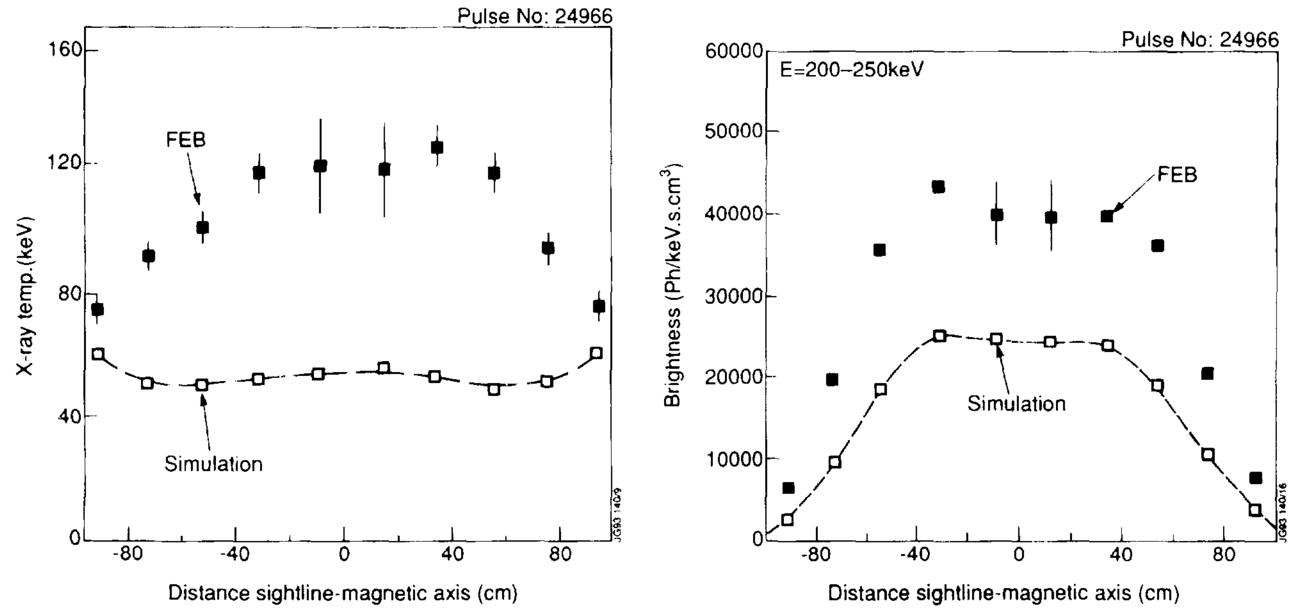

Fig.10b: Comparison between X-ray chord integrated signals and simulation code:
I_p = 1.5MA, B = 3.1T, n_{eo} = 2 10^{19} m^{-3}, T_{eo} = 8 keV,
P_{LH} = 2.3 MW, P_{ICRF} = 3.2 MW, V_{Res} = 0

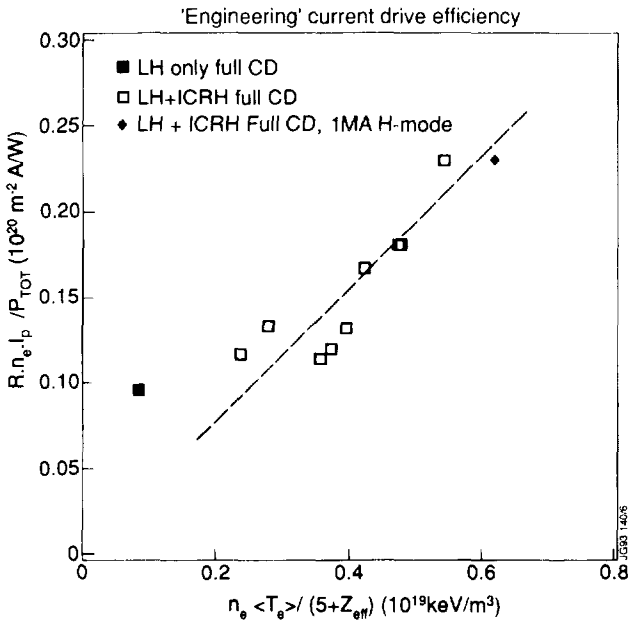

Fig.11: γ_{eng} versus $n_e < T_e >(5 + Zeff)$

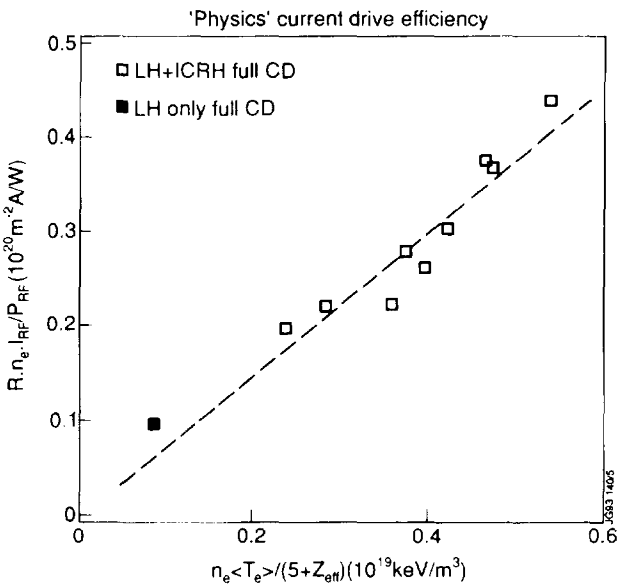

Fig.12 γ_{phy} versus n_e <Te>/(5 Zeff)

- a physics efficiency $\gamma_{phy} = \frac{\bar{n}_e R I_{RF}}{P_{LHCD} + P_{syn}}$ where $I_{RF} = I_p - I_{BS}$ (I_{BS} being the estimated bootstrap current) and P_{syn} being the part of the ICRF power which is transferred by synergy to the fast electrons created by LHCD. P_{syn} is determined from electron power balance as discussed above.

As discussed in [11], these efficiencies present a large scatter for full current drive when plotted against $<T_e>/(5 + Z_{eff})$, as in JT-60. This scattering disappears when data are plotted against $n_e <T_e>/(5 + Z_{eff})$ as in fig.11 and 12. No apparent saturation in γ_{eng} is observed in the domain of operation, i.e. for central densities up to 3.6 10^{19} m^{-3}. It is not clear if these features: (i) absence of saturation (ii) linear dependence with plasma pressure, are also a signature of the LHCD - ICRF synergism.

The already achieved high current drive efficiencies together with their apparent absence of saturation are very encouraging and we shall try to understand the underlying physics mechanism in order to optimise and make the full benefit of this synergy.

A decisive proof of principle experiment is still missing. With the experimental conditions, the density of the fast electron population is estimated to be rather low ($n_{fast}/n_e \cong 0.0015$) so the damping of ICRF wave on fast electrons via Transit Time Magnetic Pumping is unlikely to occur. Results from specific experiments:

- scan of ICRF power (fig 13) showing that up to 20% of the ICRF power can be transferred to the electron population;

- variation of the ICRF wave spectrum (fig 14) comparing very different k// spectrum;

- comparison between radial profiles of the photon temperature with and without ICRF (fig.15).

are all supporting the damping of an Ion Bernstein Wave created via mode conversion of the Fast ICRF wave at the ion-ion hybrid resonance layer [1]. This wave (IBW) has a low N// at birth and can be damped on a pre-existing fast electron population before being upshifted along its ray trajectory, as indicated in

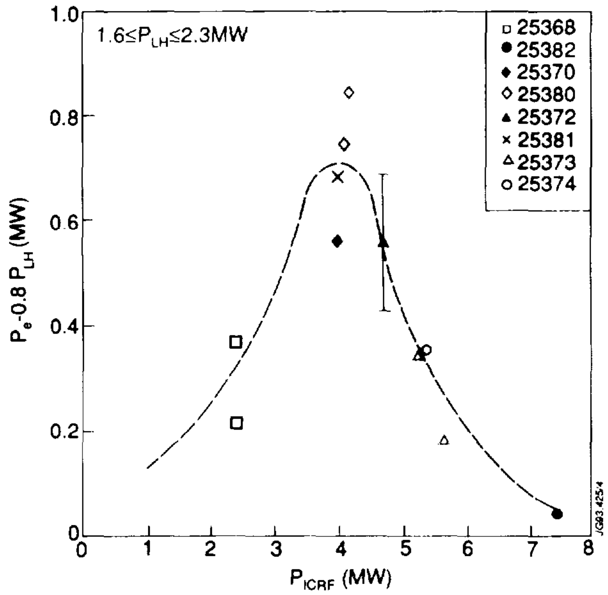

Fig.13: ICRF power coupled to electron (B = 3.4T, n_{eo} = 2 10^{19} m-3

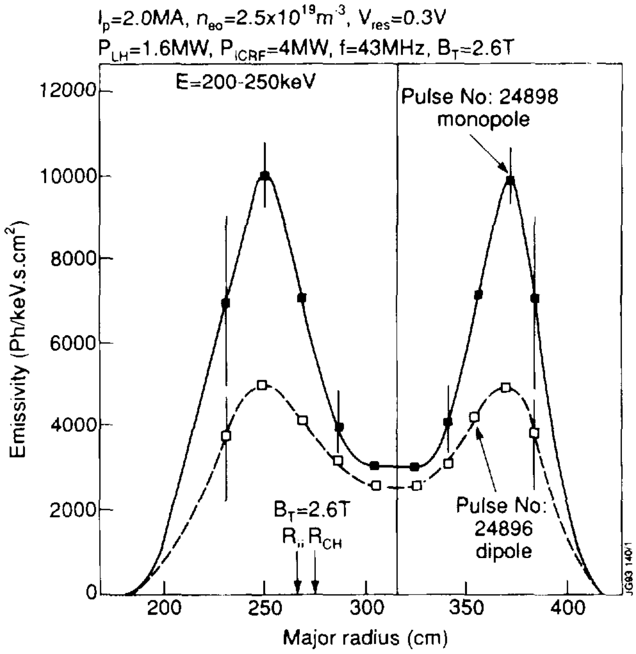

Fig.14: Comparison monopole dipole. R_{ii} corresponds to the ion-ion hybrid layer

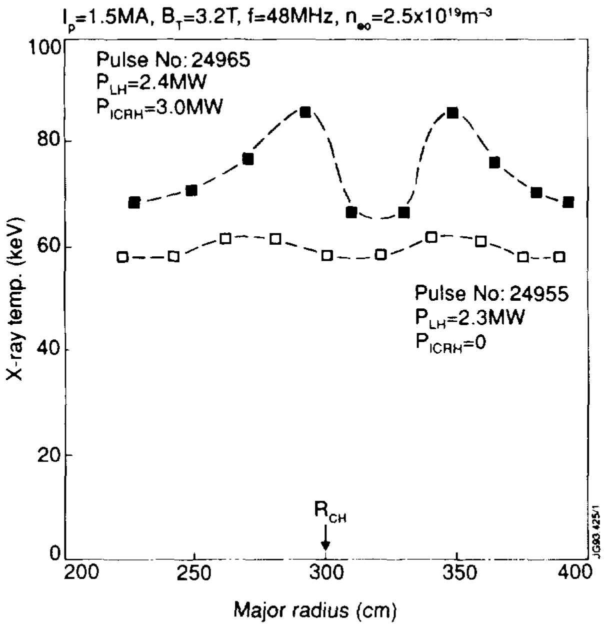

Fig.15: Comparison between ICRF and non ICRF X-ray profiles

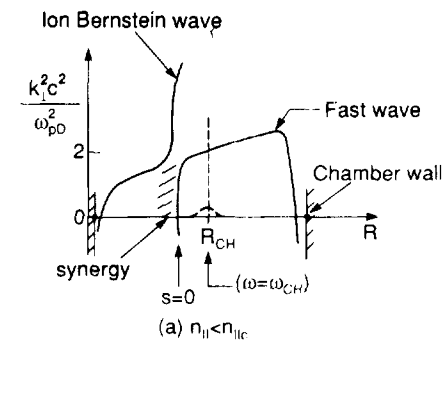

Fig.16: Mode conversion of an ICRF Fast Wave into an Ion Bernstein wave

Fig 16. This scheme has been discussed by Jacquinot in [1] indicating that up to 25% of the ICRF power at a given $N_{//}$ can be converted in an IBW in optimum conditions: (i) low $N_{//}$ values for which damping at the resonance layer is not too high, (ii) low minority concentrations (≤ 10%) so that the distance between cut-off and ion-ion hybrid layer remains small compared with the wavelength to allow tunnelling through the cut-off region, (iii) low fast ion tail energy to keep the minority damping low and to avoid blurring the ion-ion hybrid layer by the resonance layer.

The acceleration of LH fast electrons[15], which might take place near the ion-ion hybrid layer if the fast electron population is high enough (large LH power or peaked profiles) and if the Döppler broadening of the minority resonance is not too large (which occurs at high ICRF power with a low minority concentration) support the hypothesis of mode conversion to IBW. The observed localisation of synergistic effects is a strong experimental fact supporting mode conversion to IBW as the mechanism creating the synergy. However, preliminary quantitative calculations indicate that the mode converted power is lower than the experimental power coupled from ICRF to the electron population.

3. THE FULL JET LHCD SYSTEM

The characteristics of the full JET LHCD system are also listed in Table 1. It will have 3 times more power capability than the prototype with a narrower wave spectrum with 32 waveguides in an horizontal row instead of 16, the width of the spectrum $\Delta N_{//}$ is 0.13. The full launcher, L1, has been assembled and tested at high power at the level of 100 kW for 2 sec per multi-junction in vacuum. A photograph of the L1 mouth can be seen in fig 17. As sketched in fig 18, the L1 launcher will be equipped with a 100 000 l/s cryopump allowing for a proper pumping in the L1 vacuum vessel during initial conditioning and during long time duration high power pulses.

In order to achieve a speedier conditioning than during the previous JET campaigns, a procedure to produce heating of the vacuum waveguides through HF losses of the microwave power has been set up. It is intended to increase the temperature of the waveguides by 50 to 100° C above the operating temperature to insure a proper baking. For that purpose, HF will be launched into vacuum and high power loads (250kW) will be installed in the Torus Hall, behind the hybrid junctions. A new gas introduction system close to the L1 mouth is being prepared in order to increase the local density.

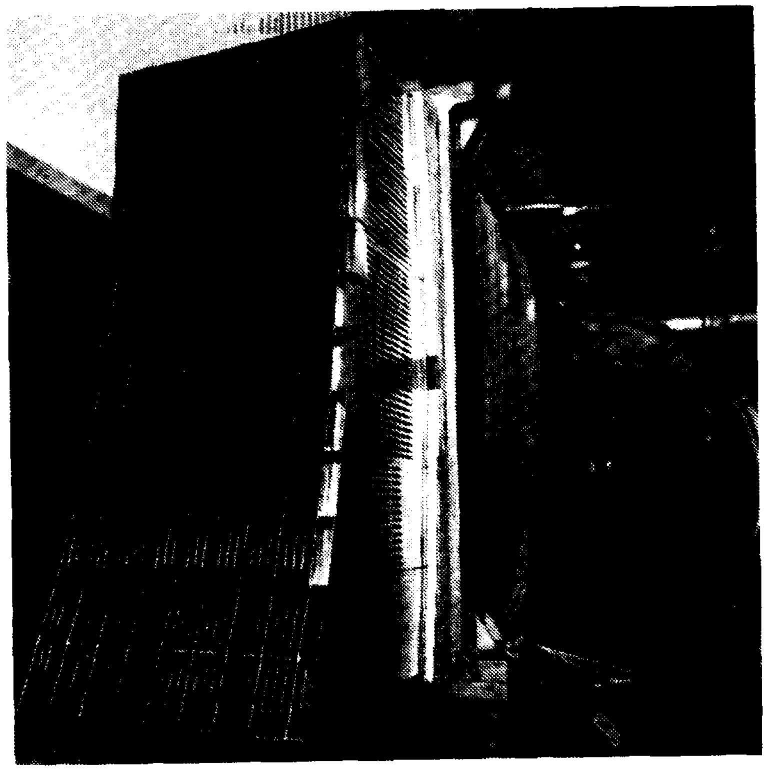

Fig.17: View of the L1 launcher mouth

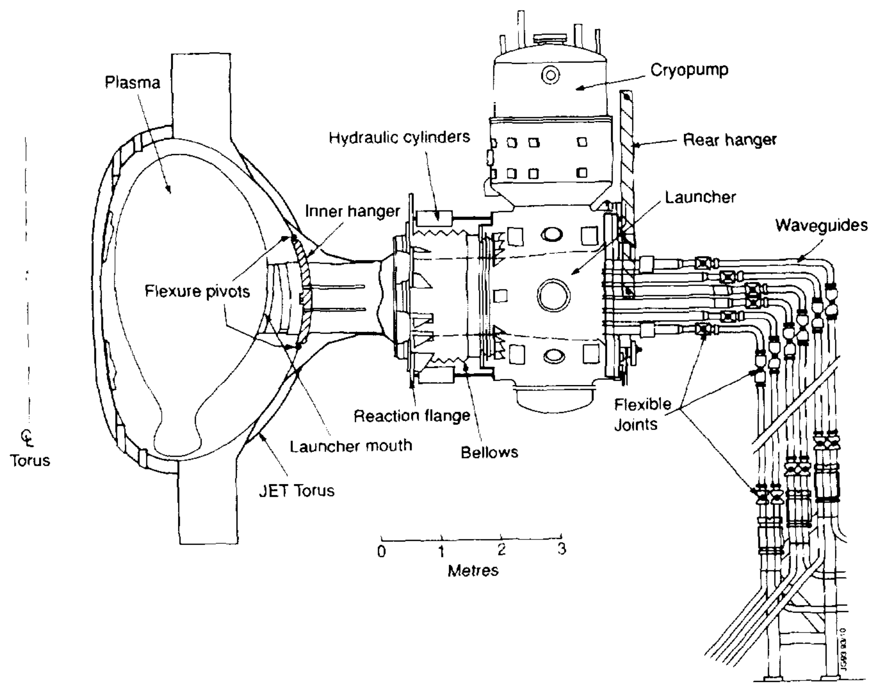

Fig.18: Sketch of the full LHCD system

The new L1 launcher will be installed in JET during the present shutdown. Among the main modifications which are being done, the new pumped divertor configuration and the new set of ICRF antennae with their new phasing capability will have a significant impact on the operation of the LHCD system. A sketch of these new systems is shown in fig 19.

The new divertor configuration will allow longer connecting lengths for the magnetic field lines linking the grill mouth to the plasma configuration. The sensitivity of the launcher radial location to the plasma coupling should be consequently be reduced.

The new A2 antennae being grouped in modules of 4 adjacent straps will have a narrower spectrum. It will be possible to superimpose both wave spectra, as shown in fig.20, by setting a 40° phasing between straps, indicating that a gain by a factor of 2 in the available "synergistic" power appears possible.

Note that optimum synergism has been obtained with $P_{ICRF} \approx 1.5\text{–}2\ P_{LHCD}$, but synergistic effects disappeared for ICRF power above 4 MW in the last JET experiments. If mode conversion is the mechanism responsible for synergy, some scenarios will have to be developed in order to use the respective maximum power of 20MW and 10MW for ICRF and LHCD systems, for instance by spreading the synergy area by using slightly different frequencies for the ICRF system or by using ^3He as a minority for damping the ICRF wave.

It is also to be noted that special emphasis will be given to the use of feedback loops including:

- active feedback on the plasma position control combined with the L_1 launcher position control;
- active feedback on the total power of the LH plant;
- possibly active feedback on the phase between multi-junctions in order to maintain some control on the current profile.

4. PROSPECTS

Several studies have been made for the prospective use of Lower Hybrid waves in a reactor. They have been summarised in [16]. Although LH waves can be used as a very effective electron heating system, as shown in Tore Supra [17], their best role remains to produce non-inductive current drive. Present LHCD efficiencies are higher, by at least one order of magnitude, than efficiencies

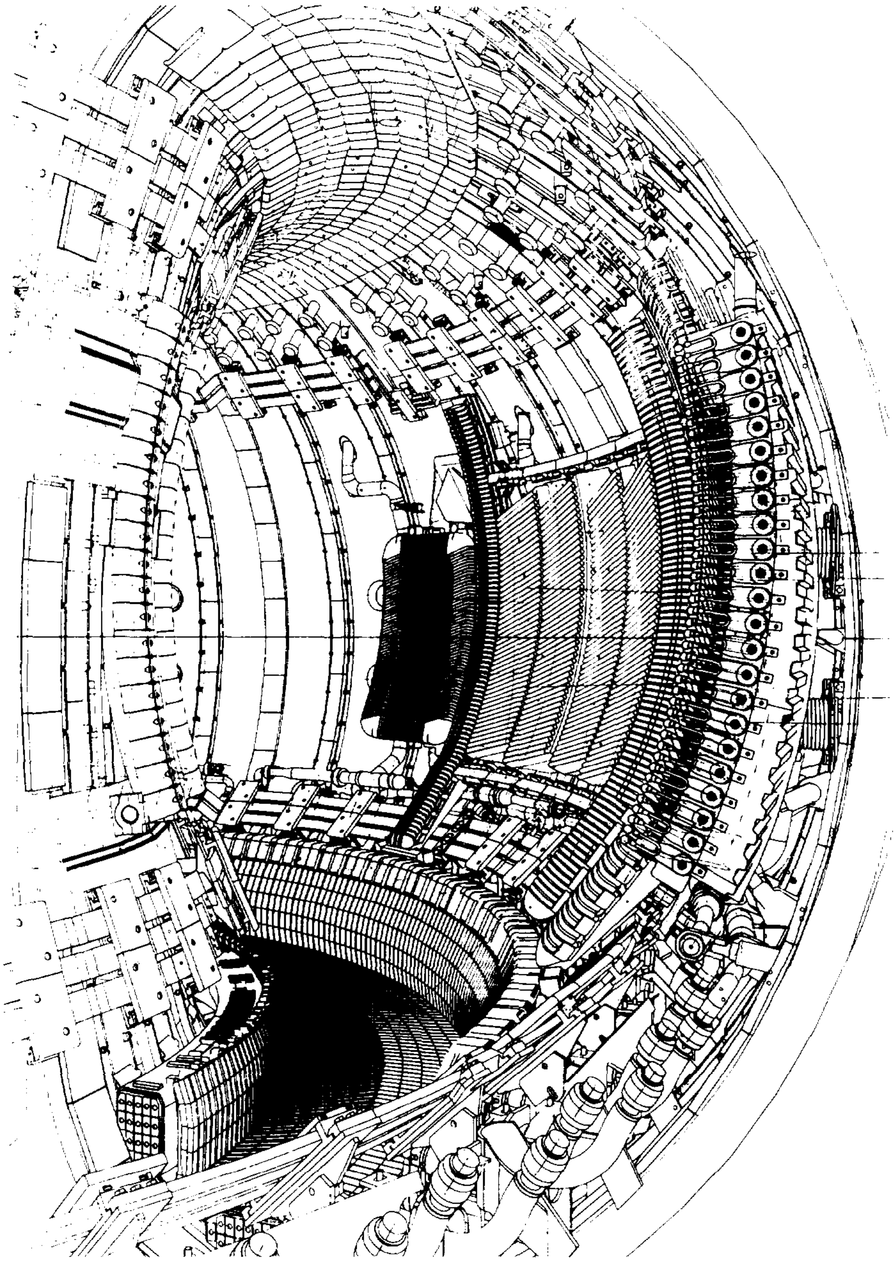

Fig.19: The new JET configuration

achieved with other methods. A record full driven current of 3.6MA with LHCD has been achieved recently in JT-60U [18].

Studies made for NET and ITER indicate that the frequency of an LHCD system should be in the range 5 to 8 GHz. Therefore, the corresponding coupler should be composed of thousands of waveguides. Several proposals have been made to overcome that difficulty, including launching LH slow waves via a quasi-optical grill [19]. JET is studying a solution using a transfer cavity: the hyperguide [20] between the grill mouth and the rest of the system as sketched in fig 21. The advantages of such a hyperguide are several:

- The mouthpiece is decoupled from the rest of the cavity, and can therefore be modified or replaced without requiring the rest of the system to be dismantled using remote handling techniques.

- The structures required in a hyperguide launcher are much lighter, simpler and cheaper to manufacture than in the conventional approaches.

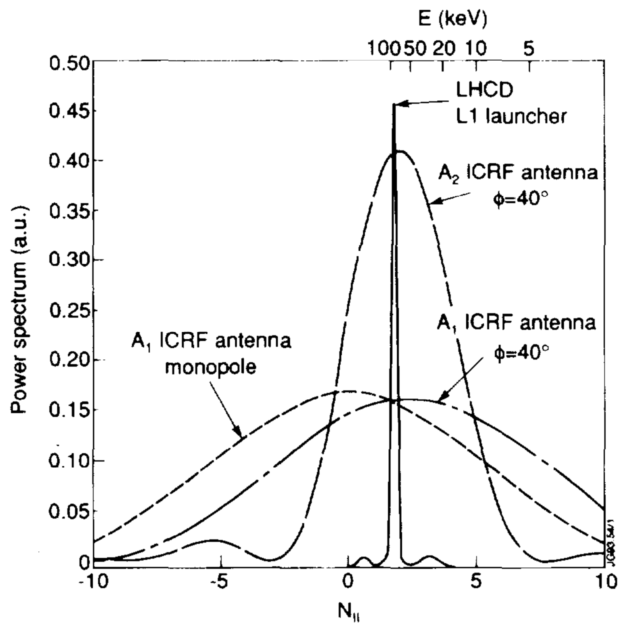

Fig.20: Wave spectrum of the L1 launcher and of the A1 and A2 antenna respectively

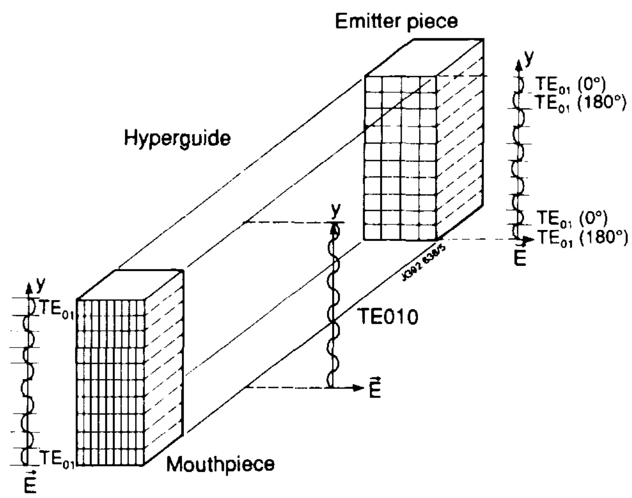

Fig.21: Principle of an hyperguide transfer cavity

- The hyperguide surface exposed to the microwave power is smaller than in the other types of antennas, and the cavity is much easier to pump. A hyperguide cavity replacing the present multi-junction system installed at JET would have an exposed surface area 4 times smaller than at present not including the mouthpiece. As the power goes through the electron cyclotron resonance within the hyperguide, this could solve the power handling problems linked to the accumulation of gas.

- Finally, as the hyperguide is not a resonant cavity, there is no inconvenience in extending its length. It is conceivable therefore to place the emitter surface outside the main shielding of the machine, allowing the vacuum windows and the associated electronics to be outside the high radiation area. In the same way, the possibility of replacing the numerous individual windows by a single one installed inside the hyperguide would further simplify the system and improve its reliability.

A low power hyperguide prototype is being prepared and will be tested at JET. It might lead, if successful, to a simplified version of L_1 allowing the LHCD system to accommodate smaller magnetic configurations.

It has been shown that the non-inductive current drive efficiency which is required to maintain an ignited steady-state reactor of the ITER EDA type, with a low aspect ratio and high plasma current, shall exceed $\gamma = 1.2\ 10^{20}\ m^{-2}$ A/W for densities in the range required for divertor operation [1,21]. The anticipated current drive efficiencies do not exceed about $\gamma = 0.5\ 10^{20} m^{-2}$ A/W for LHCD and for any other conventional method. Therefore, full current drive in a reactor can only be expected for high bootstrap current devices with improved confinement, i.e. low plasma current, unless much higher current drive efficiencies can be achieved.

A route to increase non-inductive current drive efficiency is to maintain the current with very high energy electrons, to avoid collisions even at the density required in a reactor. Fast electrons induced by LHCD have their energy limited to about 100 keV due to accessibility conditions. Acceleration of these electrons by a Fast Wave is a very attractive scheme. Synergy with Electron cyclotron waves as proposed for Tore Supra can also be an attractive scheme provided that electrons can be accelerated into the MeV range.

One of the aims in the next JET experimental campaign is to assess if this synergism can be used to achieve the current drive efficiencies required in an ITER type reactor, in plasma conditions which are reactor relevant. In addition to experiments aimed at a better identification of the physics mechanisms of the synergy, it will be attempted to extend the operational range for which this synergy is effective to higher densities ($n_{eo} > 3\ 10^{19}\ m^{-3}$) and to identify ways of coupling a larger amount of ICRF power to the fast electron population.

Current profile control using Lower Hybrid waves is a major ingredient of the so called "advanced" tokamaks scenarios where most of the plasma current is produced via the bootstrap current. It can be shown that these "advanced" scenarios require operating the plasma at very high values of the ratio $\beta_N = \frac{aB}{I}\beta_t$ for which stability can only possibly be achieved if the plasma current profile is properly tailored.

The new LHCD experiments on JET during the next operational phase will not only allow a better understanding of the physics of a large tokamak but should help to assess the potential application of Lower Hybrid waves to a reactor type plasma.

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