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ABSTRACT

Lower Hybrid current drive (LHCD) experiments were performed in JET in a first stage with one third of the final LHCD system. Good coupling with reflection coefficients as low as 1% and a power density of ~4 kW/cm^2 on the plasma interface were obtained with the prototype launcher. The complete LHCD system with a total power of 12 MW (20 s) in the generator will start operation with the begin of JET divertor experiments in early 1994. The full launcher contains an array of 384 waveguides, built up from 48 multijunctions with internal power splitting. Three different LH wave spectra can be radiated simultaneously into the plasma, applying different phase settings to the three independent sections of the grill type antenna. Testbed experiments have started on a new concept for a compact LH launcher, using a hyperguide as connection between an array of standard size waveguides and the plasma facing antenna structure which forms the slow wave LH spectrum.

CONTENTS

1. INTRODUCTION

Lower Hybrid current drive (LHCD) on JET aims at active control of the plasma current profile. It provides the potential for steady state operation in high confinement modes, together with the other sources for noninductive current drive (Fast Wave Current Drive, Neutral Beam Injection, Bootstrap Current). An LH system with a total power of 15 MW in the generator was built up with 24 klystrons at a frequency of 3.7 GHz [1]. First experiments were performed with a prototype launcher (L0), delivering up to 2.4 MW power coupled to the plasma from 8 klystrons. With the addition of 1.5 MW LHCD power during the Ohmic current ramp-up a flux of 2 Vs could be saved. The full plasma current was driven by LHCD alone in a 0.4 MA discharge. In combination with Ion Cyclotron Heating (ICRH) a discharge with 2 MA plasma current could be sustained for 1 minute. Record current drive efficiencies were obtained due to synergy with ICRH, with values up to η_{CD} = 0.44 (10^{20} $Am^{-2}W^{-1}$) [2]. This comes already close to the requirements for an application of noninductive current drive to reactor grade plasmas like in ITER. Future systems with a large number of rf tubes at high power, however, need also a further simplification in the power transmission and the coupling structure.

This paper describes the layout of the LH launcher system, operational experience with the prototype antennae and new technical developments of a compact power transmission system on JET.

2. LAYOUT OF THE JET LHCD LAUNCHER SYSTEMS

The LH power is supplied by a plant of 24 klystrons with a maximum power output of 650 kW each, at 3.7 GHz [3]. The launcher is fed through 40 m transmission lines containing slightly oversized waveguides (77.2 x 38.6 mm). At the front end an array of narrow waveguides (72 x 9 mm internal dimensions, 2 mm walls), the so-called grill, radiates slow LH waves with a parallel refractive index $N_{||} > 1$ into the plasma. The design of the LH system on JET is heavily influenced by the constraints arising from the final tritium phase. All penetrations into the primary torus vacuum need double tritium tight barriers. No electronics can be used inside the torus hall. All components in the torus hall have to be radiation resistant. All maintenance and repair has to be carried out remotely by robots. Specific solutions had to be developed therefore for many parts. A high degree of reliability is required for all systems and operations control is being automated to a maximum.

2.1. General Features of the JET LH Launcher

The different components are seen from Fig. 1. The power of each klystron is split after the penetration into the torus hall in 2 lines by a hybrid junction, with high power (250 kW/dc) loads on the fourth port. Three flexible joints in each transmission line provide a stroke of 300 mm for displacements of the launcher in the radial direction. Double BeO pill box windows of a quarter wavelength thickness separate the pressurised transmission lines (2 bar SF_6) from the torus vacuum (10^{-7} mbar). The interspace is kept at UHV by ion getter pumps. Arc detectors monitor the vacuum side of the rf windows. A focusing optics transmits eventual light emission from the window surface through a fiber onto diodes outside the torus hall. After the vacuum transition the power is split from each input waveguide into 8 narrow size output waveguides within multijunction modules as shown in Fig. 2. The incoming forward power is first split vertically into two superposed lines in an H-plane junction and then further divided horizontally in each level into 4 narrow waveguides by E-plane junctions. The phase between horizontally adjacent waveguides is set at 90° by step transformers. The fourth port in the H-plane junction is fitted with a vacuum matched load in order to maintain equal vertical power distribution in the case of imbalanced reflection. The multijunctions are manufactured from stainless steel and internally coated with a 15 μm Cu layer. The whole stack of multijunctions is held together by a rigid frame inside a vacuum vessel connected to a main port (0.9 m high x 0.4 m wide) of the JET torus vessel by 1.5 m diameter double-walled inconel bellows. This allows a radial movement of the whole launching structure. The front end of the launcher is curved toroidally and poloidally to match the shape of the plasma surface. The plasma facing waveguide walls are protected against excessive energy deposition from direct plasma contact by a surrounding frame of shaped carbon tiles. They protrude in front of the waveguides by 2.5 mm. The details of the waveguide array are described in sections 2.2 and 2.3 for the different types of launchers used on JET. The whole launcher is bakeable to 500° C for outgassing. Gas released from the inner walls of the waveguides during LH power transmission is removed through holes in the waveguides by a cryopump with 100 000 l/s pumping speed.

Coupling of the LH waves is determined by the electron density and the density gradient in front of the launcher. Therefore the proper distance between plasma and antenna structure has to be adjusted. This is obtained on JET by separate control of the launcher position and the plasma position. The launcher can be moved radially with a stroke of 210 mm during shots by means of a hydraulic position control system [4]. Hydraulic actuators move the launcher against a reaction flange fixed onto the main torus port (Fig. 1). Fail-safe operation is provided by three independent systems: An offset system consisting of three cylinders equally spaced around the launcher balances a 20 t vacuum load tending to pull the launcher (weight: 15 t) into the port. A servo system of 2 cylinders accelerates the launcher radially. A protection system of three adjustable legs buffers excessive travel and limits the innermost position. The launcher can be positioned through pre-programmed waveforms or in feedback controlled operation, using the reflection coefficient from selected waveguides or an average value for the error signal. With the active position control working in a closed loop, a static position accuracy of 0.3 mm is achieved. The system has a closed-loop resonant frequency of ~4.5 Hz, a maximum acceleration of 5 ms^{-2}, a maximum velocity of 100 mms^{-1} and a response time of 0.2 s to small amplitude steps. Fast changes of the plasma parameters in front of the launcher can be accommodated also by a second feedback loop which acts on the plasma position instead of the launcher position. Both loops operate with different time constants. Nesting of the two loops can provide flexible real time coupling control in a wide range of plasma discharge parameters.

2.2. The JET Prototype LH Launcher (L0)

The prototype launcher consists of two different stacks of multijunctions, denoted module L0C (Launcher Zero Cadarache, built by CEA Cadarache) and module L0P (Launcher Zero Physics, built by JET) [5]. The characteristics are summarised in Table 1. The multijunctions of module L0C are manufactured of zirconium copper. The multijunctions of module L0P are made of copper plated stainless steel. The internal walls of both types of multijunctions are coated with anti-multipactor layers of carbon. During operation the front ends were also coated with a beryllium layer by the evaporators located inside the JET vessel near the LH launcher. The plasma facing front end of module L0P is radially 5 mm behind that of module L0C. All multijunctions contain phase shifters which provide 90° fixed retardation between adjacent waveguides. Phase adjustment with a high precision of 10° was achieved for the whole system by careful control of all mechanical dimensions and by feedback control of the phase on each klystron. One third of the final LH generator was used for the experiments with the prototype launcher. Each module is powered by four klystrons, with the two superposed multijunctions fed by the same klystron. Adjacent multijunctions are connected to different klystrons. The phase between multijunctions is regulated with electronic phase control on the drivers in the low power stage. It was kept at 0° in all experiments with the prototype launcher. A directional wave spectrum with the maximum of the main lobe at $\overline{N}_{||}$= 1.84 and a full width of $\Delta N_{||}$ = 0.92 between the minima on both sides of the main lobe is then radiated from module L0P. No vacuum pump was used yet on the vacuum vessel of the LH launcher during the first experimental campaigns with the prototype modules.

2.3. The JET full size LH Launcher (L1)

The first full size LH launcher (L1) for the LH system on JET has been completed now. It will be put into operation early 1994 with the beginning of the experiments in the new JET divertor configuration. The features of the launcher L1 are given in Table 1. The launcher is built up from 48 multijunctions of the same type as used in module L0P of the prototype launcher, but without C coating of the internal walls. All multijunctions were tested individually in vacuum up to 100 kW in 2s pulses. The multijunctions are put together into a rectangular array without leaving gaps in between on the plasma facing front end, to form a large grill type antenna occupying the whole surface area of one main port (0.9 m high x 0.4 m wide) on JET. The whole array contains 384 waveguides total, grouped in 12 rows with 32 waveguides per row. Six rows of multijunctions are stacked vertically, with eight multijunctions per row. The eight multijunctions in a row are fed by eight different klystrons. Two superposed multijunctions each are powered by the same klystron. The electronic phase control of the klystrons provides the possibility to vary the launched wave spectrum by adjusting the phase between the multijunctions in a row. With a variation of $\Delta\Phi$ = -90° - +90°, the maximum of the main lobe of the spectrum is shifted in the range $\overline{N}_{||}$ = 1.4 - 2.3. Narrow spectra with a full width of $\Delta N_{||}$ = 0.46 are produced. Three different wave spectra can be launched simultaneously by applying different phase settings to the three sections of the antenna consisting of two vertically linked rows of multijunctions each. A combination of three different spectra, launched with equal power at $\Delta\Phi$ = -90°, 0°, and +90° is shown in Fig. 3. The spectral power density is plotted in section a, the running integral power in section b, and the running integral power weighted with $1/N_{||}^2$ in section c. The latter quantity is proportional to the LH-driven current. The spectrum with $\Delta\Phi$ = -90° ($\overline{N}_{||}$ = 1.4) should drive a plasma current about a factor 3 larger than the one driven by the spectrum with $\Delta\Phi$ = +90° ($\overline{N}_{||}$ = 2.3), as seen from Fig.3, section c.

3. OPERATIONAL EXPERIENCE

The launcher L0 was used on JET during a total of 12 months of LH experiments. The LHCD system operated in a wide range of plasma conditions, in limiter and X-point plasmas, in L and H modes, with plasma currents in the range 0.4 - 7 MA.

3.1. Power Handling

Baking of the narrow waveguide sections in the multijunctions by high duty cycle long rf pulses into vacuum turned out to be an efficient method of conditioning. Temperatures well above the normal values of 300° C during JET operation forced the outgassing of the internal walls of the waveguides. After a sequence with rf baking good power handling could be achieved. The conditioned status was maintained in the L0P multijunctions even after major leaks in the JET vacuum vessel occured during operation at around 300° C. The multijunctions of module L0C, on the other hand, did not recover to their previous status after the occurrence of the leaks. The rf losses in the multijunctions and the power absorbed in the loads in the fourth ports of the H-plane junctions were determined from the temperature increase measured with thermocouples in these sections. Most of the power reflected in the multijunctions back towards the transmission line is absorbed in the loads. The measured values of the losses agree well with the calculations for module L0P. In module L0C, however, about a factor four higher values than expected were found. This could be caused by imbalanced power distribution in the multijunctions due to the short circuit in the fourth port of the H-plane junction. The level of power transmitted without breakdown increased steadily during the twelve months of operation. The status of conditioning achieved was not lost during an intermittent period of seven months shutdown. At the end of the experimental campaign the maximum generator power of 600 kW could be transmitted with several klystrons. Launcher module L0P reached a total of 2 MW of 2.4 MW installed generator power.

3.2. Coupling

Coupling of LH waves from slow wave antenna structures into a plasma depends critically on the density and the density gradient in front of the antenna. The coupling of LH waves to JET plasmas was studied with launcher L0 in limiter and double null X-point configurations. The front end position of the grill was varied with respect to the position of the toroidal belt limiters and the protection limiters of the ICRH antenna next to the LH launcher in order to minimise the reflected power. Optimum coupling is expected for a density of $n_e = 1 \times 10^{18}$ m^{-3} in front of the launcher. The edge density profiles and the density decay length in the scrape-off layer differ strongly in the various plasma configurations, especially between limiter and X-point plasmas. The optimum distance between antenna front end and plasma boundary (last closed flux surface) depends therefore critically on the magnetic configuration. Higher reflection is found for launcher module L0P than for L0C. Module L0P is mounted 5 mm radially behind module L0C. A short density decay length is then expected in this region. The variation of the reflection coefficient with plasma - launcher distance is shown in Fig. 4 for different scenarios with launcher module L0P. Most favourable for good coupling are X-point plasmas. The weak dependence of the reflection on the antenna position in this case is due to the wider scrape-off layer and the longer radial density decay length. Reflection coefficients as low as 1% were then attained. In a 1MA H-mode discharge stable operation with low reflection of 3% on both modules L0P and L0C was maintained.

The radial electron density decay length is determined essentially by the parallel connection length $\lambda_{||}$ of the magnetic field line to the strike zone on limiters or divertor plates. For conditions with the launcher in front of the ICRH antenna, the connection length varies from $\lambda_{||} \approx 9$ m in the limiter configuration to $\lambda_{||} \approx 40$ m in the double null X-point configuration. In the limiter plasmas the connection length is given by the distance along a field line between top and bottom belt limiters. In the X-point plasmas the connection length is given by the distance along a field line between two X points. With the launcher in the shadow of the ICRH antenna, the connection length between the two neighbouring ICRH antennae side limiters determines the density in front of the LH antenna. This results in low values of $\lambda_{||} \approx 4$ m. All dependences of the reflection coefficient on the launcher position can be represented in a universal curve if the radial density decay length in front of the LH launcher is related to the parallel connection length through perpendicular particle diffusion and parallel flow with the ion sound speed [6]. The reflection coefficient is then plotted versus the ratio of plasma - antenna distance d to the square root of the connection length $\lambda_{||}$ as shown in Fig. 5. The measured values of R are well reproduced by calculations with the SWAN coupling code as shown by the dashed curve, Fig.5.

Feedback control of the reflection coefficient could be achieved by controlling the position of launcher L0 in a closed loop. The temporal evolution injected power, reflection coefficient, line averaged density and launcher position in such a discharge are shown in Fig. 6. The requested reflection coefficient there was set to 10%. The launcher position could be adjusted by the feedback system within a range of ± 3 mm around the pre-set location of 4 mm behind the ICRH antenna. The gradual increase of the plasma density would have reduced the reflection coefficient. This was corrected for by retracting the launcher backward away from the plasma. The plasma position was kept constant in this case.

4. COMPACT LAUNCHER DEVELOPMENT

The new JET divertor configuration gives large flexibility in plasma shaping. Slim elongated plasma configurations, however, can not be matched with the actual LH launcher. The stroke of the radial movement is not large enough to approach the plasma boundary sufficiently for good coupling. This led to the development of a new concept of a compact launcher system which would allow the application of LH to a wide class of plasma configurations in JET. Design principle was the mechanical decoupling of the transmission line and the antenna structure in order to facilitate modifications of the front end and adjustment to the various plasma configurations. An extremely oversized waveguide, a so-called hyperguide, shall provide power transmission between an array of standard size waveguides and a plasma facing antenna structure which forms the slow wave spectrum radiated into the plasma [7] The hyperguide cavity is strongly coupled to the emitting and receiving surfaces. It transfers power between the fundamental propagating TE_{01} modes on both sides through a TE_{0N} mode inside the hyperguide (N = number of rows of waveguides on both ends of the hyperguide). A high transmission coefficient into the TE_{0N} mode is required.
A code has been developed for the calculation of the wave propagation in the hyperguide. Arrays of waveguides are used for the emitter and the receiver. Both arrays have similar overall dimensions. They contain the same number of rows . The number of waveguides per row is larger on the receiver side, with smaller

width than on the emitter side. Up to 200 modes (TE and TM) are treated in the hyperguide and up to 6 modes in each of the receiver waveguides. The properties of the hyperguide are characterised by the overall transmission coefficient Q_T and a mode quality factor Q_M defined as the ratio of power in the TE_{0N} mode to total incident power. Calculations were performed for arrays with 4 columns x 12 rows on the emitter side and 16 columns x 12 rows on the receiver side. The single waveguides are 72 mm high each, 34 mm wide on the emitter side and 7.7 mm wide on the receiver side, according to the dimensions appropriate for the 3.7 GHz LH system of JET. The results of several case studies are shown in Table 2. The vertical phase difference between superposed rows is set at $\Delta\Psi = 180°$, with a random phase error of 0° in cases 1-3, 10° in cases 4-6 and 60° in case 7. In the ideal case without reflection all power is transmitted in the TE_{012} mode, also in the case of 10° random phase error. With a random phase error of 60°, the transmission coefficient is still high with 0.9 The mode purity, however, is not maintained in these conditions, as only 24% of the power are coupled to the TE_{012} mode. With 10% reflection from the receiver array (cases 2 and 5), only 5 % are reflected back into the emitter. The net power transmission and the mode purity remain high. The electric field distribution across the rows is shown in Fig. 7. Tripping of parts of the generator is simulated by inhomogeneous power distribution across the rows. Only rows 1-4 and 7-12 are powered in cases 3 and 6. The fraction of power in the TE_{012} mode is then reduced to 71-75% and the power distribution between different rows is strongly perturbed. The global transmission coefficient, however, remains above 90% with homogeneous distribution across the rows. The calculations show that the hyperguide should provide high power transmission in the selected TE_{0N} mode also in nonideal conditions as to be expected in the experiment and even in certain fault cases.

Testbed experiments have started with a low power prototype assembly of 1:1 scale for JET. The set-up is shown in the upper part of Fig. 8. A hyperguide of 1.5 m length connects an emitter array of 96 waveguides in 8 columns x 12 rows to a receiver array of 288 waveguides with eventually 120° phase shifters in 24 columns x 12 rows. The hyperguide is slightly tapered from 1019 mm high x 418 mm wide on the emitter side to 944 mm high x 403 mm wide on the receiver side. The dimensions of the waveguides on the emitter side are 76 mm high x 42 mm wide with 6 mm walls. The receiver is 300 mm long with waveguides 72 mm high x 12 mm wide and 3 mm walls. Emitter and receiver are manufactured in aluminium. The hyperguide is made of stainless steel plates. Phase shifters are placed in the receiver array to give a phase difference of 120° between horizontally adjacent waveguides. The emitter array is fed through a power splitting network from 6 solid state amplifiers of the same type as used to drive the JET high power klystrons, with 17 W each at 3.7 GHz. Loads are inserted into the receiver waveguides on the front end. Phase and amplitude of the waves inside the receiver are measured with probes in front of the loads. The mode structure in the hyperguide is determined from recording of the temperature distribution on the side walls with an Infra-Red camera. First measurements with an absorber plate in the place of the receiver show low reflection back to the receiver. No hot spots are seen with the Infra-Red camera on the hyperguide walls. Homogeneous temperature distribution and the heating of the absorber indicate good power transmission through the hyperguide.

The design of a high power hyperguide can be envisaged for the JET LH system after successful tests of the low power prototype. The implementation into the launcher is shown in Fig. 8, lower part. The actual stack of multijunctions would then be replaced by one single TE_{012} mode hyperguide.

The hyperguide concept presents several advantages over multijunction power splitting for the application to Lower Hybrid launchers in a reactor environment:

a) Mechanical decoupling of the transmission line and the launching structure allows remote handling maintenance and repair, including exchange of the plasma facing front end.

b) Reduction of the surface area of internal waveguide walls in the vacuum section facilitates conditioning and reliable power handling.

c) Extension of the length of the hyperguide gives the possibility to place the vacuum windows outside the radiation shielding of the machine.

5. CONCLUSIONS

High power transmission at maximum generator power level was obtained with the prototype LH launcher on JET. Feedback control of the launcher position allows maintenance of good coupling through dynamic adjustment to slowly varying plasma conditions during a discharge. The full launcher available now can transmit up to three different independent wave spectra. The hyperguide concept under study actually in low power testbed experiments provides a way to a compact reactor compatible LH launcher.

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Table 1: LOWER HYBRID LAUNCHERS ON JET

1. Prototype Launcher L0 (1990 - 1992)

2 different multijunction arrays: modules L0C and L0P, each with 8 multijunctions.

1.1. Common features of the modules:

2 rows of multijunctions superposed with 4 multijunctions in each row.
Multijunctions contain 2 rows of waveguides vertically superposed, 4 waveguides per row.
Total number of waveguides per module: 16 per row in toroidal direction x 4 rows = 64.
Dimensions of narrow waveguides: height = 72 mm, width = 9 mm, wall thickness = 2 mm.
Surface area per waveguide: 6.48 cm^2, total surface area per module: 415 cm^2.

Phasing:	$\Delta\varphi$ = 90° between adjacent waveguides in a multijunction, $\Delta\Phi$ = -90° - +90° between multijunctions.
Spectrum:	$\bar{N}_{\|\|}$ = 1.84 with $\Delta\Phi$ = 0°, $\bar{N}_{\|\|}$ = 1.4 - 2.3 with $\Delta\Phi$ = -90° - +90°. $\Delta N_{\|\|}$ = 0.92 (full width between minima on both sides of the main lobe).

1.2. Specific features of the modules:

a) **Module L0C** (CuZr with C coating, short circuits in the 4th ports of the H-plane junctions):
Vertical gap between the 2 rows and toroidal gaps of 2mm between multijunctions.

b) **Module L0P** (Cu plated stainless steel with C coating, loads in the 4th H-plane junction ports):
No vertical gap, no toroidal gaps between multijunctions. 2 passive waveguides on both sides of each row of waveguides.

2. Full Size Launcher L1 (1993 -)

6 rows of multijunctions superposed with 8 multijunctions per row.
No vertical gaps, no toroidal gaps.
Multijunctions contain 2 rows of waveguides vertically superposed, 4 waveguides per row.
Total number of waveguides: 32 per row in toroidal direction x 12 rows = 384.
Additional 2 passive waveguides on both sides of each row of waveguides.
Dimensions of narrow waveguides: height = 72 mm, width = 9 mm, wall thickness = 2 mm.
Surface area per waveguide: 6.48 cm^2, total surface area of the coupler: 2488 cm^2.

Phasing:	$\Delta\varphi$ = 90° between adjacent waveguides in a multijunction, $\Delta\Phi$ = -90° - +90° between multijunctions.
Spectrum:	$\bar{N}_{\|\|}$ = 1.84 with DF = 0°, $\bar{N}_{\|\|}$ = 1.4 - 2.3 with $\Delta\Phi$ = -90° - +90°. $\Delta N_{\|\|}$ = 0.46.

TABLE 2: HYPERGUIDE POWER TRANSMISSION CHARACTERISTICS

Case	Phase $\Delta\Psi$	Reflection	Rows fed	Q_T	Q_M
1	180° ± 0	0	1 - 12	0.998	0.997
2	180° ± 0	10%	1 - 12	0.95	0.91
3	180° ± 0	0	1 - 4, 7 - 12	0.91	0.75
4	180° ± 10°	0	1 - 12	0.99	0.98
5	180° ± 10°	10%	1 - 12	0.94	0.93
6	180° ± 10°	0	1 - 4, 7 - 12	0.93	0.71
7	180° ± 60°	0	1 - 12	0.90	0.24

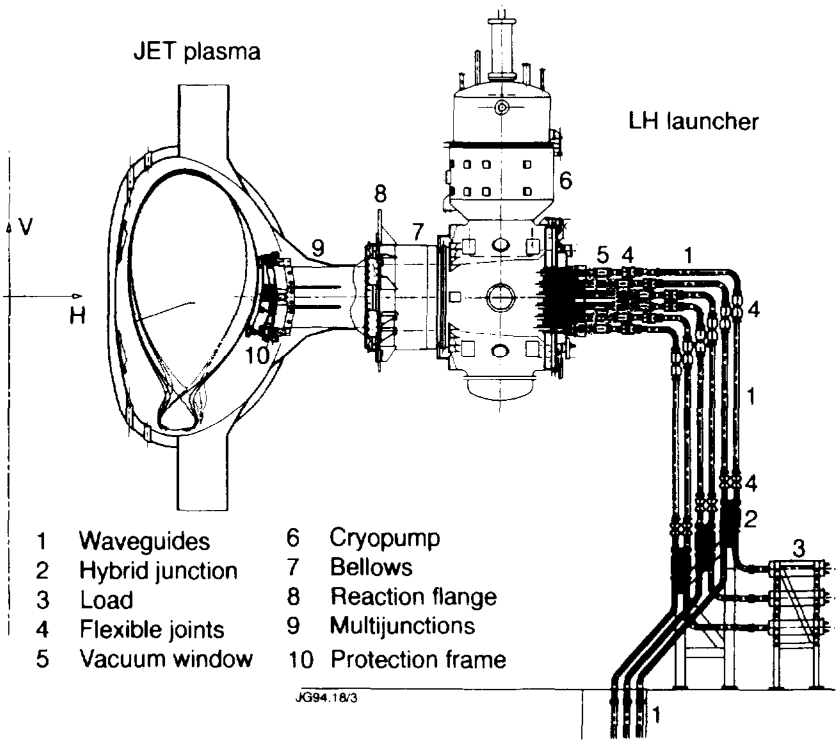

Fig. 1: Layout of the transmission line inside the torus hall and the launcher of the JET Lower Hybrid system.

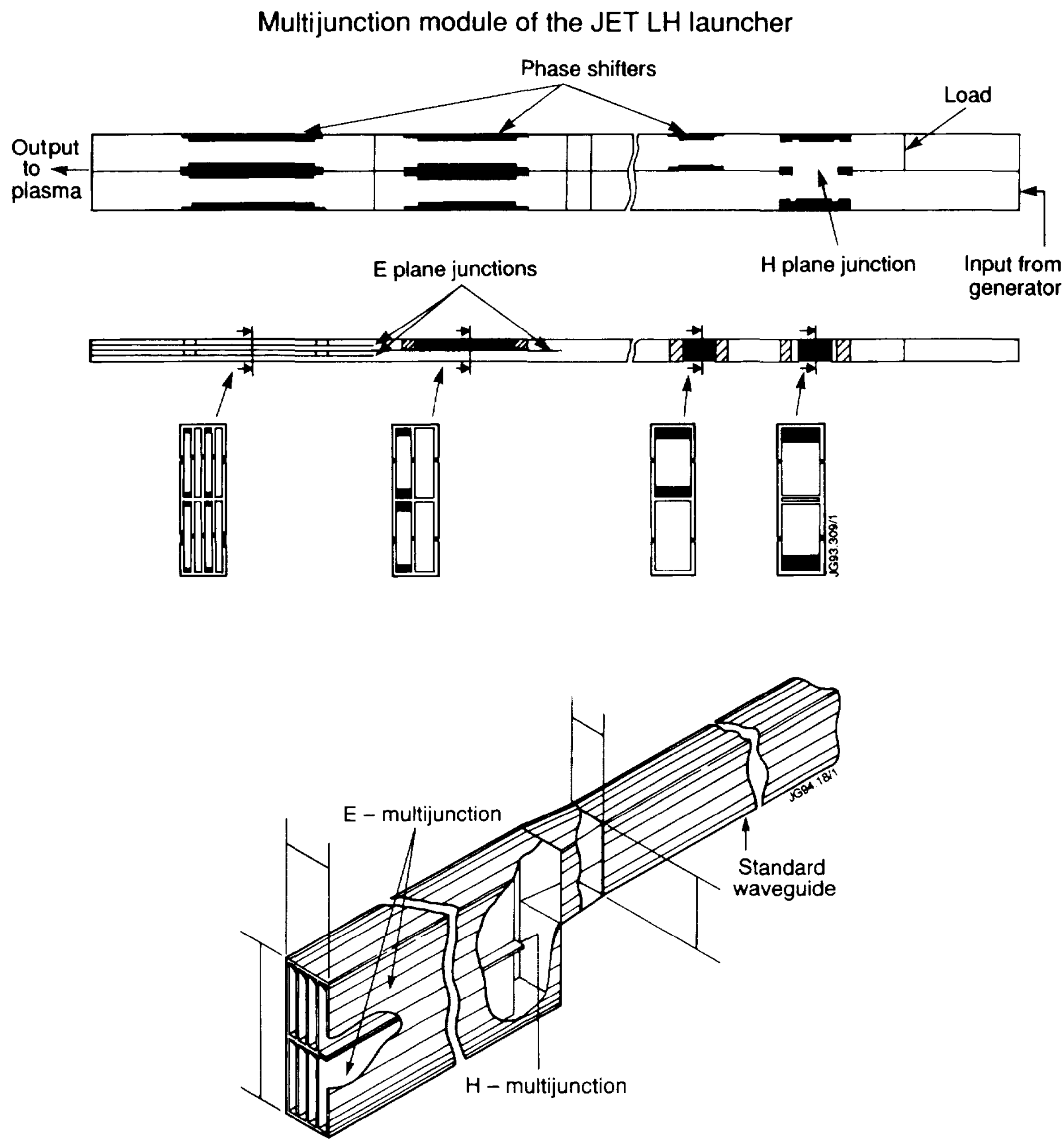

Fig. 2: Side, top and front views of a multijunction module of the JET LH launcher.

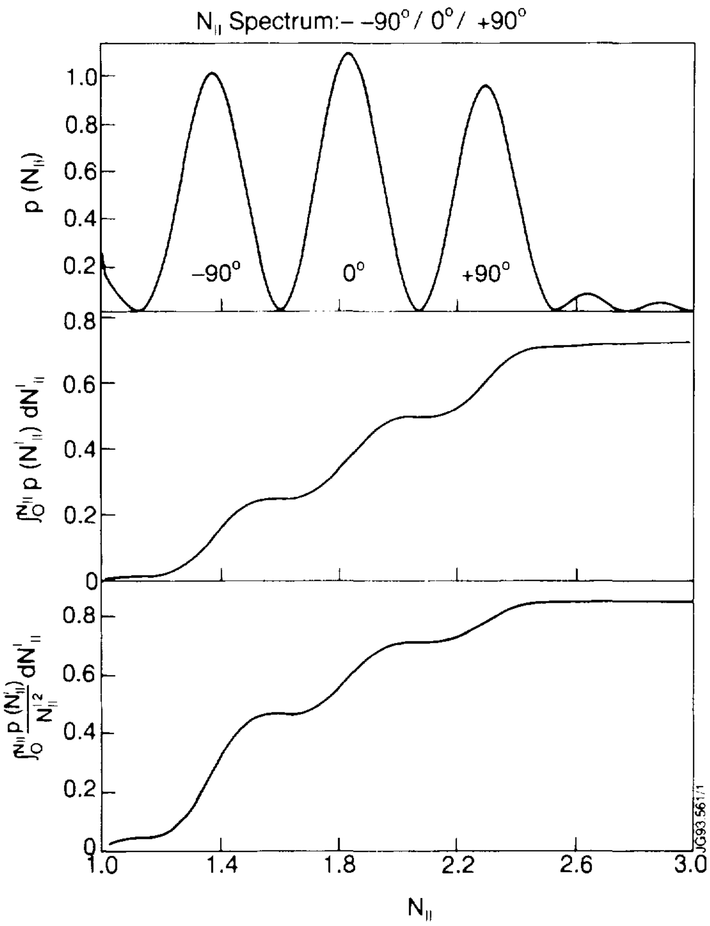

Fig. 3: LH wave spectrum for a combination of three different phase settings with equal power: a) power density, b) integral power, c) weighted integral power.

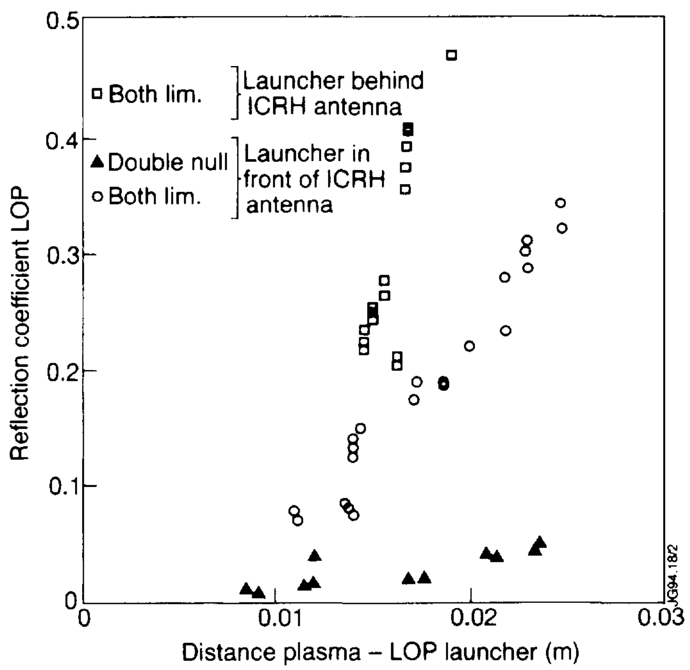

Fig. 4: Reflection coefficient versus plasma-launcher distance with the LOP module of the prototype JET LH launcher L0 for different plasma configurations and launcher positions.

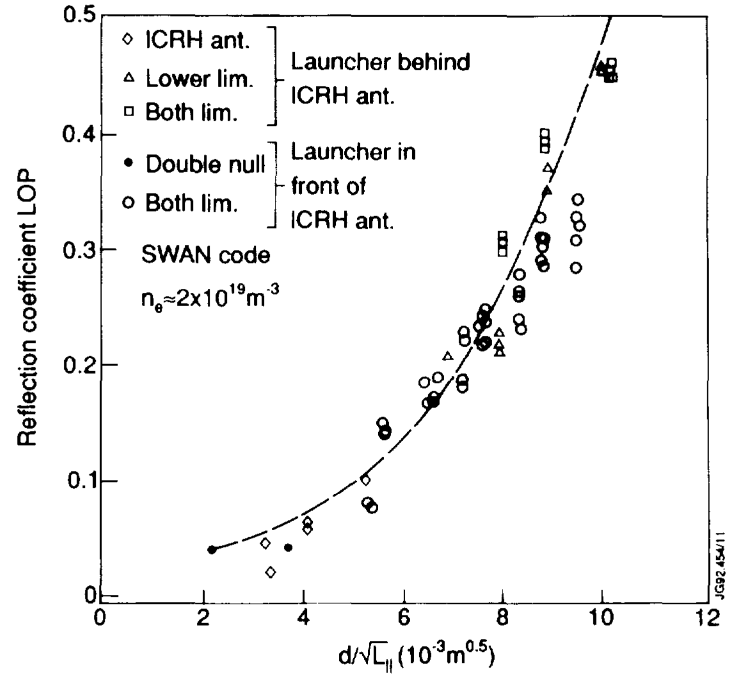

Fig. 5: Reflection coefficient versus the ratio of plasma-launcher distance to the parallel connection length with the LOP module of the prototype JET LH launcher L0 for different plasma configurations and launcher positions.

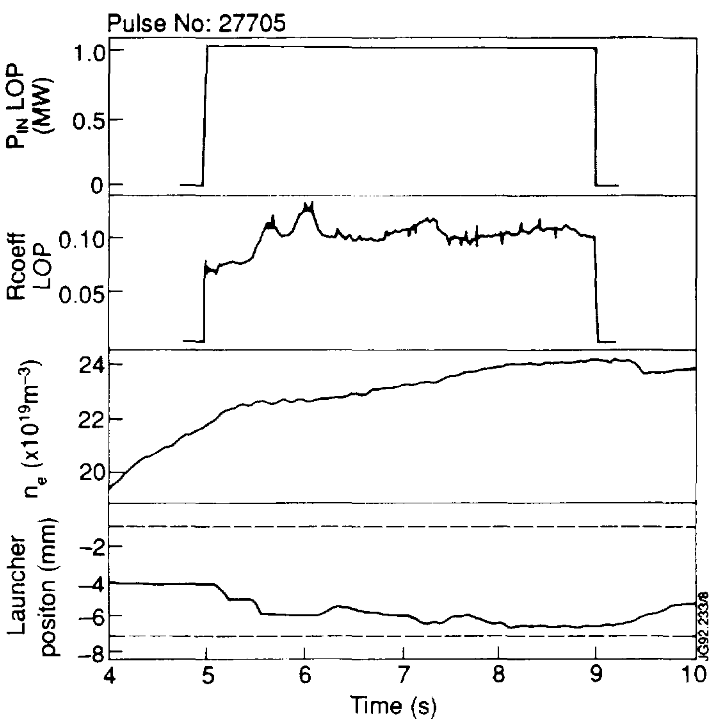

Fig. 6: Feedback control of the reflection coefficient by real time adjustment of the launcher position.

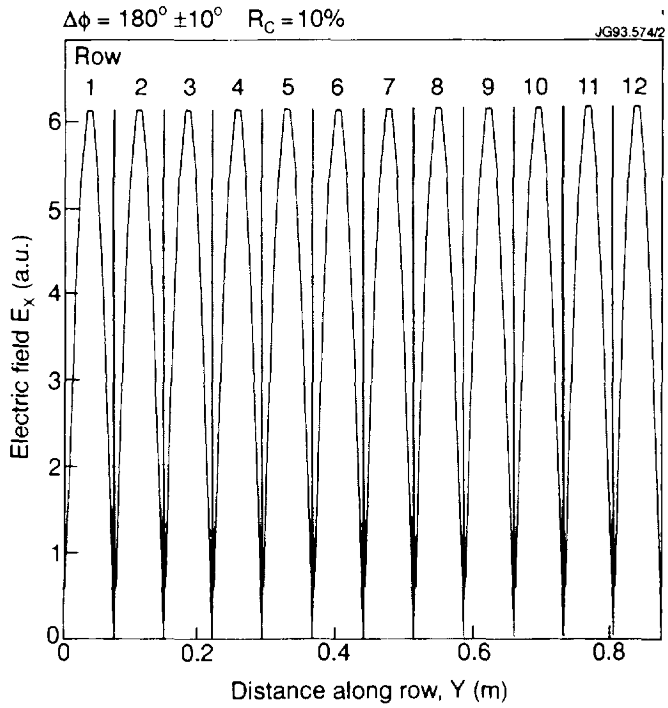

Fig. 7: Distribution of the electric field across the rows along one column of the emitter surface feeding into a Hyperguide. All emitter waveguides are fed with equal amplitude and 180° phase difference between superposed rows and an additional 10°phase error.

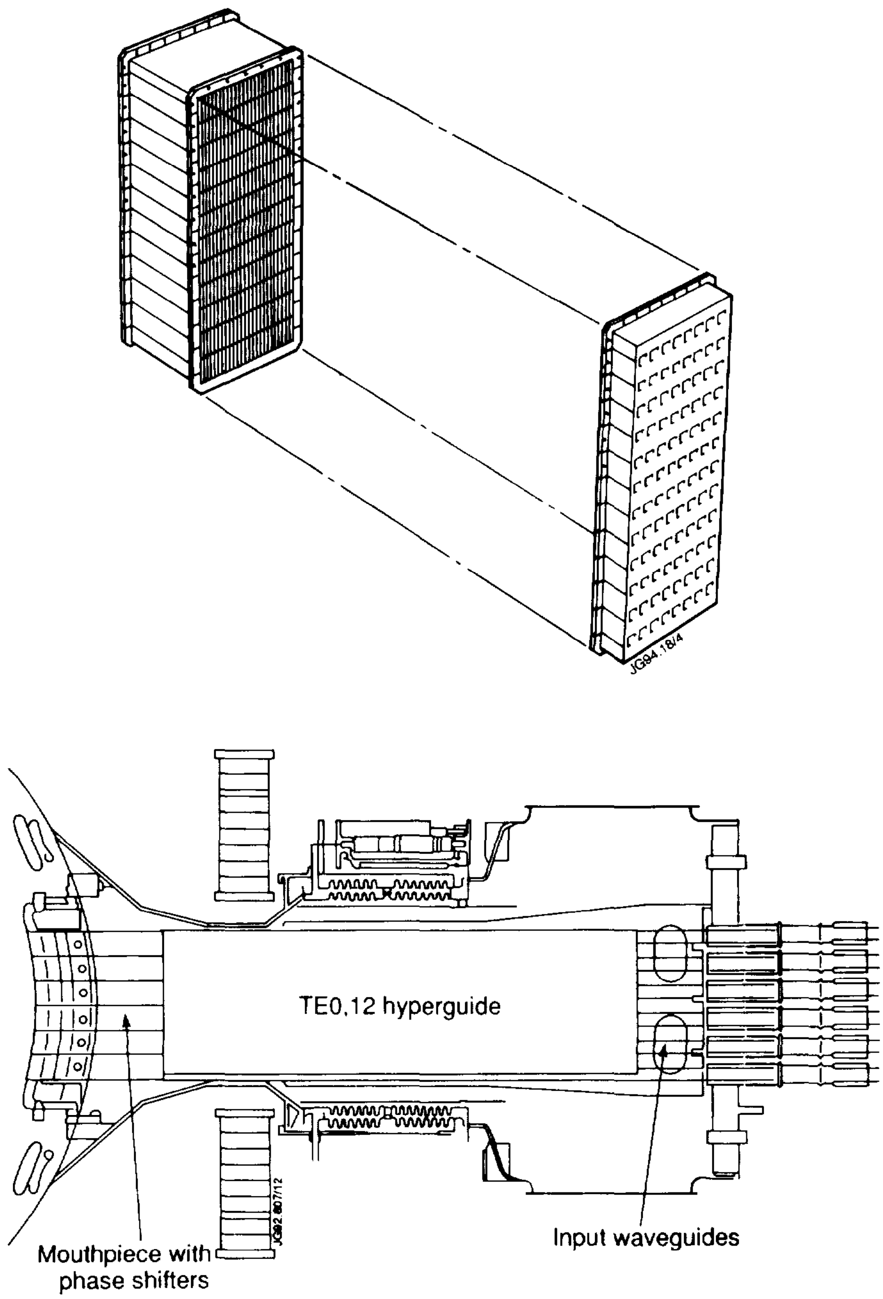

Fig. 8: a)Schematic view of the low power test module of a Hyperguide for JET with emitter and receiving grill surface. b) Layout for the implementation of a Hyperguide into the LH launcher on JET.