JET-P(96)57

RF Systems for Heating and Current Drive in Fusion Experiments

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Preprint of a paper to be submitted for publication in
the proceedings of the 48th Scottish Universities Summer School in Physics

December 1996

Radio Frequency techniques have been widely used for heating and current drive in fusion plasma physics experiments and are sufficiently mature to be presently considered for use in ITER. Their progress has followed closely theoretical predictions, understanding as well as technical progress. In early experiments the limitations were on the physics while in more recent experiments, the technical aspect has played a more important role and in some cases was the limiting factor, the increasing size of tokamaks and other fusion devices requiring more powerful RF systems.

Waves have been launched in a wide range of frequencies and can be categorised, by increasing values of frequency, as:

- ***Ion Cyclotron waves:*** ***20 to 120 MHz***
- ***Lower Hybrid waves:*** ***1 to 10 GHz***
- ***Electron Cyclotron waves:*** ***30 to 200 GHz.***

Other frequencies have been used: Transit Time Magnetic Pumping and Alfven Wave Heating at frequencies lower than a few MHz, Ion Bernstein Wave Heating at frequencies between 200MHz and 1GHz, etc. In these lectures, we will restrict to the three main areas of RF Heating and Current Drive given above. We will also restrict the domain of application to the tokamaks which is already a vast domain. Stellarators are also a big customer of RF techniques, especially for ECRH which is the main heating tool, but problems are quite similar to tokamaks.

Large amounts of RF power have been launched so far in many experiments: i) Ion Cyclotron Resonance Heating (ICRH): 22MW in limiter plasma and 16MW in diverted plasmas for a few seconds in JET; ii) Lower Hybrid Current Drive (LHCD): 9MW for a few seconds in JT-60, 6.5MW for 13 sec in JET, 6MW for 5 sec on Tore Supra, and 2.5MW for 120sec (300 MJoules) also on Tore Supra; iii) Electron Cyclotron Resonance Heating (ECRH): 2.2MW for 0.2 sec in T-10, 1MW for 1 sec in DIII and Compass-D and 0.4MW for several seconds in WVIIAS. Very effective heating has been achieved with ICRH, ECRH and LHCD, with electron temperature routinely in excess of 10keV, a central temperature of 16keV being achieved with ICRH on JET. This high grade heating has resulted in the production of H-modes for ICRH and ECRH methods, very high confinement (VH modes) being achieved with ICRH on JET in very high density plasmas produced by pellet fuelling, the so called Pellet Enhanced H-Modes and in plasmas with very high poloidal beta and a resulting high non-inductive current, the bootstrap current.

Significant amounts of plasma current were also driven by all RF methods, the largest driven current being from LHCD: up to 4 and 3MA respectively in JT-60U and JET for several seconds, 1MA for 1 minute in Tore Supra. Local non inductively driven currents such as ICRH minority ICRH current drive and ECRH current drive have allowed to modify and to stabilise some of the detrimental MHD instabilities .

All these achievements have lead to the design of RF systems for ITER to fulfil both tasks that heating and current drive systems have to play, in particular heating to ignition, driving a small amounts of central current and producing large off-axis current drive for the so called advanced scenarios suitable for steady state operation.

The physics of RF interaction with plasma and their use in Fusion Reactors are described in other lectures in this school. In these lectures, only the physics which has an impact on the engineering design of the RF systems will be discussed. Any RF systems can be divided into the following main areas:

- the **antenna and the associated transmission lines in vacuum**. They constitute an essential part of an RF system and require very often difficult compromises between physics requirements and technical constraints;
- the **windows** which constitute the interface between the transmission line and the tokamak, or the stellarator. The integrity of vacuum during an high power RF pulse is of paramount importance;
- the **Generator and Transmission Lines:** it consists of a given set of sources; tetrodes, klystrons, gyrotrons etc. which deliver their power generally in matched conditions; the transmission lines transmit the RF power from the sources to the tokamak which can be located quite far away from the generator (up to 80m in JET). Minimising RF losses in these lines is of obvious importance and also include elements allowing the required matching conditions to be achieved.

In these lectures, these elements will be reviewed for the three main RF systems, with less emphasis on some aspects of the ECRH system since several lectures are already discussing several aspects of it. Finally, the present status of the design of RF systems for ITER will be briefly reviewed.

1. ION CYCLOTRON HEATING SYSTEM

1a Physics Requirements

Two types of waves can be identified in a cold plasma:

- the transverse electric field wave (TE) with $E_z=o$
- the transverse magnetic field wave (TM) with $B_z=o$

z indicating the coordinate along the magnetic field axis. The TE wave or Fast Magnetosonic Wave is the main scheme used in present experiments such as: cyclotron heating on a minority species and cyclotron heating at second (or third) harmonic. The TM wave or Slow wave can be used for other schemes such as Ion Bernstein Wave heating, or for launching Lower Hybrid waves as discussed later in this paper. Here, we will discuss only the launching of a Fast Wave. The design of an ICRH antenna will be dictated by the physics requirements of the Fast Wave propagation in the plasma:

- The wave has to be launched with the right polarisation: Ez=o with a poloidal orientation Ey and Bz: *use of a strip-line antenna*
- The wave propagates radially inwards.
- The slow wave which propagates toroidally and deposits its energy at the edge has to be suppressed: *use of Faraday screen parallel to the magnetic field line*
- There is an evanescent region at the edge where the wave does not propagate: *the size of this region has to be minimised*

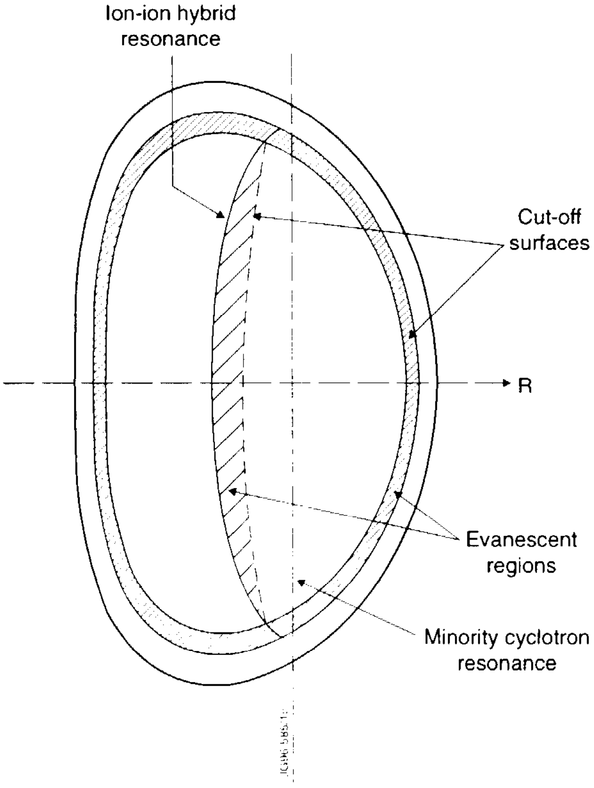

Fig.1.1: Cut-off, resonances and evanescent regions for typical ICRH waves

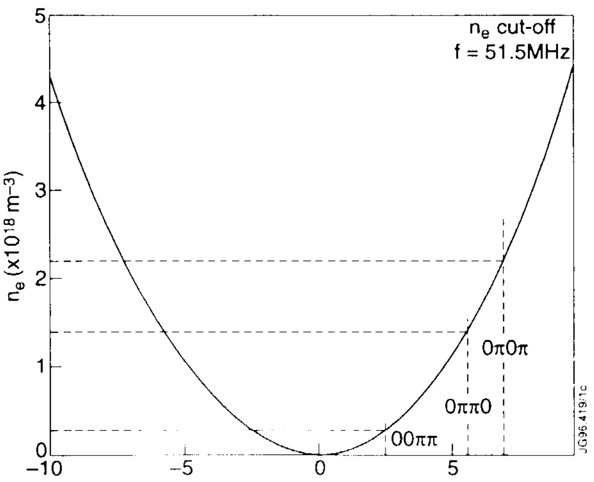

Fig.1.2: Cut-off densities as a function of k// (for a typical JET plasma)

The last effect is illustrated in fig.1.1. The value of the cut-off density for a typical example of minority heating is given in fig.1.2 as a function of the launched parallel index of the wave. The distance between the radial location of the cut-off density and the strip line determines the coupling of the antenna, the coupling (R_C) being defined as the ratio between the transmission line impedance (Z_O) and the standing wave ratio (S): $R_C=Z_O/S$. The larger this distance, the lower will be the coupling resistance, and thus the capability of the antenna to transmit power to the plasma, since $P = \frac{1}{2}\frac{V^2_{max}}{Z_0^2} R_c$ where V_{max} is the maximum voltage on the antenna or on the transmission lines and R_c the coupling impedance.

The basic design of the ICRH antenna consists of a central conductor carrying a poloidal current perpendicular to the magnetic field lines, so that Ez induced by this current will be parallel to the magnetic field lines, with a Faraday screen parallel to Ez screening other electric field components. A large distance between the central conductor and the return conductor is beneficial for increasing the coupling resistance.

1b ICRH Antenna

The art of designing an ICRH antenna consists of installing a radiating structure, with very high electric fields and high currents, very close to the plasma in order to optimise the coupling properties, and still without producing deleterious impurities. After several years of development, very acceptable technical solutions have been found. Present antennae fall into two groups. Those at JET, TEXTOR, ASDEX Upgrade are installed into the torus through a main port and mounted onto the torus wall in the gap between the wall and the plasma. Incoming transmission lines are inserted through small ports onto the back of the antennae. The JET antennae is illustrated in fig.1.3 for example. This type of construction enables the use of antennae of large frontal area and low power density at the screen and requires modest opening through the vessel, which reduces the neutron flux in the lines. The restricted depth can limit the coupling resistance.

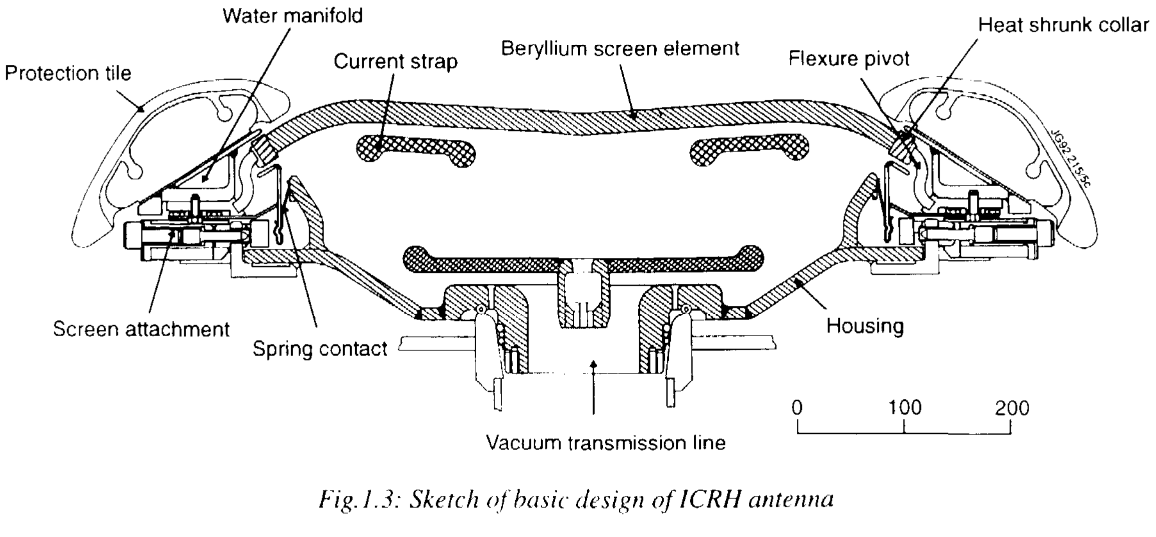

Fig.1.3: Sketch of basic design of ICRH antenna

The alternative approach is the 'plug' antenna as used on TFTR, Tore Supra, JT-60. In this case, the antenna and transmission lines are prepared as a complete self-contained assembly which is inserted into main access ports. This approach restricts the frontal area of the antenna and imposes high power density. The coupling resistance benefits from the generally larger depth available in such designs which compensates for the reduced frontal area. The coupling may now be limited by the width rather than the depth, due to image currents in the side walls.

The performance achieved to date by the various systems is summarised in Table 1.

Table 1

	Generator Power (MW)	Frequency (MHz)	Number of antennae
ASDEX-U	8	30 - 120	4
DIII-D	4	30 - 90	4
JET	32	23 - 57	4 x 4
JT-60U	9	108 - 132	2
TEXTOR	3	25 - 40	2
TFTR	14	47 (40-80)	3 x 2
Tore Supra	12	35 - 80	3 x 2

Operating systems have achieved coupled powers up to 22 MW in limiter plasmas and up to 16.5MW in divertor plasmas (JET), whilst all of the machines listed are operating in the multi-megawatt range. Coupled energies range up to nearly 200 MJ on JET. The design pulse duration's range from a few seconds to effectively continuous in the case of Tore Supra, where all parts are water cooled. The maximum pulse length is 60 seconds on Tore Supra and JET, in the latter case by operating pairs of antennae for 20 seconds each in sequence. The power per antenna ranges up to 5 MW (TFTR). The power density at the screens is up to 4 MW/m^2 on the plug type antennae of TFTR, Tore Supra and JT-60.

Of more significance in determining the limits to performance of the antenna is the electric field strength. The maximum operating voltage of a system is generally not sharply defined, and depends on such factors as conditioning temperature but is generally in the range 30-40 kV. The corresponding peak electric field is even less well defined as it depends on the fine detail of the design, notably the curvature of the surface. Substantially higher fields are sustainable across the magnetic field, such as appears between the strap and the screen in each case. The most consistent limiting parameter is the voltage. It may however be expected that the electric field is the real limitation. Design values of 1.5 kV/mm parallel to the magnetic field and 3 kV/mm perpendicular to the magnetic field are suggested by the experimental data.

An important part of the antenna is the Faraday screen whose primary role, at least historically, is to constitute the interface between the plasma and the antenna proper by preventing ionised particles from being in contact with the straps possibly inducing breakdowns. The Faraday screens on existing antennae are all of similar conceptual design: a series of parallel metal rods approximately parallel to the magnetic field. Because they can conduct currents, they are prone to circulate very large eddy currents during a disruption. Specific care is taken in the design to minimise these eddy current and the corresponding large forces on the antenna. Thus, for instance, the connection of the Faraday screen elements can be made via resistors or capacitors.

Present Faraday screens are open structures which are transparent to RF electric fields polarised parallel to the screen elements. The component normal to the screen element is reflected from the screen. Therefore the RF field is compressed through the gaps between elements which in turn entails significant RF losses and heating of the screen. The magnitude of these losses depends on the ratio of the gap to the element width and the surface conductivity of the rods. For long pulses, these elements need to be cooled either actively using water cooling of the rods (always a dangerous solution) or to reduce significantly the losses: more open structures and low loss material such as Beryllium (JET) or Molybdenum (ASDEX-U), so that end cooling can be used through good thermal contact or larger elements which can be actively cooled for very long pulses. If high Z materials have to be used, the elements have to be coated with low Z refractory material, such as plasma sprayed Boron Carbide, for protection. The skin depth at ICRH frequencies being typically several millimetres, low loss layers of a few tenths of a millimetre are sufficient. It is to be noted that several experiments (TEXTOR, ASDEX-U, PHAEDRUS) are trying to overcome this problem all together by operating without Faraday screens and a careful contour of the conductor. Preliminary data are encouraging, but further assessment, in particular when straps are operated in progressive phasing for current drive application, remains to be done.

Existing systems all use a length of co-axial line inside the vacuum system to connect the antenna proper to the window, which can be located quite far away from the main tokamak vacuum chamber, up to 3m in JET as shown in fig.1.4. This vacuum transmission line (VTL) is critical to the ultimate performance of the system. Space is limited, vacuum pumping speed is also limited (the pressure having to be lower than 10^{-4} torr to avoid arcs) and some ceramic might have to be used to support the inner conductor. In Fusion reactors, ceramic supports located close to the plasma have to be avoided due to the large neutron yield which will affect the mechanical and electric properties of the ceramic. Current carrying surfaces of the VTL are coated with high conductivity metal to a thickness of several skin depths to minimise RF losses: copper, gold, nickel or silver coatings are used.

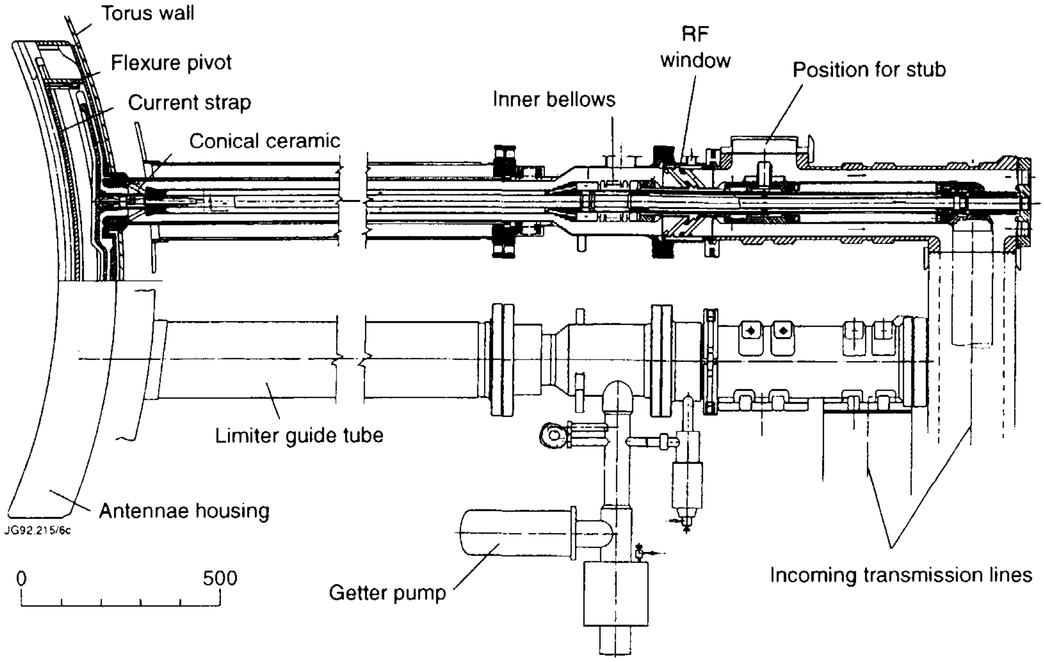

Fig.1.4: Sketch of JET antennae and vacuum transmission line

1c Vacuum windows

The vacuum barrier or feedthrough constitutes a crucial component allowing high RF power to enter the vessel safely without endangering the vacuum integrity of the machine, especially when Tritium is used. As these windows are, in most cases, located between the antenna and the tuning elements (see following paragraph), they carry a high circulating power. Because the frequency can generally be varied over a large range, they have to be able either to sustain high voltage in the range of tens of kilovolts (up to 50kV) or to carry large currents corresponding to up to 10MW of power. These windows mainly utilise metallised alumina ceramic vacuum brazed to the inner and outer conductors, although compression seals have also been successfully used. The ceramic is usually conical or cylindrical in order to reduce the field enhancement due to the high dielectric constant of alumina, and the conductors are contoured to minimise the electric field and maintain near constant impedance through the window. Present windows have been tested to power density up to 2GW/m^2, with a peak electric field of order 2kV/mm. Removing the heat coming from dielectric losses is a difficult problem for very long pulse application. For reactor application, neutron irradiation of ceramics at elevated temperature can be catastrophic in the presence of RF electric fields (or DC fields). Therefore other materials such as Beryllium oxide ceramic with a better thermal heat capacity are now being considered.

A double window, as shown in fig.1.4, using two closely spaced ceramics with a pumped interspace, is used on JET for security of Tritium confinement. Similar devices will be required for reactors. The main hazard for these windows is the occurrence of arcs at the window. The basic safety consists of detecting a significant change in the reflected power.

Because the matching systems are becoming more and more sophisticated, there is always the risk for the system to match to an arc with the consequence of destroying the window. Modern trip systems have to act fast, in about 10μs to limit the energy going to the window to less than around 10 Joules and complement the alarm from high reflection with optical arc detectors and phase sensitive electronics. Techniques looking at the broad band RF noise generated by an arc are being developed.

1d ICRH generator and matching system

The design of such an ICRH generator derives from the frequency requirements. Flexibility of the system is important. As shown in table II, the frequency has to vary in a large range in order to cope with the various schemes on a given experiment: different ion species, different magnetic fields and different physics schemes which are making use of the flexibility of the ICRH generator.

Table II ICRH schemes on JET

Notation:

(H)D Minority hydrogen ions in D-majority plasma
RF frequency tuned to hydrogen cyclotron frequency

$2\omega_{CD}$ Deuterium plasma with RF tuned to 2nd harmonic of deuterium cyclotron frequency

Heating Scheme	Frequency Range (MHz)	B(T) Range (Central resonance)
(H) D	23 - 56	1.5 - 3.7
(^{3}He) D	23 - 40	2.3 - 4.0
(H) T	23 - 56	1.5 - 3.7
(D) T	23 - 31	3.0 - 4.0
(^{3}He) T	23 - 40	2.3 - 4.0
$2\omega_{CH}$	23 - 56	0.8 - 1.9
$2\omega_{CD}$	23 - 56	1.5 - 3.7
$2\omega_{CT}$	23 - 40	2.3 - 4.0

Fortunately, high power tetrodes are commercially available mainly for broadcasting, allowing reducing cost. Nevertheless, they have required development for ICRH generators. As for all RF and microwave systems, there has been a continuous trend to use units with higher power to minimise the cost of the required ancillary equipment (driver stage, tuning elements, test loads, control electronics, etc.). Unfortunately for the Fusion community, the power requirements for broadcasting are going in the opposite direction and development of higher power tetrode has to be borne by the Fusion programme. Today ICRH generators use tetrodes with a power unit in the range of 2MW. Manufacturers have developed such tubes by reducing the losses as low as possible and by making the electrodes capable of standing these losses with sufficient safety margin. The corresponding tetrodes have a very compact cathode, losses increasing rapidly with the height of the cathode. In addition, the RF field gradient along the cathode has to be reduced and a classical cage-type cathode, excluding any moving part, has been adopted. One of the main features of these tetrodes is the use of very thin pyrolitic graphite grids limiting losses due to low electrical and thermal resistivity together with an excellent emissivity. In addition, its mechanical properties increase with temperature and dissipation up to 50W/cm^2 has been achieved without deformation.

The design of an ICRH generator is rather classical and include amplitude, phase and frequency control circuits, wideband transistor power amplifiers feeding a chain of RF tetrodes up to the final stage. Mechanical tuning is used for each frequency with a given bandwidth around each frequency, typically 2MHz. The costly high power tetrodes are protected against flashovers by ignitrons short circuiting the DC supplies causing them to shutdown rapidly.

An interesting feature for Fusion reactors of the ICRH generators is their high efficiency. With the present system, overall efficiencies, from DC to RF, in the range of 75 to 80% have been achieved by operating the tetrodes in class B operation. Some development is being made to operate in the so called class C where efficiencies in excess of 90% can be conceived.

Due to the current and voltage limitation of the active component in their last stage, the high power tetrodes can only deliver their highest output power on a specific impedance fixed by design, usually 30 or 50 ohms. The voltage standing wave ratio (VSWR) has to be rather low, in the range of 1.5. Since the ICRH antenna constitutes a rather reactive load with a reactive power up to 10 times higher than the active power, a matching system is absolutely essential. The development of matching systems has been and is still an on-going development of ICRH systems. In earlier times, this was a very painful process involving tens of plasma pulses to find the right combination of matching and tuning elements for a given plasma. The problem has been made more complicated by the evolving nature of Fusion plasmas in large devices such as JET, TFTR and JT-60U. The coupling resistance of the antenna being very sensitive to the edge density, the transition from L-mode to H-mode type edge plasma parameters results in a drop by about a factor of 2 of the coupling resistance, hence a corresponding increase in the reactive power, and this in a few tens of millisecond time scale. In addition, when an H-mode is established MHD unstable Edge Localised Modes (ELM) are normally triggered. They result in a large variation of the coupling resistance, an increase by a factor of 2 to 4, in time scale of the order of 100μs and at a frequency up to 100Hz, again resulting in rapid and frequent variation of the reactive impedance.

The two most common matching elements are a stub which is a short circuited adjustable length of transmission line put in parallel with the main coaxial transmission line and phase shifters which consists of a section of coaxial transmission line with a variable mechanical length. Other elements such as vacuum capacitors can also be used (Tore Supra). Their main role is to alter the voltage standing wave such that the normalised real part of the admittance become unity at the position of the matching element towards the generator.

In modern systems, these stubs or line stretchers are motorised and their position can be modified during a pulse, although a few seconds are needed to adjust to a new position. Faster systems (such as capacitors in TEXTOR) are being developed but still need tens of milliseconds to be adjusted. In order to react on a faster time scale, electronics systems have to be used. For instance, in JET, the generator frequency is slightly changed allowing to adjust the electrical length of the 80 long meter transmission line to the right value with frequency changes up to 100kHz. This can be done in a 100 μs time scale.

For instance, in JET each antenna is fed by one tetrode amplifier. Line stretchers (trombones) allow the transmission lines of a 4 antenna module to be of equal length. Fast changes of the plasma impedance are accommodated by a frequency change. Stubs are varied to find the proper match. A proper algorithm, which minimise the reflection at the stub, has been selected. A good match can usually be attained within one second. In order to maintain to a given value the coupling impedance of the plasma during L to H-mode transitions, the distance from the last closed magnetic surface of the plasma and the limiter is controlled through a feedback system where an error signal is produced every millisecond and sent to the plasma position control system. This offers a way to rapidly achieve and to maintain throughout the pulse a good match for the ICRH plant.

An intelligent electronics system allows to alleviate some of the problems caused by the ELMs. However, this is not enough and today several teams are developing wide band matching systems, either by utilising several matching systems in series (double stub, impedance transformer plus a stub,..) or to combine two antennas into an hybrid junction or even to develop more wide band matching antennae. These systems will soon be tested on several experiments (JET, TEXTOR, DIII-D).

2. LOWER HYBRID CURRENT DRIVE SYSTEM

2a Physics Requirements

The Lower Hybrid range of frequencies satisfies $\omega_{ci} < \omega < \omega_{ce}$ and depend upon the excitation of the so-called slow wave which propagates nearly parallel to the magnetic field with the electric field vector aligned with the magnetic field. The frequency is typically 1 to 10GHz. The wavelength parallel to the magnetic field is less than the vacuum wavelength and defined by its parallel refraction index, $N_{//}$, which is the ratio of the vacuum wavelength to the parallel wavelength in the plasma. This parameter determines the angle of propagation of the wave relative to the magnetic field and thus the trajectory within the plasma. The physics constraints for the design of an LHCD system are dictated by the coupling properties and by the choice of the damping mechanism. As in the ion cyclotron range of frequencies, the lower hybrid wave is evanescent at the edge of the plasma. To minimise the power reflected back to the LHCD launcher, the width of the evanescent layer has to be minimised. This cut-off density is a function of the frequency and is typically $510^{17}m^{-3}$ for f = 3.7MHz. In addition, once the slow wave has tunnelled through the evanescent layer at the plasma edge, the slow wave can become a backward wave if $N_{//}$ is above a critical value, the so-called Stix-Golant accessibility condition as shown in fig 2.1:

$$N_{//}^2 > 1 + (\omega pe^2/\omega ce^2)_{res} = N_{//acc}^2$$

Initial application of Lower Hybrid waves was to heat ions by locating the LH resonance in the plasma, which requires $N_{//}$ in the range of 3 to 5 in order to have $N_{\perp}$ high enough to obtain Ion Landau damping. This method was not very successful, mainly because ion heating was not very reproducible, while the use of directional waves to drive current through electrons acceleration has become very effective and very popular. The slow wave propagating parallel to the magnetic field can accelerate electrons in one direction if the wave is launched preferentially into one direction. The larger the speed of accelerated electrons, the more effective is the current drive. The ultimate is to use $N_{//} = 1$ which corresponds to the speed of light, but it is not accessible. The compromise is then, for a given plasma, to launch $N_{//}$ as low as possible for current drive efficiency but still above the accessibility value. Typical compromise values are $N_{//} \cong 2$.

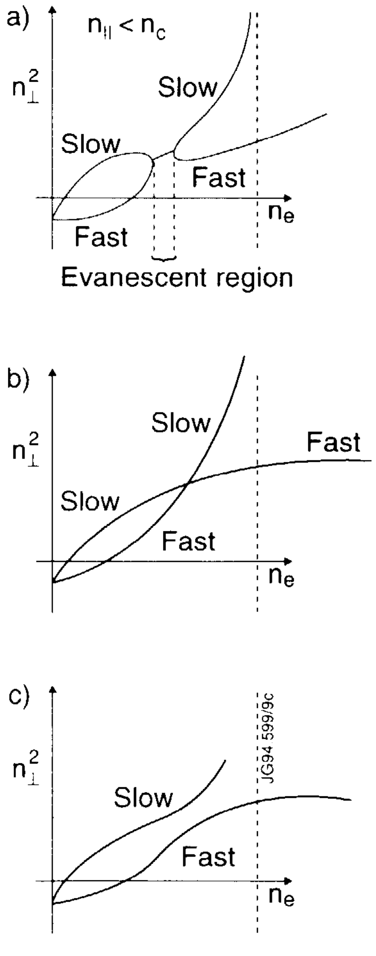

Fig.2.1: Stix-Golant accessibility condition for Lower Hybrid Waves

2b. LHCD Launcher

Therefore, an LHCD launcher has to generate an RF electric field polarised parallel to the magnetic field with a spatial distribution along the field matching the wavelength of the desired wave and at a minimum density determined by the cut-off frequency. This cannot be simply achieved by radiation of vacuum electromagnetic waves as it requires a spatial distribution of the electric field on a scale which is small compared to the vacuum wavelength. Although there are other proposals, all presently operating systems use an array of waveguides mounted close to the plasma edge, the so-called Grill as shown in fig.2.2. Single mode waveguides are used with propagation possible even if the width of the waveguide is very narrow provided that the height is more than the half wavelength. Introducing a controlled phase shift between waveguides results in a field distribution which propagates across the array with a velocity, thus an $N_{//}$, which is determined by the phase shift: $N_{//} = \frac{\lambda}{2a}\frac{\Delta\varnothing}{\pi}$, where a is the distance between two adjacent waveguides, λ the vacuum wavelength and $\Delta\varnothing$ the phasing between two waveguides.

In vacuum, such an array will not generate a propagating electromagnetic wave since $N_{//} > 1$: all the power will be reflected back into the grill. Coupling will only be produced when the density at the edge is in the vicinity of the cut-off density.

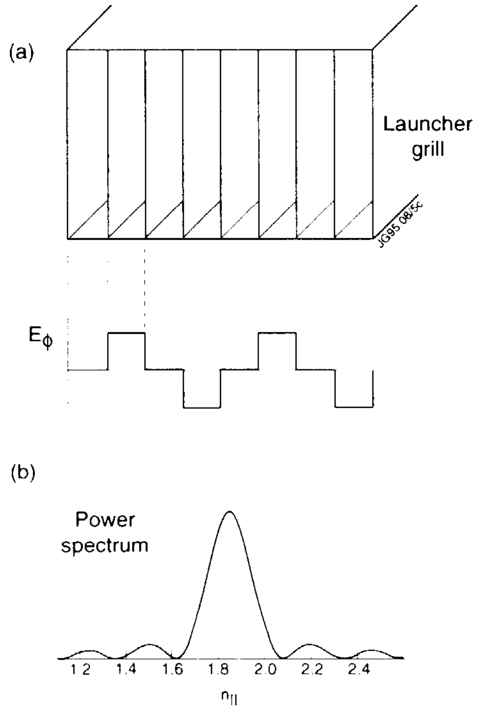

Fig.2.2: Sketch of an LHCD Grill

Early LHCD launchers were made of independently fed waveguides each with a vacuum window, and a vacuum waveguide. Modern multimegawatt systems require a large number of waveguides, up to 384 in JET. Therefore vacuum junctions allowing the power to be split and the complexity of the system to be reduced have been developed. A technique which combines the function of a splitting network, phase shifters and circulators in vacuum has been developed. This so-called multijunction is sketched in fig.2.3. The incoming waveguide is split using two successive (3 port) E-plane junctions into 4 waveguides at the grill. After each junction, phase shifters are incorporated into each line. These have the effect of producing, in the example illustrated in fig.2.3, a 0-90-180-270 degree forward power phase distribution at the grill. From multiple internal reflections it can be shown that the overall reflection coefficient at the input is now squared and the reflected power to the klystron much reduced. For instance, in a typical reflection coefficient at the grill mouth of 20%, only 4% of the power is in effect reflected back to the klystron. Both theoretical modelling and experimental measurements have confirmed this effect.

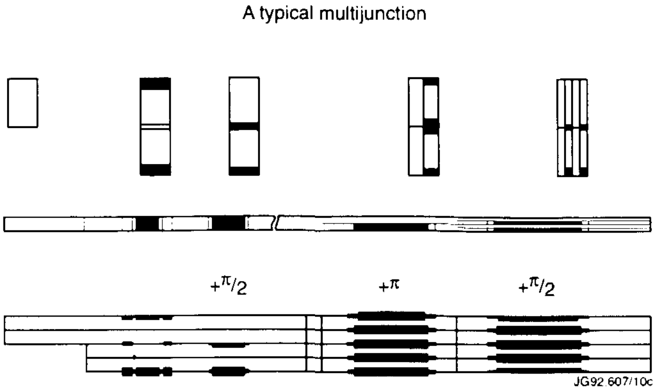

Fig.2.3: Sketch of a Multijunction Grill

This technique has been developed in the PETULA tokamak and then extensively used in TORE SUPRA, JET, and JET-60U. There are many variations on this design based on the same principle. JT-60U used, for instance, a junction from one to three output waveguides with a 60 degree shift between waveguides. They have also successfully used oversized waveguides. All large machines now utilise multijunctions which give reliable high power operation with a reasonable wave directivity when the toroidal number of waveguides per multijunction is not too high (up to 4) and when adjacent multijunctions are properly phased.

It is to be noted that the effectiveness and the compactness of multijunctions as compared to a conventional waveguide grill has a price to pay in addition to the lack of flexibility in $N_{//}$ wave spectrum. Different junctions act as a resonant cavity resulting in an increase of the electric field in the grill, 1.4 for instance for the example given above. Therefore the use of multijunctions makes easier the operation of high power klystrons, but does not resolve the problem of high voltage handling in the waveguides composing the grill. Also, directivity is altered when the reflection coefficient is too high because the amplitude and the phase distribution at the grill mouth are dependent on the amplitude and phase of the reflected power.

The limiting performance of grills appears to be linked to the maximum electric field in the waveguide or the associated multipactor effect. Multipactor arcs have been recognised as a problem with RF systems in vacuum for many years, in space and particle acceleration applications as well as fusion research. The mechanisms involved are well described theoretically. An electron born at a surface is accelerated by the RF field. On impact with another surface, this electron releases secondary electrons. If this impact coincides with a reversal of the RF field, these secondary electrons are accelerated back to impact the first surface, or another surface. An avalanche process can then result if the secondary electron coefficient (SEC) is greater than one. Space charge field can limit the density of these "multipactor" electrons to harmless levels. But, generally, production of secondary electrons is associated with gas release from gas embedded in the surface. In turn, this gas can be ionised by the "multipactor" electrons, space charge field are cancelled and the plasma density can then rise to breakdown level.

The condition for multipactor effect is that the electron transit time must equal the RF half period, or its harmonics. This condition can be fulfilled not only when electrons bounce back and forth between two surfaces, but also with a single surface when magnetic field is present, the resonance condition being such that the electron gyro frequency equals the RF frequency or its sub-harmonics.

This effect is a severe limitation when the RF wavelength is of the order of the dimension of the vacuum transmission line. In addition, the SEC has a maximum value depending upon the angle and the energy of the impinging electron. At high energy, electrons penetrate deep into the surface and secondary electrons remain buried. Multipactor effects are not harmful for ion cyclotron waves, because the transit time in coaxial lines is much smaller than the ICRH period and thus the energy of secondary electrons is small. In contrast, the problem is unavoidable with higher frequencies because the secondary electrons are in resonance with the RF field. Therefore, this effect constitutes a difficulty for frequencies in the range of a few hundred MHz to a few GHz where waveguides are normally used. This is precisely the range of Lower Hybrid waves and a large amount of effort has been generated to overcome the problem with different techniques: glow discharge cleaning, RF discharge cleaning (conditioning or ageing) with baking, special coatings on the surface with low SEC material (carbon, rough gold), etc. All these techniques have been more or less successful. Modern Lower Hybrid systems are using higher and higher frequencies which reduces the extent of the problem. With a proper combination of clean surfaces, high temperature baking, good pumping of the vacuum transmitters and RF conditioning, multipactor can no longer constitute a limit to voltage handling. The limit in voltage appears now to be limited to the value of the maximum electric field in the narrow part of the waveguides facing the plasma, especially in the presence of neutral and ionised particles escaping the main plasma. Electric fields in the range of 0.5kV/mm appear reliable at 3.7GHz, both on JET and Tore Supra. Higher electric fields can be maintained at higher frequency.

The choice of the material for the fabrication of the grill is a compromise between several requirements: high conductivity to reduce RF losses (active cooling is nevertheless required for long pulse operation), capability to resist high stresses induced by disruption forces, difficulty of fabrication in particular for multijunctions, baking at higher temperatures, etc. Copper coated stainless steel has been used on JET and extruded copper/zirconium alloy in Tore Supra. As experienced in Tokamak de Varennes and JT-60U, the newly developed dispersion hardened "Glydcop" material, which is a high stength copper alloy with low conductivity and good mechanical properties at high temperature, is now the favourite material.

Another important problem to be solved is the pumping of narrow waveguides which can be several metres long. A significant pumping speed is needed in order to evacuate the gas emitted through desorption of the waveguide walls under intense electric field and high surface heating. Pumping is achieved via hundreds of pumping holes on the narrow side of the waveguides and a large pumping system such as a 100,000l/s cryopump on JET.

There have been a number of proposals to simplify the existing systems. Such a proposal is the hyperguide system as sketched in fig.2.4 which has already been tested on a bench at low and high power. Several single mode guides (48 for JET) are coupling into a single overmoded TE0,12 guide which in turn is terminated by a short waveguide array of 384 guides. Both theoretical analysis and experimental observations suggest that such a system provides the required phase and amplitude pattern and that high order modes are not a problem. Such an hyperguide has the advantage of a much simpler fabrication, less cost , low losses and moreover a higher vacuum pumping efficiency, in particular near the electron cylotron resonance.

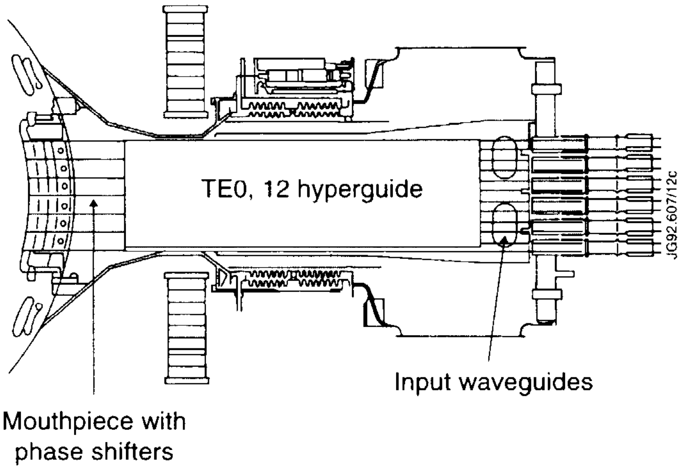

Fig.2.4: Hyperguide system

A fundamentally different alternative to the waveguide array has been proposed using quasi-optical systems. They use parallel rods mounted in the edge plasma which are spaced at regular intervals and irradiated at an angle such that the only propagating diffraction lobe from the array excites the required $N_{//}$ slow wave. Such quasi-optical systems are being developed but need critically to be tested in a plasma to be validated, in particular because high fields will be generated in the array.

2c Vacuum windows

Location of the vacuum windows is an important issue. In early experiments, it was possible to locate the windows quite close to the grill mouth, typically 0.5m. This had the important advantage of placing the electron cyclotron resonance zone outside the vacuum system and thus avoiding the multipactor arcing at this zone. Conditioning of these systems was therefore easy. However, this approach is not applicable where active cooling or remote handling of the windows is required, or in fusion reactors where the neutron fluence close to the plasma prohibits the location of ceramics in this region.

Recent experiments use internal splitting networks which allow the number of windows to be minimised. The number of windows is then determined by the global power requirement of the system and the power handling capability of an individual window. It also enables the window to be screened from the high neutron fluence and to be handled remotely. The disadvantage is that the electron cyclotron resonance is located inside the vacuum system and the resulting multipactor arcing causes problems with conditioning of the launcher.

High power windows presently used on recent machines are similar to klystron windows. They are half wavelength ceramic windows with tuning rods in vacuum. At frequencies of a few GHz, long pulse or steady-state operation at hundreds of kilowatts is routinely achieved using water cooled, beryllium oxide, pill-box ceramics. The JET window has two such ceramics in series with a pumped and monitored interspace to ensure integrity of the tritium confinement. Windows are protected by light detectors and by monitoring reflection coefficients both in phase and amplitude. Integrity of vacuum interspace is monitored by looking at the current of an ion pump which is permanently pumping the interspace. These windows are very safe when normal precautions are taken.

2d LHCD generator and transmission lines

Sources for LHCD are generally conventional high power klystrons. The Fusion LHCD community has benefited from developments made for military applications (radar) of very high power short pulse high frequency klystrons and developments made for scientific applications (accelerators) of high power steady state low frequency klystrons. A popular frequency is 2.45GHz where industrial development of microwaves has taken place.

The specific development for fusion applications is linked to maximise the power per klystron to reduce the investment cost and to optimise efficiency to reduce the cost of operation. There has been also a trend for using higher frequencies, up to 8GHz in the FT-U tokamak. At this frequency, industry (Thomson, Varian) has preferred to develop gyrotrons at a power level of 500KW for several seconds. High power klystrons developed so far are conventional multicavity klystrons which are easily controlled in phase and amplitude. They are very robust and reliable and can be operated in large numbers:

- 24 klystrons on JT-60U (1MW, 10sec, 1.7 to 2.3 GHz)
- 16 klystrons on Tore Supra (0.5MW, 30sec, 3.7GHz)
- 24 klystrons on JET (0.6MW, 10sec, 3.7GHz)

with a relatively good efficiency: 45 to 60%. Development of more advanced klystrons is taking place trying to make use of the depressed collector technique to increase substantially the efficiency, up to 70%. There is also a trend to use higher power per single unit: up to 1MW at 5GHz.

These klystrons deliver reliable power provided that the reflection remains very low, typically SWR lower than 1.3. This requires either the use of circulators or of matching circuits. Long pulse circulators at this power level are very difficult to procure and most of the experiments prefer to use matching circuits. On JET, both systems are used in order to extract more power from the klystrons by operating at an even lower SWR: 1.15.

In some of the present systems, as it will be in a fusion reactor, the LHCD generator is located far away from the tokamak, up to 50m for JET. RF losses can then become important, especially for frequencies above 3GHz. Efforts have been made to reduce these losses either by using large non-standard single mode waveguides or over-moded waveguides, limiting the losses to about 10%. As usual, there is a compromise between the losses and the cost of developing a low loss transmission lines.

The design of matching circuits is dictated by the respective unit power of klystrons, of the vacuum windows, of the single waveguide at the grill mouth as well as the requirement to keep the power reflected towards the klystron below a maximum level and the desired $N_{//}$ spectra. Substantial splitting networks are therefore required. They will also determine both the amplitude and phase distribution, thus $N_{//}$ at the grill mouth. Hybrid junctions or magic T's are widely used to divide the incoming power to suit the launcher. Such 4-power junctions may have a matched load on the fourth port. This has two substantial advantages. Firstly, the power split and phase distribution is independent of the reflected power from the launcher. Secondly, the junction can be designed to partly fulfil the role of a circulator by deflecting much of the reflected power into the matched load.

In modern large experiments such junctions are used both in the vacuum system and externally. For example in JET, the power from a 600kW klystron is divided in two in order to feed two 300kW vacuum windows using a hybrid junction located close to the launcher. The phase of the waveguide network beyond the junctions is carefully balanced so that all the reflected power goes into the load at the hybrid junction. The incoming power is further divided with the same principle, but in vacuum with a vacuum load in the fourth port of the junction. Not only, can such systems provide a good match, they can also be used to detect arcs. Any non-symmetric changes in phase or in amplitude generate an increase in reflected power which allows detection of an arc and to cut the RF power off.

The control electronics are mainly classical. Again, they have to respond in a few microseconds time scale to prevent damage due to an arc, limiting the energy to 5 to 10 Joules. The main difficulty is to ensure that the phase at the grill mouth has the desired value. When possible, phase detectors are mounted close to the grill. If not, as in JET or in future fusion devices, sophisticated phase control systems based on signals reflected back from the grill front end have been developed which appear to work satisfactorily.

Another problem is to maintain a low reflection at the grill mouth, which is sensitive to the density at the grill. Since LHCD launchers are mounted through a main vacuum port, the position of the grill relative to the torus wall has been adjustable off-line in many devices. Recently, JET and Tore Supra have been equipped with the facility for rapid on-line position control. These systems use hydraulic cylinders controlled by electro-hydraulic servo valves in closed loop configuration to set the position with millimetre positional resolution with 100 ms time response. In JET, this system has been used to maintain to a given value, typically 3 to 5%, the reflection coefficient of the 12 tons LHCD launcher in real time by using this reflection coefficient in the position control loop, thus allowing to launch the maximum power for long pulses in spite of varying plasma conditions.

3. ELECTRON CYCLOTRON RESONANCE HEATING SYSTEMS

3a Physics requirements

The distinctive feature of Electron Cyclotron waves is the absence of an evanescent region between the antenna and the plasma, although cut-offs can exist within the plasma. As a result, there are no requirements to the location of the antenna vis-a-vis the scrape-off plasma. This feature has also the consequence that a variety of wave configurations can be used on the plasma: low field or high field launch, O-mode or X-mode, fundamental or second harmonic, etc. The constraints lie mainly on the availability of the source at the desired frequency and on the plasma characteristics, in particular its density and magnetic field. Propagation normal to the magnetic field is described by:

$N_\perp^2 = 1 - \frac{\omega_{pe}^2}{\omega^2}$ for the O-mode, i.e. for a wave linearly polarised parallel to the magnetic field

and by:

$$N_\perp^2 = \frac{\left(1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{|\omega_{ce}|}{\omega}\right)\left(1 - \frac{\omega_{pe}^2}{\omega^2} + \frac{|\omega_{ce}|}{\omega}\right)}{\left(1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{\omega_{ce}^2}{\omega^2}\right)}$$

for the X-mode, i.e. for polarised wave with the electric field perpendicular to the magnetic field. There are two X-mode cut-offs at low and high density and one O-mode cut-off as illustrated in fig.3.1. Therefore, the location of these densities in the target plasma will impose the location of the antenna on the high field or on the low field side.

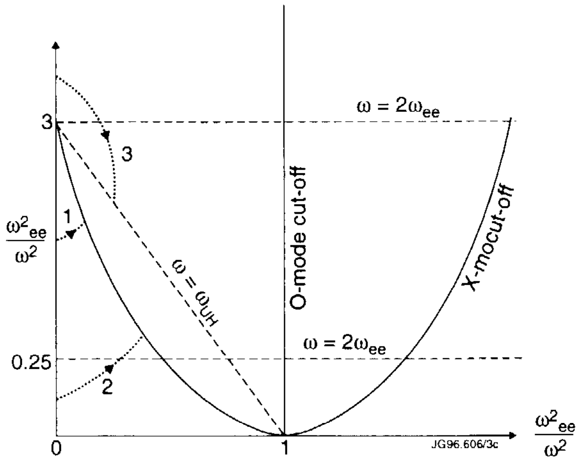

Fig.3.1: X-mode & O-mode cut-off (SMA diagram)

More sophisticated theories have been developed for more complex cases and are discussed in other courses. In particular full ray tracing codes have to be used to determine the path of the wave and the location of the interaction. An effect which has to be taken into account is the relativistic effect. The width and the location of the resonance will depend upon the velocity of the interacting electrons. The broadening of the resonance is due to the velocity distribution of the electron population. An eventual asymmetry is due to relativistic effects and is strongly related to the angle of propagation. This effect has to be especially taken into account for current drive applications where the wave is launched with a substantial poloidal angle. In today's experiments, the resonance can already be shifted by several centimetres due to these relativistic effects. Modern ray tracing codes reproduce rather well these effects. Trapped electron effects are also important for current drive applications.

Current drive requirements impose constraints on an ECRH system which are different from those for ICRH and LHCD where phasing between RF current straps or between adjacent waveguides can be used to impose a directionality to the wave. This is not possible for Electron Cyclotron Current Drive experiments. Directionality will be given by the angle of launch of the wave which has to be adjusted accordingly.

3b ECRH antennae

ECRH antennae do not pose by far the same problems as for the other RF systems. In early experiments they have been made of simple waveguides matched to the vacuum impedance via a horn. In more recent experiments, overmoded waveguides were used to transfer the power from the source to the plasma. In practice these transmission lines were very well matched and could be matched to the vacuum without problems. These overmoded waveguides are normally quasi optical transmitters and deliver a gaussian beam. By choosing the launched angle, a microwave beam can then be directed to a specific part of the plasma. Reflectors, which are generally elliptical stainless steel quasi-optical reflectors can be used in order to launch the wave at the right angle. Rotatable reflectors can be conceived. The present limitation on today's experiments is due to the restriction on available space which limits the size of the reflector or prevents the use of double reflectors. Single reflectors have been successfully used to launch 0 and X-mode polarisations in high field side and low field side positions in both tokamaks and stellarators.

The vacuum transmission lines were of the same type as developed for the main transmission lines: circular waveguides with smooth corrugated walls. Due to the relatively low power and short duration time used so far in ECRH experiments, thermal loading has not been a problem. This will not be the case in longer pulse experiments, such as Tore Supra and future fusion experiments and active cooling will need to be used. One of the main problems encountered was breakdown in the vacuum transmission line when the magnetic field required for cyclotron resonance is present within the waveguide. This is the case when fundamental resonance heating using high field side launch is used. In this case, the vacuum waveguides have to cross the cyclotron layer and breakdown was observed limiting the available power. Extensive conditioning still needs to be used: glow discharge cleaning, RF conditioning, etc., mainly to reduce the amount of outgassing and the associated breakdown at higher electric field. Long pulse experiments with electric field in the range of 1kV/mm have been achieved.

3c Vacuum windows

As for the LHCD system, these crucial elements which are being used so far in plasma devices are based on windows developed for the main generator tube, now gyrotrons. Most of the problems are linked to the cooling of these windows and no experience has yet been gained on long pulse operation on a plasma device. It is also to be noted that operation with double windows and a pumped interspace is not available.

Present windows with moderate power (200 to 400KW per window) for relatively short pulses, up to 5 sec, are not a serious problem. They are readily matched to the transmission line unless a very large band of frequencies is considered. Using fused silica or boron nitride, ECRH energies in the range of 1 Megajoule can be launched without cooling, albeit that their temperature can substantially increase. However these materials can stand the large thermal gradients generated.

There is much window development, being discussed in another course, which is taking place in the framework of gyrotron development with a very promising route: the diamond window. Several other concepts have been or are being developed such as: double sapphire windows at room temperature with a fluorocarbon coolant in between, sapphire windows at cryogenic temperature to reduce the tgδ losses and increase the thermal conductivity (with the risk of condensation), the distributed windows, or even the possibility to avoid windows altogether by using a fast shutter in the evacuated transmission line in case of a problem. Recent advances in the production of a low loss large diameter diamond disk at room temperature or an Au-doped silicon at 200°K open new perspectives in finding an 1MW CW window in the desired frequency range. Therefore this weak link in ECRH systems can be substantially improved.

3d ECRH generator and transmission lines

The key element in an ECRH system is its source which so far have been gyrotrons and in one case a free electron laser. These sources are discussed extensively in other courses. Listed below, are the present ECRH generators which are in operation, or close to operation:

ASDEX-U	140 GHz	2MW/2 sec	
COMPASS-D	60 GHz	2MW/5 sec	(in operation)
FT-U	140 GHz	2MW/0.5 sec	
TCV	83 GHz	3MW/2 sec	
	118 GHz	1.5MW/2 sec	
Tore Supra	118 GHz	3MW/210 sec	
W7-AS	70 GHz	0.8MW/3 sec	(in operation)
	140 GHz	2.5MW/3 sec	(in operation)
DIII-D	60 GHz	2MW/5 sec	(in operation)
	110 GHz	5MW/2 sec	
T-10	84 GHz	4MW/2 sec	(in operation)

Early gyrotrons were difficult to tune and were not very reliable. The latest generation of tubes is now more robust and their availability has much improved. It is to be noted that gyrotrons are very sensitive to variations in load, for instance, when it happens that the plasma is not a free space load any more. This is the case when the cut-off density is too close to the antenna or when quasi-optical conditions are not met. The only solution is to push the plasma away from the radiating antennae and normally reliable operation can be achieved. Low losses in the range of 15% at 60GHz for a 50m long transmission line, are achievable.

The generators are equipped with conventional electronics which do not present specific problems. Also there are no matching problems. Extensive theoretical and experimental efforts have been made to developing low loss overmoded transmission lines, effort which is described in another course. An example of the complexity of the transmission lines as used in COMPASS is shown in fig.3.2. In order to avoid the production of unwanted high order modes all elements of the line are very carefully designed. The required mode at the antenna, generally the HE11 mode closely matches the free space impedance. Less than 2% power is reflected back to the gyrotrons.

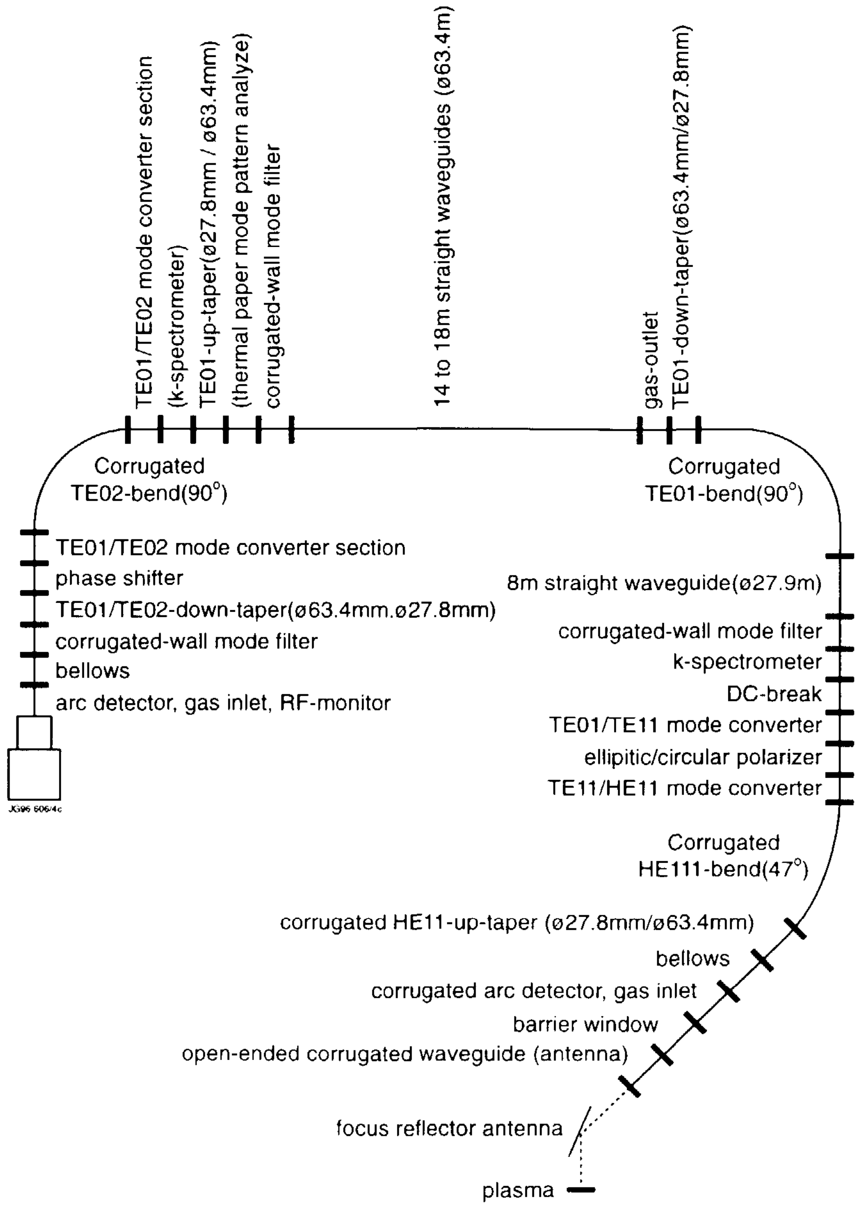

Fig.3.2: WVII AS transmission lines

The substantial effort which has been made both by industry and by laboratories to produce high power tubes and low loss transmission lines in the 100GHz range of frequencies is now paying off and, although expensive, reliable ECRH generators are now available for the present generation of fusion devices.

4. RF SYSTEMS FOR ITER

The present main parameters of ITER in this EDA phase are the following:

Major radius	$R = 8.14$m
Minor radius	$a = 2.80$m
Single null diverted configuration	
Plasma elongation	$k = 1.6$ to 1.75
Plasma current	$I = 21$ MA (nominal)
Toroidal Field	$B = 5.68$T
MHD safety factor	$q_{95} = 3.05$
Fusion Power	$P_{fus} = 1.5$ GW (nominal)
Average wall loading	$P_n = 1$ MW/m^2 (nominal)
Density	$<n_e> = 1.3\ 10^{20}$m^{-3} (nominal)
Temperature	$<T_e> = 10.5$ keV (nominal)
Burn duration	$t_{burn} = 1160$ sec (nominal)

The main parameters of importance for RF systems in ITER are the nominal values of the magnetic field, the density and the temperature. Due to uncertainties in plasma position control and also due to non confined alpha particles, a gap of 15cm is foreseen between the last closed magnetic surface and the first wall. Also of importance is the finite number of ports, up to 20, only a fraction of them being available for additional heating, as well as their size: about 2.5m in height and 1.5m in width. An order of magnitude of the size of an RF system on ITER is illustrated in fig.4.1 where a possible LHCD system is sketched. Note the scale. Auxiliary power systems on ITER have to be designed to perform the following functions:

1. Heating, which further subdivides into: a) providing sufficient power across the separatrix to access H-mode confinement, b) increasing the temperature to ignition, c) supporting driven burn scenarios if confinement proves to be inadequate, d) maintaining adequate temperature during the current termination phase when the density exceeds the Greenwald limit.
2. Driving on-axis current (0.5MA to 1MA) to provide the seed current for high bootstrap current steady-state tokamak discharges.
3. Driving off-axis current (3MA) to maintain the current profile needed to access high performance plasmas in steady state tokamak discharges.

4. Stabilising MHD instabilities either by local heating or current drive (rotating modes) or by inducing sufficient plasma rotation (locked modes).
5. Pre-ionising the plasma to ease breakdown conditions and allows a good start-up.

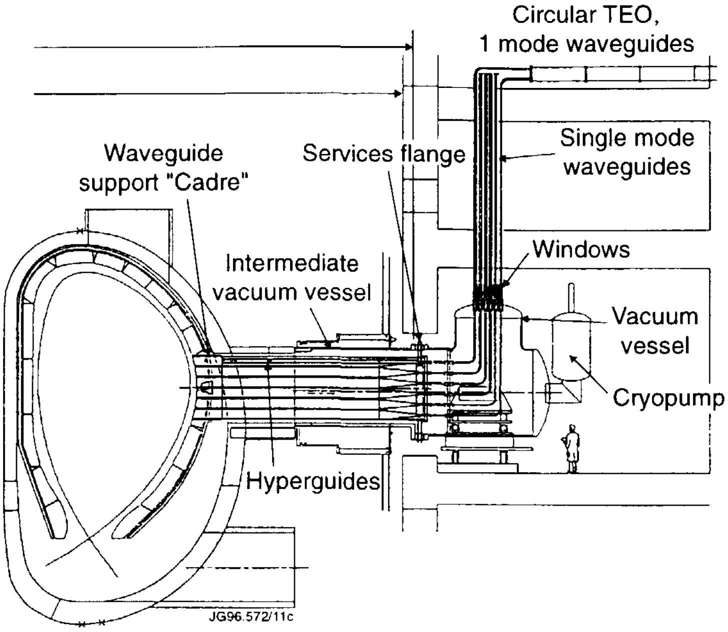

Fig.4.1: Sketch of possible additional heating system (LHCD) on ITER

Typically, the required power is 100MW for 1000 sec. It is now recognised that no single additional heating system is capable of fulfilling all these tasks and that two or more systems will have to be used. For the time being, all main additional systems: Neutral Beam Injection, ICRH, ECRH and LHCD are still being considered and design efforts are pursued along these lines. These designs are still evolving together with the main design of ITER and only a snapshot of the status of the present design and of the problems encountered will be given here. Proposals have to be formalised by the end of 1998, for the final Engineering Design Activity (EDA) report of ITER. The challenges that the RF systems will have to face for ITER are formidable, as for every subsystem in ITER, and can be summarised as follows:

- capability of the antennas, in particular for ICRH and LHCD, to be **plasma facing components**: *disruption forces, alpha particles losses, radiation, neutron flux, etc;*
- **steady state operation**: *active cooling of radiating structures and high efficiency operation of the generator;*
- **high neutron yield:** *antennas being located in a vacuum port will have to provide their own shielding structure to block most of the neutrons as will do the blanket in ITER. This will have the consequence that all insulators might suffer from neutrons in particular in the presence of DC or RF fields and that line of sight has to be blocked;*

- **remote handling:** *all systems have to be capable of being removed hands off. It is unlikely that repairs will be done in the same way;*
- **high degree of reliability and availability:** *number of pulses for conditioning, tuning, matching, etc., will likely be kept at a bare minimum. Intelligent control electronics systems will have to be extensively used.*

RF system machines which are using already Tritium operation (JET, TFTR) are facing similar problems but can only be considered as test beds as far as ITER needs are concerned.

4.1 ICRH system for ITER

The unique features of ICRF, in ITER conditions are: a) the absence of density limit allowing heating of the plasma centre whatever the density, b) the possibility of direct ion heating (up to 60%), all other heating methods including Neutral Beam Injection heating preferentially electrons, which provides additional alpha heating power during the crucial phase of the path to ignition, and c) the decoupling of the heating and current drive functions by phase and frequency control. The first two features: absence of density limit and direct ion heating are of obvious importance.

The main focus of design effort has centred on the antenna design. Blanket antenna were initially proposed allowing large area antennas to be installed with the advantage of having low voltage handling for a given power and being able to operate in a large frequency range. Due to the complexity of the ITER blanket and the associated remote handling, as well as its evolving design, the design has been re-directed toward the concept of a compact launcher easily accessible and maintainable based on conventional coupling straps grouped in 4 x 2 array modules. Four ports would be required to couple 50MW. The anticipated voltage is 38kV at 60MHz (possibly up to 50kV in dipole phasing) for the coupling as estimated for an ITER burning plasma located at 15cm away from the antenna with a 2cm density gradient scrape-off layer. The frequency range: 40 to 70MHz allows compliance with the required magnetic field range using second harmonic tritium resonance. Current Drive in this frequency range will not be done in optimum conditions but still will be adequate for the ITER needs (central current only).

A sketch of such an antenna is shown in fig.4.2. The straps are fed by coaxial extensions inserted in the neutron shield. A key issue is to produce an effective system in conditions of varying plasma loads as discussed above. The ITER team presently favours a resonant structure with a variable tuning element, such as a stub, in vacuum. Each array is composed of four modules each including two current straps and one Faraday shield. This plasma facing component is considered to be made of high yield strength copper with Beryllium coating and water cooled at high pressure. A screen-less array is also being considered, in view of the

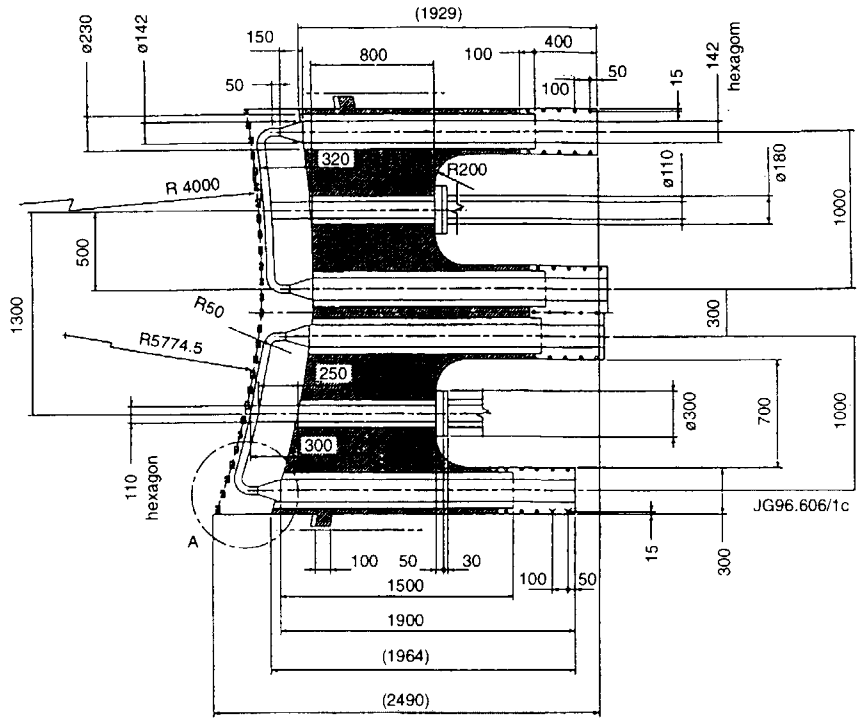

Fig.4.2: Sketch of a possible ICRH antenna for ITER

recent successful operation in medium size tokamaks (ASDEX, TEXTOR). Other issues which are being considered are:

- development of all metal vacuum transmission coaxial lines, including support of the inner conductor;
- the double vacuum window will be located far away from the vessel to reduce neutron irradiation and to ease maintenance;
- wide band matching systems;
- operation at 2MW per strap (total power of the plant: 64MW);
- possible operation of the plant in class C allowing improved efficiency.

The key points in the operation of an ICRH antenna on ITER will be to achieve the anticipated coupling and to operate routinely with high voltage. Alternative antennae such as folded waveguide antenna are also being considered in the hope that higher voltage handling could be attainable.

4.2 Lower Hybrid Current Drive System for ITER

An LHCD system can provide the main features of heating and current drive but its real speciality is to achieve good efficiency for off-axis current drive as demonstrated in JET. For the main ignition scenario, its main role might be to modify the current profile during the current ramp phase so that harmful sawteeth can be suppressed during the burn phase. Sawteeth are not only harmful by reducing the fusion yield but also because the corresponding request on plasma control is too demanding on the poloidal field system. However, the main role of an LHCD system is to enable operation of ITER in steady state. A possibility which is the present focus of experiments in several devices (JET, DIII-D, Tore Supra, etc.) is to operate ITER under so-called advanced scenarios: simultaneous use of shear reversed magnetic configurations and high bootstrap current allows to conceive high fusion yield operation (1 to 1.5GW) of fusion power at reduced plasma current ($I_p \cong$ 12MA) in steady-state. A key feature of these advanced scenarios is the capability of operating with a slightly hollow current profile and therefore to produce about 3MA of non inductive current drive at about mid radius of the burning plasma, in addition to the 9MA of natural bootstrap current.

The choice of frequency and of the parallel wave index has consequently been geared by this demand. In addition, a potential problem is the damping of LHCD waves on the alpha population. These alphas, which would be the MeV range, can be in resonance with LH waves with a low $N_\perp$ wave index which is associated with low $N_{//}$ wave index. To avoid that damping which will prevent the production of the required current, higher frequencies are beneficial. The compromise between physics requirements and technical requirements (reduction of losses) are frequencies in the 5GHz range and $N_{//}$ values in the range of 2. A typical simulation for an advanced scenario is the following:

Plasma parameters: $n_{co} = 5 10^{19} m^{-3,}$ T_o = 12keV, I_p = 13MA, I_{BS} = 10.4MA

LHCD parameters: f = 5GHz, $N_{//}$ = 2.2, P = 25MW, I_{LH} = 2.6MA at r/a = 0.5.

It is to be noted that it appears that such a steady-state operation will need complex feedback schemes to control the discharge against non-linear interaction between external and bootstrap current generation, current diffusion, heat transport and alpha particle heating. This is a very interesting problem which involves careful feedback on LHCD power (and possibly on $N_{//}$ spectrum) as well as on other heating and current drive systems.

As for the ICRH system, the main focus of research and design efforts has been to design a robust LHCD coupler, which ultimately has hundreds or more of small waveguides facing the burning plasma, and to find solutions to have a reasonable coupling even if the plasma is at 15cm. The present proposed design of the launcher is based on existing techniques which require only modest development It is shown in fig.4.3 with the following features:

- an active/passive waveguide structure which has the disadvantage of reducing the average power density but the great advantage of allowing safe installation of the required active cooling channel. A substantial benefit is also to make the grill 60% dense and therefore to provide adequate neutron shielding;

- one 25MW launcher per port with an average power density of $22MW/m^2$;
- 336 TE06 waveguides (9.2 x 300mm) and 48 vacuum windows per launcher;
- these waveguides are fed by an hyperguide as described in section 2.3. Mode converters are used to couple incoming power from a standard waveguide to the hyperguide;
- the launcher is enclosed within a high pressure vacuum vessel extending through the cryostat inside a double bellows. RF windows are outside the cryostat where the neutron flux is below the allowable flux for degradation of ceramic.

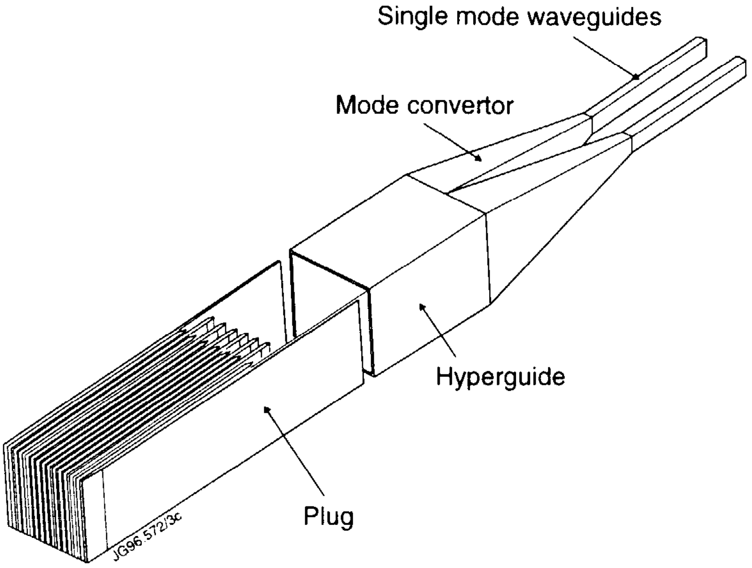

Fig.4.3: Proposed design of an LHCD grill for ITER

The coupling issue is being addressed in today's experiments. Promising results are obtained by installing a gas injection in an adequate location. A small part of the LH waves ionises this gas thus producing its own coupling plasma. This technique remains to be fully demonstrated.

The LHCD plant will be composed of 48 klystrons (rated at 700 kW) per launcher, i.e. a total of 67MW of 5GHz power for a launched power of 50MW. These klystrons do not represent a substantial development unless klystrons with higher efficiency which requires, for instance, a depressed collector technique, have to be used.

4.3 Electron Cyclotron Resonance Heating Systems

The main attraction of using ECRH in ITER is the capability of the technique to provide effective and well localised heating and, in particular, to be independent of the plasma edge parameters, allowing the antenna to be recessed from the plasma, since the EC waves can propagate in vacuum. This last point is certainly very attractive in reducing the technical demand on the antenna. In addition, ECRH can provide on-axis current drive and to some extent off-axis current drive. In principle, ECRH is very flexible since the location of the absorption can be adjusted through steering of the launched beam. ECRH can also fulfil other tasks on ITER. The highly localised nature of the ECR heating and current drive offers a wide range of instability control possibilities as shown in several experiments. ECRH is also an established scheme for pre-ionisation and start-up assist in tokamaks and stellarators. To be noted that the technical specifications for start-up applications are by far less demanding than for heating to ignition, in particular only a few seconds of power are needed for the start-up phase.

During the design phase of the ECRH system for ITER, the main discussions have been around the choice of frequency which has to be a compromise between the ideal frequency which will allow to fulfil safely all the missions of an additional heating scheme on ITER, and the frequency which can realistically be expected from the ongoing gyrotron on free-electron maser technology. The most convenient location of antennae is within a port, therefore from about the mid plane on the low field side of the tokamak. A polarised ordinary mode will then suffer a density cut-off. To be on the safe side, a frequency of 170 GHz has been selected for which the cut-off density is about 3.5 10^{20} m^{-3}, well above the envisaged 1.5 $10^{20} m^{-3}$ as the maximum density in ITER. High frequencies, typically 230GHz, would be more beneficial for current drive applications. The maximum current drive efficiency is estimated to be in the range $\eta = 0.28$ to 0.33 $10^{20} m^{-2} A/W$ for frequencies above 200GHz while it is only 0.16 to 0.19 at 170 GHz. As for the ICRH system, the heating function has been favoured since the demand for on-axis current drive is not very large. As a consequence, a 170GHz, 50MW ECRH is being proposed.

Because of the cyclotron resonant nature of the heating scheme, it is often assumed that one has little control over the heating location, which is determined by the magnetic field and the chosen operating frequency. In fact, effective control of the heating zone at fixed magnetic field is possible by making use of relativistic effects of an oblique launch. The relativistic resonance condition for oblique launch is given by:

$$\omega - k_{//}\vartheta_{//} = n\omega_{ce} / \gamma$$

where $k_{//}$ is the component of the k parallel to magnetic field, γ the usual relativistic correction: $(1 - \frac{\vartheta^2}{c^2})^{1/2}$ and $\vartheta_{//}$ the parallel velocity of the interacting electrons. It is shown that by launching the beam at a poloidal angle of 27°, the heating zone will move to $r/a = 0.4$. Similar effects can be achieved by launching the beam with a toroidal angle, but then the heating and current drive function are no longer independent since injecting at a toroidal angle will heat and drive current at the same time. Although it is in principle conceivable to rotate reflectors both in poloidal and toroidal angle, the option to launch only at a toroidal angle has been chosen. Therefore, it will be possible to heat the plasma centre at a fixed frequency of 170GHz even if the magnetic field varies from 4 to 5.8T by careful adjustment of the toroidal angle. For instance, the corresponding angles are 20° for $f = 170\text{GHz}$, $T_e = 20\text{keV}$ and $B_t = 5.74\text{T}$ and 45° for the same parameters but $B_t = 4\text{T}$. In addition it can also be shown that parasitic relativistically-broadened second harmonic absorption will remain small and that these angles are not too dependent upon the electron temperature, with some limitations if T_e is too low.

The ECRH is composed of waveguides illuminating a double reflector system as shown in fig.4.4. The first reflector allows the microwave beam to reflect at 90° on a toroidal rotating mirror. Such an arrangement allows to block the line of sight and to shield the containment vessel and in particular the vacuum windows against the main bulk of the neutron yield. An earlier proposal where the microwave beams were launched using entirely quasi optical propagation has been rejected due to this problem and to the fact that a collection of finely tuned mirrors has certainly to be avoided in such an hostile environment.

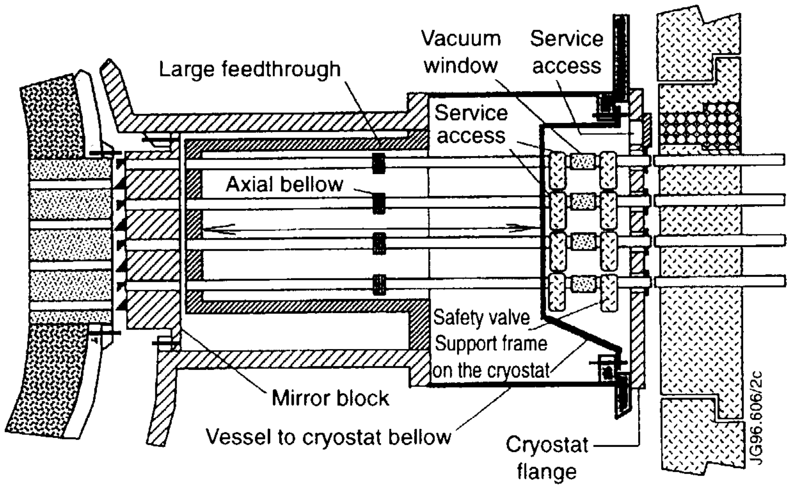

Fig.4.4: Proposed design of an ECRH launcher for ITER

The key and most difficult elements in the ECRH launcher are the rotating mirror which has to be reliably rotated at the desired angle and the vacuum windows with all the problems described in a preceding section. Long evacuated transmission lines (8 metres) made of overmoded corrugated waveguide and transmitting 1MW/line are envisaged to connect the windows to the mirrors. Valves are foreseen to allow for maintaining and replacing the windows. Note that the beam divergence due to self-diffractive effects have to be analysed for the steerable mirrors.

Whilst some experience is already gained in high power transmission lines, both for the evacuated and the pressurised part of the line, a large development is needed for the windows and the source. The target is known: 1MW-CW tube at 170GHz with an efficiency of about 50%. It is to be noted that present machines already called for similar performances although at lower frequencies: 118GHz and 140GHz and will be soon available from European and Russian gyrotrons. Japanese and Russian laboratories are developing 1MW - 170GHz cylindrical cavity gyrotrons. As already discussed new advances have been made for the windows, but certainly this is the crucial area of the ECRH programme.

4.4 Summary

Application of RF techniques to ITER, taken as an example of a Fusion Reactor, is a challenging task faced by the corresponding scientific community. The alternative systems, Neutral Beam Injection, faces similar challenges. The four techniques which are presently being considered: NBI, ICRH, LHCD, ECRH have advantages and drawbacks. The cost, which has not been discussed here but will be in the range of 100 Million Dollars, is also an important element.

So far, several meetings have been devoted to the discussion of the physics arguments. Now, regular meetings review the progress of the respective designs. There is no urgency to select one or more systems now except for the provision of access and specific building requirements, in particular for the NBI system. It is to be noted that no single system can fulfil all the tasks required by ITER. Design and some development activities are proceeding on the following basis: 50MW for each of the systems with 3 ports possibly allocated for NBI, 4 ports for ICRH, 2 ports for LHCD and 1 port for ECRH, but no more than 7 ports for all heating systems.

I have personally no doubt that one or more of the RF systems discussed in these lectures will constitute an important part of the ITER Fusion programme.

Fruitful discussions with V. Bhatnagar, A. Kaye, B. Lloyd, F. Söldner, D. Start, T. Wade and A. Whitehurst are gratefully acknowledged.

BIBLIOGRAPHY

Summaries and relevant papers can be found in the following books and articles:

Stix, T.H, Waves in plasmas, American Institute of Physics, (New York) 1993.

Porkolab, M., Review of RF heating. In Theory of magnetically confined plasmas. Proceedings of the International School for Plasma Physics, Varenna 1977, p.339. Pergamon Press, Oxford (1979).

Hwang, D.Q. and Wilson, J.R., Radio frequency wave applications in magnetic fusion devices. Proceedings of IEEE 69, 1030 (1981).

Cairns, R.A., Radio frequency heating of plasmas, Adam Hilger, Bristol (1991).

Lashmore Davies, C.N., in "Tokamaks" by John Wesson, 2nd edition.

Course and Workshop on Applications of RF waves to tokamak plasmas, Varenna 1985 (International School of Plasma Physics, Piero Calderola).

Plasma Physics and Controlled Fusion: Vol.35, Feb.93: Special Issue: Invited papers from the Europhysics Topical Conference on Radio Frequency Heating and Current Drive of Fusion Devices.

Series of 10th and 11th Topical Conference on Radio Frequency Power in Plasmas: American Institute of Physics Conference Proceedings (AIP Press), 289, 355 (1993,1995).

Technical papers on additional heating systems for ITER are not yet readily accessible. A general paper on ITER can be found in the proceedings of the 15th Conference on Plasma Physics and Controlled Nuclear Fusion Research (Seville 1994) by Rebut et al (Vol.II, p.451) together with more specialised ITER papers.