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## New Millimeter-Wave Access for JET Reflectometry and ECE

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* See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. $19^{\text {th }}$ IAEA Fusion Energy Conference, Lyon (2002).

Preprint of Paper to be submitted for publication in Proceedings of the 23rd SOFT Conference,
(Venice, Italy 20-24 September 2004)

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#### Abstract

. Millimeter-wave diagnostics at JET, mainly reflectometry, are employing state of art electronics but are limited in performance by the existing waveguides and antenna system that are inadequate and obsolete. The use of long runs of waveguides with high losses and non optimized antennas lead to difficult measurement conditions for reflectometry. The new access system presented in this article has been designed to improve the performance of reflectometry measurements and enable the installation of antennas for oblique viewing ECE. These two new antennae will allow the ECE radiation to be collected at different angles with respect to the magnetic field. This oblique ECE set-up [1] is expected to be extremely useful in improving the interpretation of ECE temperature measurements in fusion experiments with significant additional heating. For reflectometry there is an urgent need to improve the edge density measurements as both the lithium beam and Thomson scattering exhibit resolution limitations at lower densities.

The project proposal states that the expected improvement in reflectometry $\mathrm{S} / \mathrm{N}$ ratio is 30 dB . If realized, this will allow broad band reflectometry, for the measurement of the electron density profile, for the first time in JET.


## 1. INTRODUCTION

The project aims to install a millimeter-wave access system consisting of six antennas/waveguides arranged in a cluster of $3 \times 2$ (horizontal $x$ vertical) at the plasma end, for probing the mid-plane of the JET plasma. Four of the waveguides, grouped as an inverted ' $T$ ', are dedicated to reflectometry measurements while the remaining two are employed to collect the emitted radiation. This layout appears to be optimum for both diagnostics: the location of the reflectometry waveguides offers enough flexibility to perform edge density profile as well as correlation measurements, and two observation angles would be the minimum configuration required to satisfy the purpose of the Oblique ECE diagnostic in JET.

Access to the plasma will be done using a port with direct line of sight to the plasma: a limiter guide tube. This port allows a complete bundle of antennas and waveguides to be inserted from the outside of the vessel and its height is very close to the magnetic axis of JET. These four antenna apertures take advantage of the excellent coupling of the propagating $\mathrm{HE}_{11}$ waveguide mode to the free-space Gaussian beam which is also inherently broadband. ECE measurements, with a wider frequency range, $70-400 \mathrm{GHz}$, use smooth circular waveguides and the oblique detection is achieved at two toroidal angles: $\phi=10^{\circ}$ and $20^{\circ}$ (where $\phi$ is the angle with respect to the normal to the magnetic field), by using different combinations of fixed mirrors. The common final mirror is elliptical in order to control the size of the final beam. This arrangement has been chosen in order to accommodate a minimum number of mirrors into the limited space available.

A vacuum boundary with double dielectric windows and inter-stage vacuum was designed to operate in the $60-190 \mathrm{GHz}$ range. Existing instruments will be coupled to the corrugated waveguides by quasioptical (QO) boxes. These boxes are built in such a way to allow for flexible configuration of input/
output ports along with the capability of adjusting polarization and frequency separation. This paper presents the analysis and design of the antennas, corrugated waveguides, vacuum windows and instrument interface for reflectometry measurements. The analysis for the design of the antennas for the Oblique ECE diagnostic is presented in a separate paper [2].

## 2. OVERALL SPECIFICATIONS

The microwave access enhancement consists of:

- 4 antennae and low-loss microwave transmission lines for existing reflectometers,
- 2 oblique viewing antennae and transmission lines for ECE measurement of the ECE spectra. The antennae assembly will be located in the upper Limiter Guide Tube (LGT) at octant 8 , sector B. This is a plug-in assembly composed of 6 in-vessel antennae and waveguide connections.

Six double windows, set at the outer end of LGT, will form the vacuum boundary. Outside the vessel there will be 6 waveguides ( 4 corrugated for reflectometry and two smooth bore for ECE) from the Torus to the instruments in the Diagnostic Hall. Waveguide runs are about 40m long and require about 9 changes in direction. The two smooth bore waveguides and one corrugated are to be relocated from the lower main vertical port of octant 4 . The remaining three corrugated waveguides are new. The corrugated waveguide runs will be built up from 31.75 mm internal diameter tubes, in which corrugation has been optimised for HE11 hybrid mode propagation. A window box assembly at the output of the cluster will provide connection between antennae and waveguide lines, using a Gaussian telescope. Another function of the window box is to form a boundary between the high Torus vacuum $\left(10^{-9} \mathrm{mbar}\right)$ and the ambient atmosphere in the Torus Hall. Eight QO boxes, that are modular and stackable, will be provided to interface the corrugated waveguide with existing microwave systems [6]. After the QO boxes, fundamental waveguides will allow further in-band coupling/splitting as required, depending on the specific systems to be connected. This new access will enable the immediate use of the existing reflectometry instruments at JET. These comprise the four correlation reflectometers of KG8b and one full band swept reflectometer experiment, KG98a (although simultaneous operation of KG8a and KG8b instruments may have frequency restrictions due to mutual interference between the systems). The detection system for the Oblique ECE diagnostic is a new multi-channel Michelson interferometer with fast scanning capabilities [3] that is currently being installed at JET. This instrument can acquire and ECE spectrum in the frequency range of $70-500 \mathrm{GHz}$ approximately every 10 ms and will allow simultaneous measurements of the ECE spectrum at different angles.

## 3. PLASMA PARAMETERS AND FREQUENCY RANGE

To estimate the frequency ranges available to use in the new millimeter wave access to the JET plasma simulations were performed using data from two different discharges at specific times
i) Pulse No: 52735 at $60.0 \mathrm{~s}-$ high- $\delta \mathrm{H}$-mode, with peaked $\mathrm{n}_{\mathrm{e}}$ profile, $\mathrm{B}_{\mathrm{T}}=2.4 \mathrm{~T}$; ii) Pulse No: 52972 at $62.5 \mathrm{~s}-$ high- $\delta \mathrm{L}-$ mode, $\mathrm{B}_{\mathrm{T}}=1.7 \mathrm{~T}$. All data was scaled to two different values of the magnetic field, $\mathrm{B}_{\mathrm{T}}=3 \mathrm{~T}$ and $\mathrm{B}_{\mathrm{T}}=3.5 \mathrm{~T}$, being the scale factor defined as $\mathrm{s}=\mathrm{B}^{\prime} / \mathrm{B}_{\mathrm{T}}$ ( where $\mathrm{B}_{\mathrm{T}}^{\prime}$ is the expected
magnetic field) and corrected for relativistic effects due to temperature.
For $\mathrm{B}_{\mathrm{T}}=3 \mathrm{~T}$, the range of frequencies available to reflectometry is $65-125 \mathrm{GHz}$, slightly reduced to $65-120 \mathrm{GHz}$ in the H -mode peaked ne profile case (Fig. 1). For $\mathrm{B}_{\mathrm{T}}=3.5 \mathrm{~T}$, the range of frequencies available is $75-145 \mathrm{GHz}$ for both cases.

For ECE measurements, the broad spectral coverage of the Michelson interferometer ( $70-500 \mathrm{GHz}$ ) allows the observation of the fundamental, second, third and fourth harmonic of the electron cyclotron frequency for toroidal magnetic fields typical of most JET plasmas (1.7T-4T).

## 4. WAVEGUIDE DESIGN

The required minimum frequency range for the MWA reflectometry system is $60-160 \mathrm{GHz}$. The usable bandwidth of a corrugated waveguide is defined by the ohmic attenuation which exhibits a minimum where the boundary condition for the low loss $\mathrm{HE}_{1,1}$ mode is fulfilled, i.e. the corrugation depth is close to a quarter wavelength. This bandwidth also increases with the square root of the waveguide diameter. The waveguide corrugation is defined by three parameters: (i) the corrugation depth $d$, (ii) corrugation width $w$, and (iii) corrugation period p. Fig. 2 shows the calculated ohmic loss for a circular corrugated waveguide carrying the $\mathrm{HE}_{1,1}$ mode with an internal diameter of $31.75 \mathrm{~mm}, w=0.5 \mathrm{~mm}, p=0.75 \mathrm{~mm}$ at two different corrugation depths.

For both corrugations, Bragg reflections and the excitation of surface waves occur only at higher frequencies [4]. Bragg reflections depend on the corrugation period with the Bragg condition for coherent back scattering:

$$
\begin{equation*}
f \frac{2_{0}}{2 p} \tag{1}
\end{equation*}
$$

where f is the frequency, p the corrugation period and $\mathrm{c}_{0}$ the speed of light. In our case Bragg reflections occur for frequencies $f \geq 200 \mathrm{GHz}$.

The excitation of the lossy EH1,1 surface wave depends on the corrugation depth $d$ and is expected to occur slightly before: $\mathrm{f}=238 \mathrm{GHz}$, for $d=0.63 \mathrm{~mm}$, and $f=187 \mathrm{GHz}$, for $d=0.8 \mathrm{~mm}$, i.e. where the corrugation depth is approximately half the wavelength.

An open-ended waveguide carrying the $\mathrm{HE}_{1,1}$ mode exhibits good radiation characteristics as it couples excellently ( $98.5 \%$ ) to the fundamental Gaussian free space mode ( $\mathrm{TEM}_{0,0}$ ) [5] (Fig.3). The directivity could be enhanced by increasing the waveguide diameter or by adding a waveguide taper at the end of the transmission line.

The fourth corrugated aluminum waveguide, and both the smooth copper waveguides for Oblique ECE, are being taken from an obsolete scattering experiment at JET. The corrugated aluminum waveguide has the same general properties as the new waveguide but is optimized for higher frequencies ( 100 to 180 GHz ).

## 5. VACUUM WINDOW DESIGN

A box containing six double vacuum barriers with wedged windows (Fig.4), grouped in a hexagonal pattern, is used to couple the in-vessel waveguide and antenna system to the transmission lines. Detailed simulations on the reflection and transmission characteristics of a double wedged window as shown in Fig. 4 were performed. The calculations were done for fused silica with a refractive index of about 1.938 and $\tan \partial \approx 2.5 \times 10-4$. The coupling behavior of the two mirrors on either side of the window assembly was included. Results of simulations with parallel wedge angles show that the main beam exiting the window is off axis with relatively large output beam angles and beam shifts. Furthermore, it was observed in this case that the beam displacement factor is not constant across the diameter of the beam, which is not preferable. For this reason opposite wedge angles (Fig.4) are to be preferred. This gives a constant displacement factor which can be simply compensated in the design by slightly shifting the coupling mirrors off-axis in the design. Simulations were done with opposite wedge angles of $5^{\circ}, 7.5^{\circ}$ and $10^{\circ}$ for E- and H-plane polarizations. Output beam shifts and angles are given in Table 1.

| Wedge angle $\left[{ }^{0}\right]$ | Beam offset $[\mathrm{mm}]$ | Beam angle $\left[{ }^{0}\right]$ |
| :---: | :---: | :---: |
| 5.0 | 1.4 | 0.026 |
| 7.5 | 2.1 | 0.087 |
| 10.0 | 2.8 | 0.207 |

## Table 1- output beam offsets and angles

The power transmittance for the fundamental mode is better than -3.1 dB at all wedge angles. The wedge angle of $7.5^{\circ}$ has an optimal transmission ripple, that is within the objectives from about $80 \mathrm{GHz}(0.46 \mathrm{~dB})$, but the reflection characteristic for this wedge angle does not meet the objective ( $<-14 \mathrm{~dB}$ ). Although the reflection characteristics also do not meet the objectives at a wedge angle of $10^{\circ}$, the difference is small. Therefore, it was decided to use a wedge angle of $10^{\circ}$, which is a compromise between acceptable transmission ripple and reflection levels.

On JET, vacuum integrity is paramount so all windows consist of two disks. The inter-space between the disks is filled with neon at a pressure of 0.5 bar so that the breakage of either disk is immediately evident. The region surrounding each window is lined with Macor, a machineable glass-ceramic. This is done to reduce the amount of stray radiation that is reflected into the waveguide.

## 6. INTERFACE, QUASI OPTICAL BOXES

The connection of the instruments to the transmission lines is done using Quasi Optical Boxes that consist of a modular quasi-optical system of mirrors, with focal length 120 mm , in co-focal arrangement, with a magnification factor of one[6]. Alignment and matching of the focal planes are provided by the mechanical structure. Each mirror box can hold a splitting element, either a grid or a Frequency Selective Surface, so the fundamental block is a one-in-two divider/combiner.

The splitting element can be either rectangular (polarization adjustment by rotating of the boxes) or circular (able to rotate but smaller). The additional truncation loss in the later case (worst case is 2.66 w for an active splitter diameter of 74 mm ) has a negligible impact on performance.
Coupling with fundamental waveguide is achieved with small flare angle conical horns ( $5^{\circ}$, limited by mechanical constraints). Horns end with a circular waveguide port large enough for the lowest frequency required, using commercial transitions for interfacing to the proper rectangular waveguide. The interface with horns and between boxes allows rotation, either free or in $22.5^{\circ}$ increments, for maximum flexibility and optimization of polarization.

The interior of the boxes is covered with Eccosorb TM AN72 to provide absorption of stray radiation. In the case of the ECE diagnostic, the emitted radiation is optically coupled to the Michelson interferometer entrance. A polarizing grid at the waveguide output will select the desired polarization (X- or O-mode).

## 7. INSTALLATION AT JET.

Waveguides attached to the JET vacuum vessel have to withstand two loading conditions, thermal expansion of the vacuum vessel ( 20 mm radial) and acceleration following a plasma disruption $(7 \mathrm{~g}$, 30 ms radial and toroidal). Stress analysis of the waveguides close to the torus has resulted in the copper ECE waveguides being changed to high strength brass (>160 MPa yield stress) in this region. The 6 antenna tubes entering the JET vacuum vessel through a Limiter Guide Tube port are subjected to fast magnetic field variations during disruptions. The design had to be compatible with these electromechanical loads. In particular the tubes used needed to be supported at seven positions in order to limit the bending moments. As the chosen supplier for the antenna tubes is able to produce only short segments to the desired accuracy, the antenna tubes are made by screwing together segments, which are joined at the intermediate supports. Tests have been carried out to confirm that tube joints are compatible with the electromechanical torque and bending moment they will experience during disruptions. The design of the antennae and window box has been constrained by the requirement to repair or remove it by remote handling techniques. The waveguides will penetrate the ground floor of the Diagnostic Hall, and the area assigned to the microwave diagnostics is the area around the floor perforation. The microwave reflectometers are sensitive to the polarization therefore the layout of the quasi-optical boxes must take this into account using the scarce space available. The instruments will be placed axially around close to the position where the waveguides emerge from the floor.

## 8. PERFORMANCE TESTS.

In order to adapt the instruments to the new transmission line, all the blocks involved should be tested, this comprises; the instruments, quasi-optical boxes, oversized waveguides and antenna cluster. With respect to the antenna/waveguide system, it is very important to characterize the transmission losses, cross talk level, mode conversion, and beam pattern. The alignment of the ECE antenna will be also checked. From the previous list the performance of the quasi-optical box will be characterized by

CNR, and the waveguide transmission line (waveguides and miter bends) by IPP, the other two blocks will be tested at JET by the associations involved.

From a reflectometer point of view, it is very important to characterize the transmission losses, cross talk level, mode conversion, and beam pattern.

The tests performed to the antenna cluster should give all the information about these values at least for the bandwidth in use in reflectometry: KG8b 75-77, 86-87, 92-96 and 100-106GHz; KG8a $50-75 \mathrm{GHz}$. In the case of the ECE measurements some of the tests will be performed at higher frequencies (up to 200 GHz ) in order to secure reliable measurements at least for the frequency range corresponding to the second harmonic emission for typical JET magnetic fields of 1.7T - 3.7T. All the work related to the characterization of this new millimeter wave JET access system will be presented in future publications.

## CONCLUSIONS

The difficulties on millimeter wave reflectomety at JET determined by the poor performance of the existing waveguides and antenna system lead to the development of a completely new millimeterwave access. This new access system was designed to improve the performance of reflectometry and enable the installation of antennas for oblique viewing ECE. This project comprised design development and manufacturing efforts for both in-vessel and ex-vessel components, namely antennae, waveguides, vacuum windows and instrument interfaces. The project proposal states an expected improvement in reflectometry $\mathrm{S} / \mathrm{N}$ ratio is 30 dB . If realized, this will allow broad band reflectometry, for the measurement of the electron density profile, for the first time in JET. On the other hand, the installation of the ECE antennas in JET will provide a unique opportunity to investigate oblique ECE spectra (the reader is referred to [1] for more details) in high-Te plasmas under conditions approaching those relevant to a tokamak reactor.

These measurements can contribute significantly to improve the ability to interpret accurately ECE measurements in ITER.

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Figure 1: Pulse No: 52735 at 60 s scaled to $B_{T}=3$. The $75-110 \mathrm{GHz}$ ( $W$ band) is indicated by the dashed magenta

Figure 2: Calculated ohmic attenuation of corrugated $H E_{1, l}$ waveguides with different corrugation depths. lines.


Figure 3: Calculated far field radiation pattern for the open-ended waveguides type B.


Figure 4: Schematic design of the window assembly with two wedged windows.


Figure 5: Reflected and transmitted power for wedge angles of $\pm 10^{\circ}$.


Figure 6: Example of arrangement of the splitting blocks. One port (bottom right) terminated with a horn to connect an instrument and one or two (top right) available for further cascading, depending on grid orientation. The corrugated waveguide input is top left. Each of the blocks can be rotated around the interconnecting flange.


Figure 7: Instruments disposition at the Diagnostic Hall (J1D).

