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**ABSTRACT.**
A new system has been installed on the JET tokamak consisting of 6 independent fast-sweeping reflectometers, covering 4 bands between 44 and 150GHz and using orthogonal polarisations. It has been designed to measure density profiles from the plasma edge to the centre, launching microwaves through 40m of over-sized corrugated waveguides. It has routinely produced density profiles with a maximum repetition rate of one profile every 15s and up to 100,000 profiles per pulse.

## 1. INTRODUCTION
In magnetically confined fusion experiments, fast sweep reflectometry is a standard diagnostic used primarily for electron density profile measurements. Such systems have been installed on various tokamaks and have produced reliable density profiles [1-3]. On the JET tokamak, a test system was installed in 2007 to demonstrate the feasibility of FM-CW reflectometry through long waveguides [4]. The positive results from this system demonstrated the viability of fast sweep reflectometry on JET. A multi-band reflectometry system has now been designed and installed on JET to complement the existing density profile measurements provided by Thomson Scattering (TS) systems.

## 2. OVERALL DESIGN
While TS systems have proved their reliability and their ability to measure density and temperature profiles in almost all plasma conditions, they are not adapted for fast events or edge plasma studies. The aim of this new diagnostic is to measure density profiles from the plasma edge to mid-radius or, depending on plasma parameters, up to the centre with a high time resolution. For a precise localisation of the profile and to be able to measure density profiles at very low density (plasma edge), X-mode polarisation is needed. X-mode is also required for probing flat central density profiles.

From these main requirements the accessibility of a density profile reflectometer has been drawn for different magnetic configurations (on JET, the main magnetic field on axis $B_0$ can vary between 1 and 3.4T). Figure 1 shows the diagnostic accessibility at 2.7T for different densities. If the density is high enough, the probing wave can be absorbed by Electron Cyclotron (EC) harmonics. It has been decided that such positions will be measured by an O-mode reflectometer working in a different band.

To cover most of the JET plasma conditions, 6 reflectometers are needed. They are described in table I. The usual bands have been expanded by 1GHz on both ends of the band to allow a 2GHz overlap between the contiguous bands in order to ease the numerical inversion of the measurements. Simulations have also shown that the maximum frequency needed to cover all JET discharges is 150GHz, the D-band reflectometer has thus been reduced in term of band coverage. The reflectometers are using long over-sized corrugated waveguides and coupling systems that have been installed recently on JET [5]. This Microwave access has been designed for reflectometers working between 60 and 190GHz. It provides 4 waveguides for reflectometery. Each waveguide is about 40m long and has 9 bends. Multiple microwave systems can be coupled to one waveguide using specially designed quasi-optical boxes [6]. Previously two of the waveguides have been used by 4 correlation reflectometers [7] in W-band and one by fast-sweep reflectometer in V-band [4]. The use of the Microwave access allows the reflectometer to be installed outside the JET torus hall, in a dedicated room, far from any neutron emission. This setup is close to what will be the ITER reflectometer's accessibility [8].

Tests have been carried out during the design period to estimate the minimum frequency the Microwave access can be used. It was shown that the Q-band reflectometer would be limited to 44-50GHz: no signal was detected below 44GHz. It is believed that the losses are due to the size of the vacuum windows and mirrors which were designed for frequencies above 60GHz. This limitation restricts the accessibility of the diagnostics to plasmas with $B_0$ > 1:9 T.

The reflectometer designs are not presented in this paper but rely on technologies developed by CEA9, France and IST10, Portugal. They used a fast 12-18GHz source driven by an embedded controller followed by active multipliers. Heterodyne detection is achieved using frequency modulation and waveguide compensation in coaxial cables. The IF frequency (between 400MHz and 1.8GHz depending of the reflectometer) is finally demodulated using I/Q mixers. The output power of these reflectometers is between +6 dBm and +14dBm.

The use of long waveguides, partly outside of their specifications, is a source of a strong dispersion of the signals for frequencies below 80GHz. This is overcome by measuring the echo from the vacuum vessel inner-wall before every plasma. The subsequent plasma measurements are then calibrated against this reference sweep to remove the effects of dispersion in waveguides, quasi-optical boxes or cables.

The diagnostic has been designed to be able to track fast events (ELM crashes, pellet injections) with a repetition interval as low as 15μs but also to monitor JET density profiles for the whole discharge with a 1 ms time resolution. Up to 100,000 profiles can measured during a JET plasma. The 15s interval can been achieved by having all 6 bands sweeping simultaneously in 10s. Simulations have shown that a 200MHz data acquisition system is needed. Each data acquisition card can store up to 1GB of data for 2 heterodyne channels. The 6GB of total memory can then be filled in a 1.5s acquisition at full speed, in a 100s discharge at 1ms repetition rate or with a free combination of different sampling rates throughout the discharge.

## 3. QUASI-OPTICAL BOX LAYOUT AND FILTER PERFORMANCE

Six new reflectometers and 4 existing correlation reflectometers have been integrated using a combining system allowing these 10 instruments to share 4 waveguides. In order to optimise the signal over plasma noise ratio, 3 waveguides are used for microwave emission and one is used for reception. The microwave beams are split using traditional tungsten wire polariser grids or custom made multi-mesh low pass filters placed into quasi-optical boxes. Two sets of filters have been designed and manufactured: 60GHz and 90GHz lowpass filters. Figure 2 describes the layout used to split the microwaves coming from the plasma to the different reflectometers. On the emission side, the layout used is much simpler with only 3 quasi-optical boxes per waveguide coupling to 3 reflectometers.

Working with a beam incidence of $45^{o}$, the transmission losses of the multi-mesh filters are below 1dB while in reflection the losses can go up to 2dB. Using multi-mesh filters, the overall losses introduced by the combining system has been minimised: on emission they have been measured between 1 and 3 dB and on reception they are between 4dB (O-mode) and 8 dB (X-mode).

## 4. DENSITY PROFILE MEASUREMENTS

After every JET discharge, density profiles are generated automatically and are made available for physics analysis in between shots. The automatic process uses a modified Xmode inversion [11] that usually runs on 6 PCs and takes less than 10 minutes to process 100,000 profiles. An O-mode inversion is also available on-demand.

Figure 3 shows an example of density profiles measured during an ELM crash. The fast collapse of the density pedestal can be clearly seen followed by the recovery of the plasma edge and then the build-up of the density at the pedestal top. This result is a direct measurement confirming previous statistical ELM studies made on JET with other diagnostics [12].

This diagnostic has also been successfully used for studies including transport, ELM pacing by pellet ablation or RF heating. Its main strengths are its ability to cover the whole discharge with a good time resolution and its capacity to measure low densities in the plasma edge as well as high ones in the core.

## CONCLUSION

A fast sweeping reflectometer system for electron density profile measurements has been designed and installed on the JET tokamak in an environment comparable to ITER reflectometers. Existing technology has proven to be able to mitigate the inconvenience of sharing long waveguides. The system has demonstrated its ability to measure useful density pro- files for physics studies.

## ACKNOWLEDGMENTS

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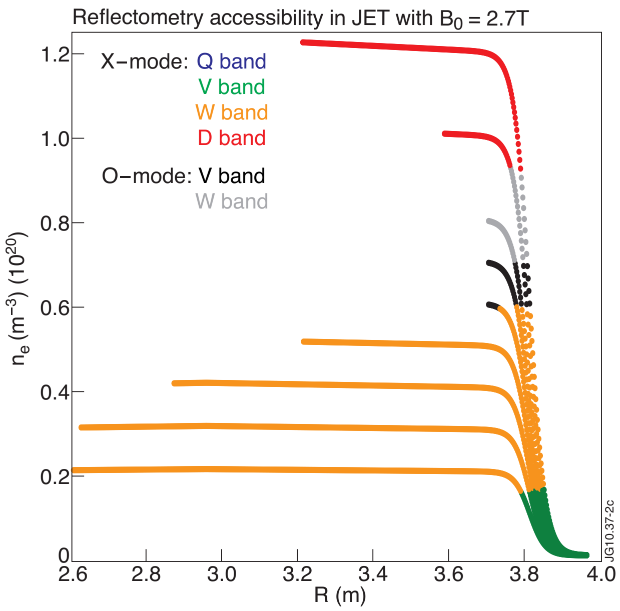
| | **Frequency band** | **Polarisation** |
|---|---|---|
| 1 | Q (33-51GHz) | X-mode |
| 2 | V (49-76GHz) | X-mode |
| 3 | W (74-111GHz) | X-mode |
| 4 | D (109-150GHz) | X-mode |
| 5 | V (49-76GHz) | O-mode |
| 6 | W (74-111GHz) | O-mode |

*Table 1: The new reflectometers installed on JET.*



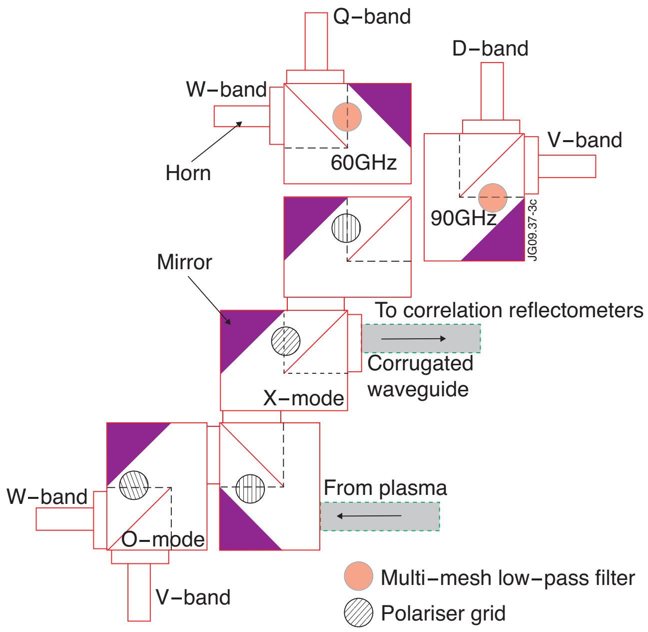




*Figure 1: Reflectometer accessibility with $B_0 = 2.7$ T. O-mode polarisation is only shown at positions where X-mode is absorbed by EC harmonics. Only X-mode polarisation can probe flat density profiles. Q-band reflectometer is used for $B_0 < 2.4$T*

*Figure 2: Layout of the quasi-optical boxes used on reception. Each box is a quasi-optical box as described in6. The boxes are fitted with either a polariser grid or a low-pass filter. Reflectometers (not shown) are coupled to the boxes through horns.*

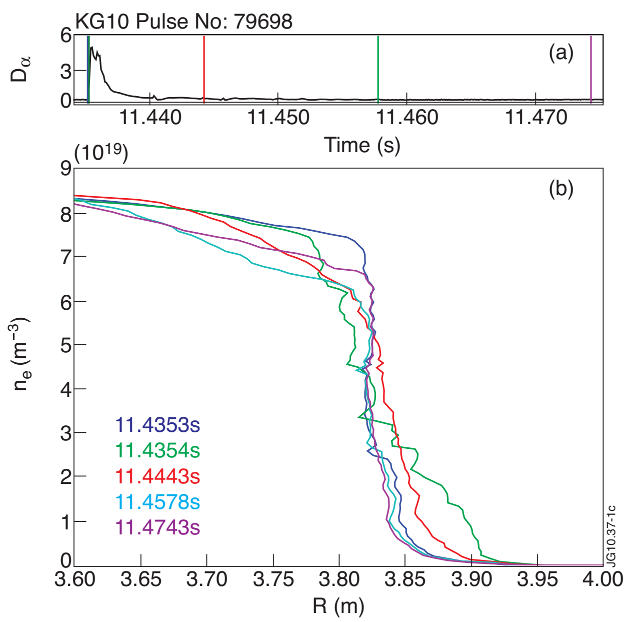



*Figure 3: Example of density profiles measured with the reflectometer. a) $D_\alpha$ emission signal; b) electron density profiles measured on JET midplane. The time resolution is 15μs but only selected profiles are represented. The first profile is measured just before the ELM crash seen on the $D_\alpha$ trace. The subsequent profiles show how the pedestal collapses in a few μs and its slow recovery after tens of ms.*