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A two color mm-wave interferometer for the JET divertor[a)]

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An interferometer with compensation for vibration and large scale mechanical movements has been designed and built to measure the line integral electron density along three different lines of sight through the JET divertor plasma. Overcoming the effects of a long transmission path, having an estimated 65 dB loss, requires oversized waveguide transmission lines, sensitive heterodyne detection, low loss quasioptical circuits, and highly stable sources. The sources are frequency doubled, phase-locked, Gunn oscillators producing 15 mW at 130 GHz and 10 mW at 200 GHz. Waveguide Schottky mixer diodes generate reference and output signals at an IF of 10.7 MHz and the LO Gunn diodes are phase locked to the reference IF. Corrugated feedhorns and ellipsoidal mirrors are used for beam control and polarizing wire grids for beam splitting and recombination. To minimize unwanted, direct coupling of source power into the signal detectors, Brewster angle beam dumps and Faraday rotation isolators are used in the transmit and receive QO circuits, which in turn are separated, on opposite faces of a vertical plate. Martin–Pupplet polarizing interferometers are used to multiplex the two colors into a single coaligned, copolar output beam and to demultiplex the return beam. Constant fraction discriminators are used to optimize the accuracy of the phase detectors, which have sampling and recording rates of 1 MHz and a resolution of ~7° (0.02 fringe).

I. INTRODUCTION

An important aspect of the future JET programme will be the control of plasma impurities, which degrade the properties of the bulk plasma, by the operation of a divertor. This system, including a toroidal target plate assembly and four divertor coils, has recently been installed inside and at the bottom of the JET torus. The electron density is a vital parameter which must be measured in the divertor region in order to validate theoretical models of divertor action. One type of diagnostic suitable for measuring the electron density in the divertor is the microwave interferometer. This paper discusses an instrument designed to measure the line-integrated electron density of the plasma in the flux bundles below the "X" point of the divertor.

II. GENERAL DESIGN

Simple models of the plasma in this region suggest that suitable source frequencies are in the range 100–200 GHz; the actual frequencies chosen being 130 and 200 GHz. Due to very limited access in the divertor region only three lines of sight are possible through the divertor plasma, see Fig. 1. Since the system must be compatible with the D-T phase of operations on JET, when radiation levels within the Torus Hall will be high, sensitive components such as sources and detectors must be located outside of the Torus Hall. This means, however, that the waveguide runs connecting the antennas in the divertor to the sources and detector systems in the Diagnostic Hall each have a length >40 m and therefore

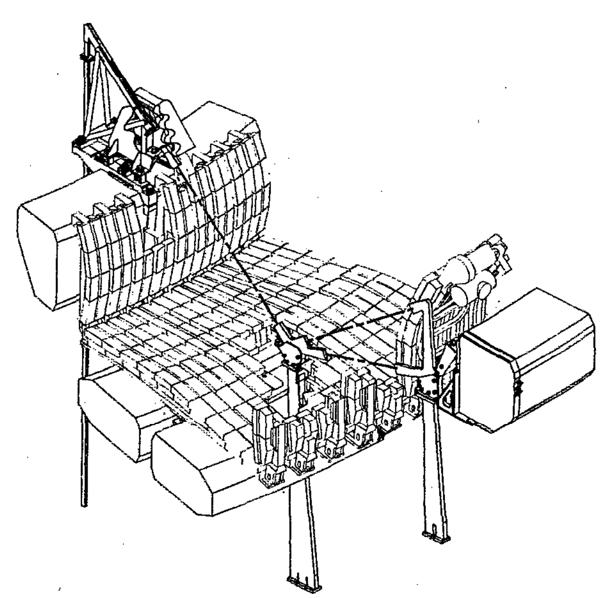

FIG. 1. Lines of sight in the divertor, defined by the transmit and receive antennas. Two pass through the outboard flux bundle and one through the inboard flux.

[a)]The abstract for this paper appears in the Proceedings of the Tenth Topical Conference on High Temperature Plasma Diagnostics in Part II, Rev. Sci. Instrum. **66**, 425 (1995).

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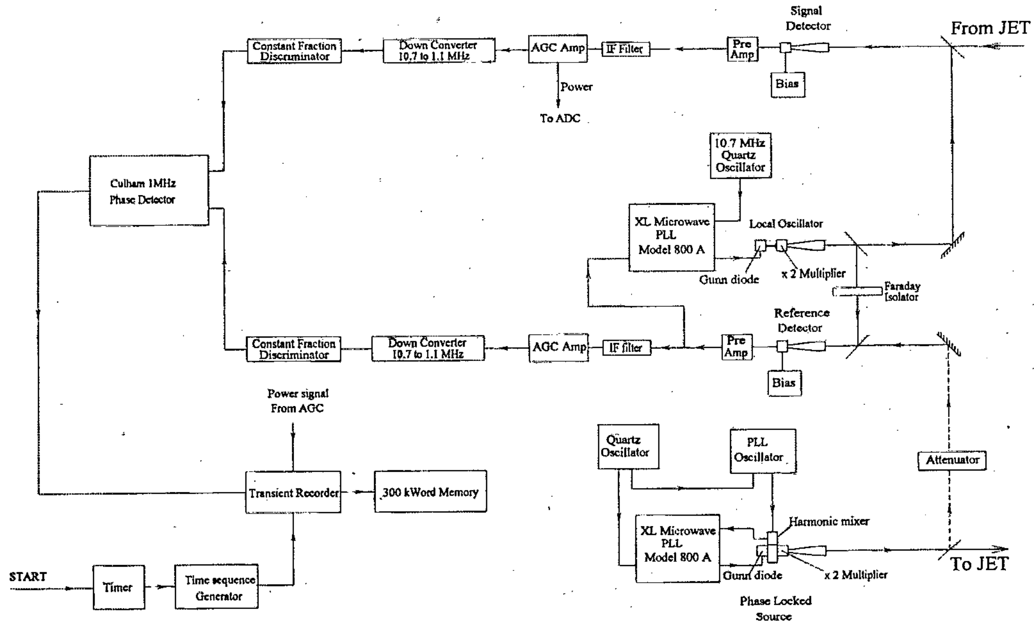

FIG. 2. A schematic of one channel showing the heterodyne detection system, sources, and electronics.

must be oversized to avoid unacceptable levels of attenuation. Nevertheless, the total attenuation of a waveguide circuit, including the transmission loss between the antennas in the divertor, is estimated to be about 65 dB. Cross-talk levels in the source/detection system must therefore be kept very low to avoid corruption of the genuine signal, and additional losses in this section of the instrument must also be kept low. JET plasmas have a typical lifetime of 40–50 s so, with long waveguides and heating in the divertor region, changes in the optical path length of the measurement arm are also likely to be a problem. Phase changes due to the mechanical effects can be distinguished from those due to the plasma by having two interferometers with different source frequencies operating simultaneously along the same transmission paths. Assuming O-mode propagation through the plasma and that the critical electron density for each probing frequency is much greater than the maximum density in the line of sight, then the line integrated density and the magnitude of any mechanical movement can be easily calculated from the two phase measurements. If the probing frequencies are f_1 and f_2, where $f_1<f_2$, and the measured phase shifts are ϕ_1 and ϕ_2, respectively, then the line integrated density is given by

$$\int n_e dl=\left(\frac{4\pi\epsilon_0 m_e c}{e^2}\right)\left(\frac{f_1 f_2}{f_2^2-f_1^2}\right)(f_2\phi_1-f_1\phi_2), \qquad (1)$$

and Δx, the magnitude of the relative change in lengths of the arms of the interferometer, is given by

$$\Delta x=\frac{c}{2\pi}\left(\frac{f_2\phi_2-f_1\phi_1}{f_2^2-f_1^2}\right). \qquad (2)$$

The oversized waveguide systems incorporate mitred bends and tapers which, if the source frequencies are swept, can cause varying levels of mode conversion, which in turn can corrupt the phase measurements. The sources are therefore operated with fixed frequencies in a heterodyne circuit[1] (Fig. 2) which has a reference arm IF signal as well as a measurement arm IF signal. The evolution of the phase difference between these two signals provides the phase output of the instrument. This arrangement enables the sense of the phase measurements always to be known even though the source frequencies are fixed. An additional advantage of the heterodyne system is that the effects of source and detector noise are minimized, giving a low-noise receiver with high dynamic range.

By phase locking the sources to stable, low-frequency oscillators with low-frequency jitter, the requirement for a long compensating reference arm is removed.

III. THE MICROWAVE CIRCUIT OF THE SOURCE/DETECTION SYSTEM

This section of the diagnostic has three main functions:

To multiplex the 130 and 200 GHz source beams into a single coaxial, copolarized beam for transmission through one of the waveguides to the divertor and demultiplex the return signals to feed the separate signal detectors.

To strip off small fractions of the transmitted signals and relay these to the reference detectors, to provide phase reference signals. Local oscillator signals must also be provided for both signal and reference detectors.

To ensure that the only effective path for source signal is via the plasma arm and that leakage from any other route is kept to a level so low that it cannot change the output of the phase detection system by more than 7°. The leakage field should therefore be <tan(7°) of the returning signal field. Since the attenuation of the plasma arm is about 65 dB, any crosstalk must be kept at a power level at least 83 dB below the source signal. This is a demanding requirement and dominated the design.

A quasioptical (QO) approach was used to meet these requirements. QO provides lower loss, wider bandwidth, and

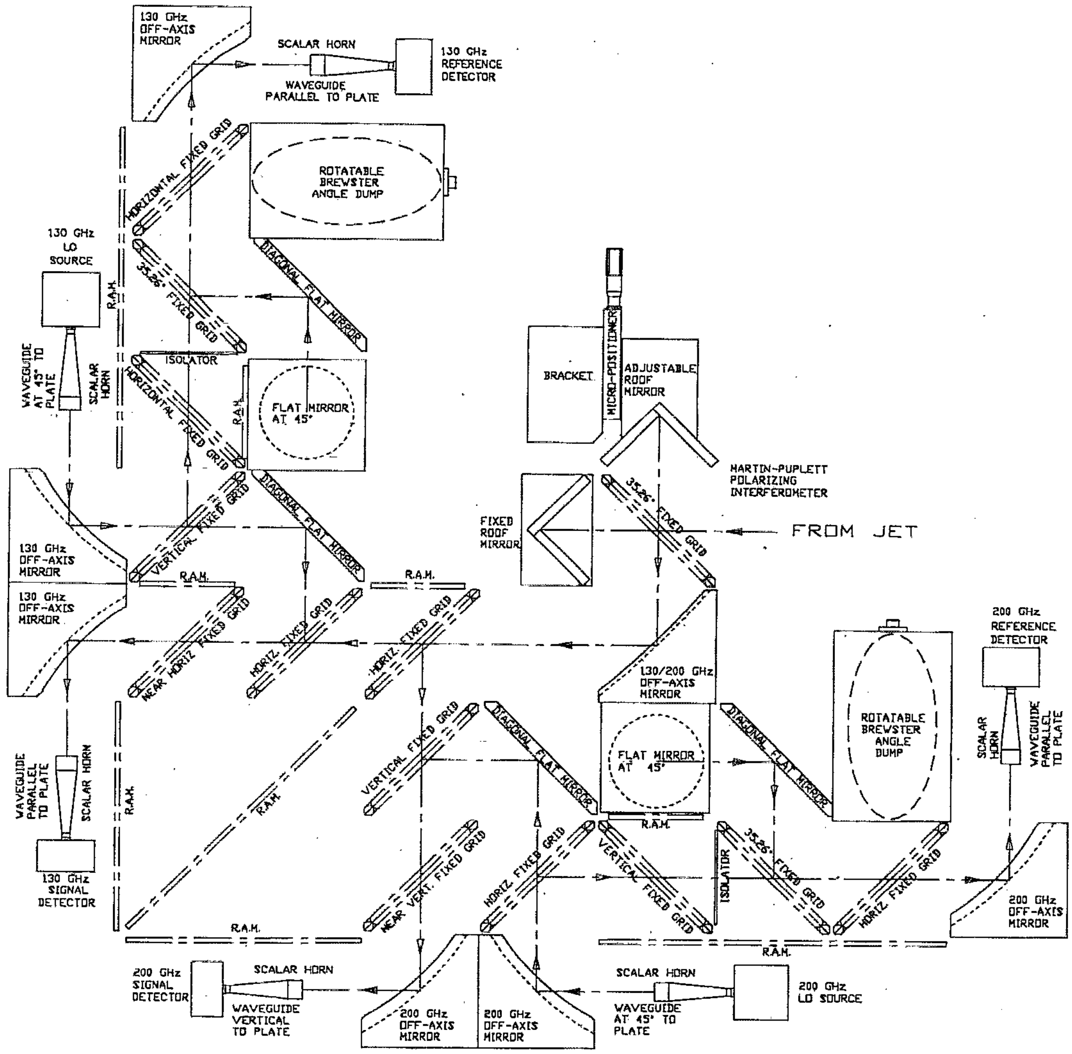

FIG. 3. A simplified drawing of the receiver QO system. Many support components for individual QO units have been omitted for clarity.

leads to lower VSWR than conventional waveguide construction. QO is also cost effective above 100 GHz.

Gaussian beam-mode analysis was the main analytical tool used to design the optics. Given the leakage requirements, maximum truncation at any optical element was set to four beam widths, where a beam width is the $1/e$ amplitude radius. The arrangement of components was based on a "modular cube" design in which each cube has the same size and carries one optical element. The truncation level and the need to transmit the 130 GHz beam across four cubes before refocusing determined that a cube of size 125 mm with apertures of 100 mm should be used.

Corrugated horns provide beam-forming and source/detector impedance matching.[2] These horns were electroformed using sacrificial aluminium mandrels. Longitudinal grooves were machined into external cylinders formed at the aperture end of the horns, to provide polarization alignment. Polarizing wire grids act as beam processing elements, separating and recombining beams to form multiplexers, demultiplexers, and beam sampling units. The grids were formed using 10 μm tungsten wire spaced on a 25 μm pitch. Off-axis ellipsoidal mirrors control the diffractive spreading of beams. Mirrors placed close to the feed horns form beams which propagate through four cube units before requiring reconvergence by an internal refocusing mirror. The mirrors were machined to surface tolerances better than 10 μm and then hand polished. Hard ferrite sheets Faraday rotate the plane of polarization to form, with polarizing grids, isolators. Isolation levels of 17 dB at 130 GHz and 14 dB at 200 GHz are provided.[3] Microwave dumps, formed from solid radar absorbent material (RAM) provide absorbers for unwanted power. The material is Eccosorb MF110 set with a Brewster angle of 62°. Its thickness was chosen such that reflections from the front surface caused by the effective angular spread of the incoming beam ($\approx 1°$) would be greater than the power returned from internal reflection on the back surface. The predicted return loss performance for these dumps of >30 dB was achieved.

All of the components making up the QO circuit are mounted on a large (1375 mm by 1562.5 mm) 20-mm-thick aluminium plate. To achieve isolation, transmit components lie on one side of the plate and receive components on the

TABLE I. The harmonic numbers and precise values of the frequencies used in the sources.

Doubler output frequency (GHz)	130	200
Quartz oscillator frequency (MHz)	90.40334	94.78673
PLL oscillator (GHz)	4.3394	4.5497
Mixer harmonic No.	15	22
Gunn diode frequency (GHz)	65.000	100.000

TABLE II. Detector characteristics.

RF frequency (GHz)	130	200
Input waveguide size	WR 7	WR 5
IF frequency (MHz)	10.7	10.7
Noise temperature (DSB)	800 K	1000 K
Conversion loss (dB)	5	6

other side. On the transmit side, both color signals are formed into Gaussian beams by horns and refocused by off-axis mirrors. For both frequencies, a small and adjustable fraction of the transmitted beam is stripped off by a polarizing grid, the wires of which are set at an angle close ($<1°$) to the pass plane, to provide one of the two signals for the reference signal detector. Both transmit signals are then multiplexed together in a Martin–Puplett polarizing interferometer (MPI).[4] Losses in this part of the QO circuit are measured to be 0.6 dB. Finally, the copolarized signals are coupled into oversized WG16 (WR90) waveguide for transmission to the divertor. The low-power reference beam stripped from the main beam is further attenuated by two rotatable grids backed by Brewster angle dumps. Finally, it is reflected by a fixed grid, before being directed through a hole to the receive side of the plate. On the receive side (see Fig. 3), the returning two color signals are demultiplexed by an identical MPI. Copolarized LO signals are added by grids and the beams are received by the detector feed horns. LO signal is also passed to the reference detectors through free-space Faraday isolators, whose function is to ensure that none of the small reference signal is allowed to pass through the LO chain and contaminate the returning plasma signal.

IV. SOURCES AND DETECTORS

Phase-locked microwave sources at 130 and 200 GHz produce 15 and 10 mW, respectively. The source modules consist of a Gunn diode (at 65 or 100 GHz), a 17 dB coupler which samples the Gunn output, and a frequency doubler. A harmonic mixer is attached directly to the coupler. The sources are phase locked by controlling the bias voltage of the Gunn diodes using an XL Microwaves model 800A phase-lock loop module. The IF signal for the phase-lock loop is generated by the harmonic mixer which is pumped by the PLL oscillator, the output frequency of which is 48 times that of a separate quartz oscillator. When the Gunn source is locked, the harmonic mixer's IF signal has a frequency equal to the quartz oscillator frequency, see Table I.

Close to each of the two RF frequencies, a second, frequency-doubled source is used as a local oscillator to generate an IF signal at 10.7 MHz, from the output of a room-temperature Schottky diode detector, see Table II. A part of the power from the phase-locked source is mixed with a fraction of the power from a local oscillator on a reference detector. A fraction of the IF output from the reference detector is used to phase lock the output of the local oscillator Gunn diode by controlling its bias voltage. In this case the RF reference for the phase-lock loop electronics is from a 10.7 MHz quartz oscillator. In fact the same quartz oscillator is used to frequency lock both the 130 and the 200 GHz local oscillators at 10.7 MHz above the respective source frequency. In each channel the signal returning from the divertor is mixed on a second detector with a LO signal to produce a nominal 10.7 MHz IF signal, modulated by the phase changes induced by the plasma, or by changes in the electrical length of the plasma arm waveguides.

V. ELECTRONICS AND DATA ACQUISITION

The signal from any detector is first passed through a low-noise (1.8 dB) preamplifier, with a gain of about 45 dB, and then through a ceramic filter, bandwidth ~100 kHz, which has constant group delay over the passband to avoid distortion of fast changes in the IF signal. This unit limits the bulk plasma electron cyclotron emission signal, which can be the dominant source of noise. Following the filter, an automatic gain control (AGC) amplifier, with a frequency response of ~200 kHz, provides a constant amplitude IF signal for the phase measurement circuits when the input varies over a range of 70 dB in power. The AGC amplifier also provides an output directly proportional to the input power, over a range of 70 dB, which will be used to monitor the signal returned from the divertor. A frequency downconvertor then changes the IF frequency from 10.7 to 1.1 MHz, so the best possible phase resolution is 6.6° with a clock frequency of 60 MHz in the phase detector. The downconvertor output is fed to a zero-crossing module which uses constant fraction discriminators to make the timing of the output pulses less prone to variations due to fluctuations in the amplitude of the input signals. Finally, zero-crossing pulses pass to a phase detector having a local 12-bit register, updated at a 1 MHz rate, whose value is the algebraically integrated phase from the time of a reset pulse. The value of the register is periodically sampled and stored.

VI. PERFORMANCE TESTS

All four phase-locked circuits are stable and have been observed to remain locked without adjustment over periods of many hours.

An external, dummy measurement arm of length 5.2 m was constructed for the instrument using a sequence of mirrors. Over a period of several hours the phase differences between the measurement arm and reference IF signals were observed to drift less than $\pm 10°$.

A roof mirror unit with micrometer adjustment was included in the dummy arm. By recording the phase output of both channels at a rate of 50 Hz over a period of about 80 s, while stepping the micrometer every few seconds, datasets were generated which were used in Eq. (2) to calibrate the phase detectors. Results from this measurement show that the responses of the phase detectors are accurately linear over several "fringes." Calculations using the phase measurements gave the positions of the roof mirror with a standard deviation from the true positions ≈ 0.043 mm, which gives a corresponding standard deviation on the line-integrated density measurement $\approx 5.5\times 10^{16}$ m^{-2}.

[1] C. A. J. Hugenholtz and A. J. Putter, Course and Workshop "Basic and Advanced Diagnostic Techniques for Fusion Plasmas," Varenna, Italy, Sept. 1986. EUR 10797 EN, Vol. II, p. 469.

[2] R. J. Wylde, Proc. IEE **131**, 258 (1984).

[3] Graham Smith, Department of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, KY16 9SS, Scotland (private communication).

[4] D. H. Martin, in *Infrared and Millimetre Waves*, edited by K. J. Button (Academic, New York, 1982), Vol. 6, p 65.