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A multichannel interferometer for electron density measurements in COMPASS

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(Presented on 18 March 1992)

A compact seven channel interferometer has been designed and built to measure electron density profiles in the COMPASS (compact assembly) tokamak. Two far-infrared (FIR) laser cavities are optically pumped with a single continuous-wave CO_2 laser, generating two similar beams at $\lambda = 433$ μm with a small, tunable difference frequency (0.5–1.0 MHz). The COMPASS facility incorporates a complex set of poloidal field coils close to the vacuum vessel as well as a versatile set of close coupled "helical" resonant magnetic perturbation windings which severely restrict diagnostic access. As a result a novel approach to the optical circuit has been necessary. Wire grid polarizers are used to divide the laser power equally between channels and to overlay probing and local oscillator beams after the probe beams have made a double pass through the plasma. Gaussian beam-mode optics is used to minimize the size of the optical components.

I. INTRODUCTION

COMPASS (compact assembly) is a small noncircular cross-section tokamak experiment ($R = 0.557$ m, $a = 0.22$ m, $b/a = 1.7$, $B_T = 2.1$ T, $I_p \leqslant 400$ kA) designed to study a wide range of plasma phenomena associated with the various limits to tokamak operation. A particular area of interest is that of stability close to tokamak density and β limits. High power ($P_{\rm rf} \sim 2$ MW) electron cyclotron resonance heating (ECRH) at 60 GHz will be used both for bulk heating and current drive. 200 kW of ECRH at 28 GHz is also available for preionization studies at 1.1 T as well as 300 kW of lower hybrid current drive at 1.3 GHz. The 60 GHz rf will be used to locally modify the current profile by both localized heating and direct local current drive. Modulated ECRH will also be used to interact with the rotating $m = 2$ island which plays an important role in disruption phenomena. The measurement of the density and current profiles is therefore a crucial requirement for the physics program. A density profile diagnostic for COMPASS therefore should have as many spatial chords as possible and good time resolution is essential because of the time scales of the plasma phenomena to be studied. Since current profile modification is an important physics objective, an interferometer which can be modified or converted to polarimetry is preferred and this suggests that wavelengths longer than ~ 300 μm should be used in order that the Faraday rotation angles are sufficient for accurate measurement. For this reason and because of the additional difficulties associated with vibration of the interferometer structure, shorter wavelengths were not used even though considerably more power is available from the laser system at 118 μm.

II. INTERFEROMETER

Dual beam interferometers using CO_2 gas discharge lasers to optically pump twin far-infrared (FIR) lasers have been reported elsewhere.[1,2] In the COMPASS interferometer system the CO_2 laser (Edinburgh Instruments PL6) operates stably at 160 W after a period of about 1 h to warm up. The CO_2 laser output beam is divided equally between two FIR laser cavities containing formic acid vapor at a pressure of $\sim 2 \times 10^{-1}$ Torr. Each FIR cavity produces an output power >50 mW at a wavelength of 433 μm. More than 90% of the output of the FIR lasers is in the transverse-electromagnetic TEM00 mode and these predominantly Gaussian beams are coupled into oversize circular glass waveguide[3] which are used to propagate the beams over a distance of about 5 m to the load assembly. The 70-mm-diam glass tubes are fitted with mica end caps and can be filled with dry nitrogen gas to minimize water vapor absorption power losses. Close to the machine the output of the glass waveguides is reformed using off-axis ellipsoidal mirrors and a small fraction of each beam is split off and mixed onto a Schottky corner cube detector to produce a reference signal for the phase detection electronics. The output from all eight detectors is at the intermediate frequency (IF) between the two FIR lasers. By tuning either of the two laser cavities the IF can be varied in the range 0.5–1.5 MHz. At present there is no feedback control of the IF frequency and some thermal drift does occur. Nevertheless the IF frequency is stable at 1 MHz to about ±10 kHz for >5 s.

III. OPTICS DESIGN

The probing beams must be limited in width to pass through windows in the plasma vessel without significant attenuation. Diffractive spreading of Gaussian beams provide limits to the maximum distance beams can be thrown before they expand beyond their initial size, whatever optical phase front is chosen for the launched beam. This "maximum throw" constraint[4,5] is a strong limiting factor on the design of the system. For the D shaped vacuum

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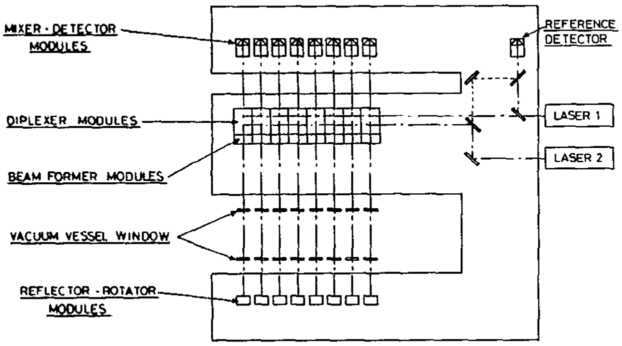


FIG. 1. Schematic of COMPASS interferometer.

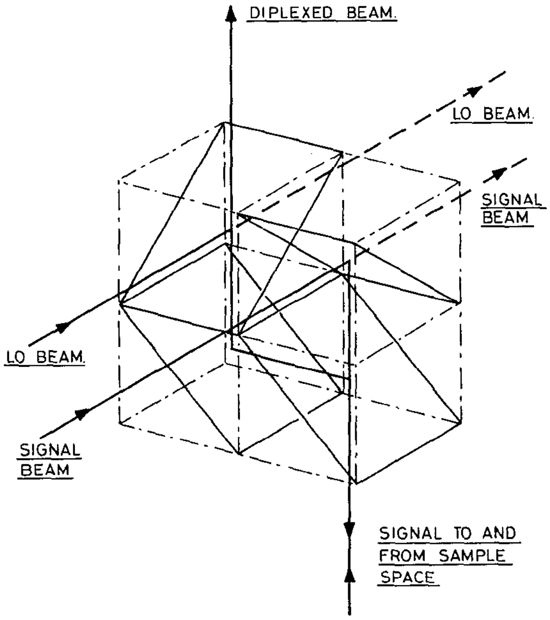


FIG. 2. Layout of grids in simple diplexer.

vessel the vertical diameter from window to window is 1.09 m. At 433 μ, the minimum beamwidth ($1/e$ amplitude radius) at the window is approximately 12 mm for a beam to propagate to the other widow and still remain no larger than 12 mm. This is associated with a beamwaist at the middle of the torus of 9 mm. The window size is 35 mm and so beam truncation will occur at the 18 dB level.

The complete optical system is illustrated schematically in Fig. 1. The output from one of the laser cavities is directed through a train of seven diplexer modules. Each diplexer module strips off a fraction of the incident beam to provide equal-power *signal beams* which are directed in parallel across the sample space. Each of these beams is returned, along the same path, to its diplexer module by a rotator-reflector module. The output from a second laser is similarly directed through the same trains of diplexer modules to give seven *local-oscillator* (LO) beams. The signal beam and the LO beam in each of the seven diplexer modules are overlaid there are the diplexed beam is directed to one of seven Schottky diode mixer detectors.

The double pass of the sample space made by each signal beam allows the paths of the signal and local-oscillator beams to be close together (apart from the transits of the sample space), thereby minimizing errors due to vibrations which cause changes in the optical path. The double pass also increases the sensitivity of the system by doubling the phase change produced by the interferometer for a given density.

The reflector-rotator module uses an off-axis ellipsoidal mirror to condense the beam to a beamwaist onto a roof-edge reflector with its roof edge at 45° to the polarization of the incident beam. The signal beams are returned across the sample space with their planes of polarization rotated by 90°. This allows polarizing grids to be used to recombine the returning beam with the LO beam in the diplexer modules. It also provides for discrimination in the diplexer against the signal power reflected at the windows in the plasma vessel, which suffers no rotation of the polarization.

The diplexer modules are based on the polarizing properties of planar grids of parallel metal wires. A beam incident on such a grid is decomposed into its two orthogonally polarized components. The basic diplexer module comprises three such grids and a mirror, whose rectangular frames have the relative orientations shown in Fig. 2 (each lies in a diagonal plane of a cubic unit). The incoming signal beam is incident on the grid in the first cube, the wires in which are orientated so that the appropriate fraction of the incident power is split off by reflection, the rest being transmitted onwards to the next channel. The split-off reflected beam passes through the grid in the second cube, the wires of which have the orientation required for 100% transmission of the beams, and thence to the sample space, to return with its polarization rotated through 90°. It is therefore wholly reflected from the grid in the second cube and passes out of the diplexer after reflection from the mirror in the third cube and transmission through the grid in the fourth cube, the wires of which are orientated to give 100% transmission for this beam.

The incoming LO beam on the other hand is incident on the grid in the fourth cube as shown in Fig. 2. The wires in the grid have the orientation required to allow through the appropriate fraction of the incoming power for onward transmission to the next channel. The reflected component is overlaid with the signal beam which, as noted above, passes through this grid; the outgoing diplexed beam is thus formed, leaving the diplexer with its signal and local-oscillator components having orthogonal polarizations.

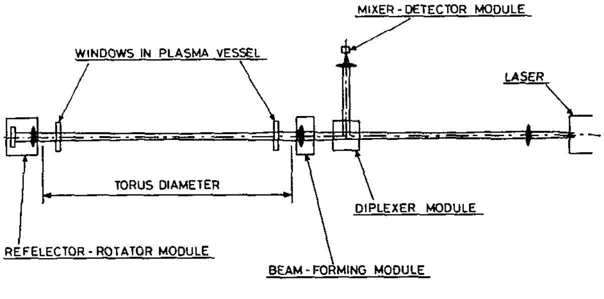
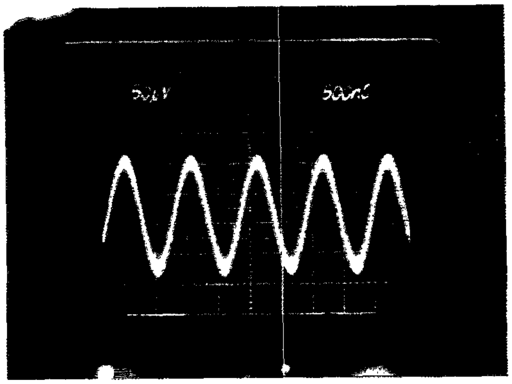
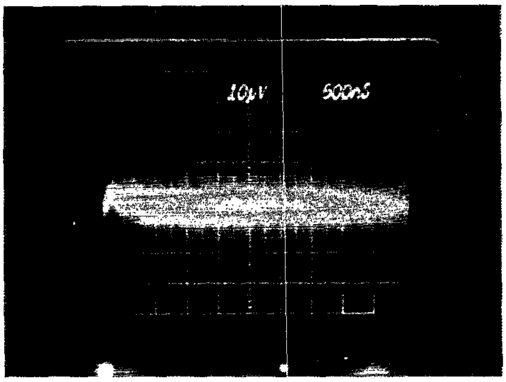


FIG. 3. Interferometer optical circuit.



a) Channel 7 IF signal



b) Channel 7 IF with scene beam blocked

FIG. 4. Channel 7 IF signal, (a) normal operation, (b) with absorbing material blocking the return beam.

The mixer diodes are mounted in corner-cube reflectors. Each is fed by an off-axis ellipsoidal reflector which produces a beam correctly matched to the corner-cube antenna. Also included in this module is a wire grid which mixes the orthogonally polarized LO and signal beams to give a co-polarized beam onto the corner cube mixer. The angle of the corner cube is set to match the polarization of this combined beam.

The full optical circuit is shown in Fig. 3 where lenses are shown to simplify the figure but off-axis ellipsoidal mirrors, rather than lenses, are actually used. Off-axis mirrors introduce path folding but similar path folding would be required with lenses too if provision is to be made for beam alignment reflectors. A beam-forming module, containing a plane reflector and an off-axis ellipsoidal reflector, is used in tandem with each diplexer module. The parameters of the ellipsoidal surface are determined by the size of the laser beamwaists.

The mechanical design is based upon the use of split cubes. The polarizing wire grids are placed on the diagonals of the cubes. The cubes are held on plates and positioned by dowels. Buildup errors are controlled by minimizing the number of mating surfaces between any one component and any other. The polarizing grids are made of 10 μm tungsten wire wound and glued on a 25 μm spacing onto stainless steel frames.

IV. SIGNAL CONDITIONING

A single detector bias/head amplifier module amplifies the IF signal from the Schottky detector. This has an adjustable gain of up to 32 dB or can be switched to operate in automatic gain control (AGC) mode. The fringe amplitude is also monitored by a precision rectifier and the smoothed dc output from this is separately digitized for each channel. The integrated phase change along each of the seven vertical interferometer paths is measured by feeding the amplified 1 MHz IF signals via a filter to a fringe counter where the phase of the signal is compared with that from the reference detector. Zero-crossing pulses are generated from the IF signals and these are used to start and stop a scalar which counts pulses from a 60 MHz clock generator. The phase resolution of this system is $\sim 6°$ corresponding to a density resolution for the central channel of $\sim 0.6 \times 10^{17}$ m^{-3}. The phase change during an IF cycle are stored in a register and compared with that during the previous cycle. A real time continuous analog output is then generated via a digital-to-analog converter (DAC).

The signal-to-noise level of the fringes achieved with the interferometer in the absence of plasma is shown in Fig. 4. The top trace is the output from one of the Schottky diodes without any amplification or filtering. The bottom trace shows the level of the same signal with the return beam blocked with an absorbing material.

V. CONCLUSIONS

A novel approach has been taken to the optical design of a FIR interferometer for the COMPASS device. This has been necessary because of the very limited diagnostic access close to the vacuum vessel. Vertical access is restricted by the comprehensive set of poloidal field coils which are very close to the port flanges while feeders bars to the helical resonant magnetic perturbation (rmp) windings limit the optics support structure in the toroidal direction. A seven channel system has been built and functions satisfactorily, generating stable fringes with good signal-to-noise. The performance in the presence of magnetic fields and tokamak plasmas will shortly be established and later the system will be extended to include simultaneous measurement of the Faraday rotation along the same chords.

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