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OCTOBER 1980

PPPL-1714
UC-20a,d

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PDX MULTICHANNEL INTERFEROMETER

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PDX Multichannel Interferometer

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Abstract

A 10 channel, 140 GHz homodyne interferometer is described for use on PDX. One feature of this interferometer is the separation of the signal source and electronics from the power splitters, delay line, and receiving systems. The latter is situated near the upper and lower vacuum ports between the toroidal field magnets. A second feature is the signal stabilization of the EIO source by means of an AFC system. The complete interferometer is described including block diagrams, circuit diagrams, test data, and magnetic field test conducted on the preamplifiers, microwave diodes, isolators, etc., to determine the extent of magnetic shielding required. The description of the tracking filters and digital phase display circuit is referenced to accompanying reports.

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1. Introduction

Homodyne interferometry has been much discussed in the literature.¹⁻⁵ Generally the phase difference is measured between two paths, the reference path and the path through the plasma. The power from the source is split between these two paths and then recombined at the receiving system, usually in the form of a phase detector. The unequal length of the two paths and the dispersive microwave network results in a frequency sensitive system. When the source is frequency modulated with a linear ramp voltage, there will be generated sine wave-like "fringes" at the phase detector output resulting from the unequal time delay in each path. The linear ramp is controlled by a 1 MHz clock (which is the reference signal) and the amplitude of the ramp is adjusted to produce 2π radians of phase delay in one linear sweep forming a single sine wave-like waveform. This sine wave will slip in phase with respect to the reference signal when there is a phase change in either path. When the effective path length of the plasma leg of the interferometer changes as a result of the varying electron density, there will be a corresponding phase change. This phase change is linearly proportional to electron density up to values of $n_{\text{avg}}/n_c \approx 0.2$ (where n_{avg} is the average line density being measured and n_c is the plasma cutoff density). Long plasma paths and peak densities to be measured result in multi-radian phase changes requiring special "fringe" counting circuits. Such circuits have been developed by Cutsogeorge⁶ and Greenberger.⁷

In multichannel interferometry, the source signal is split up between several reference paths and plasma paths. In order to reduce the phase difference between channels, the differential path lengths must be minimized. The PDX multichannel interferometer divides five channels from

each microwave source. Figure 1 is a block diagram of the 10 channel interferometer.

In the past, the multichannel interferometers were constructed so that the source, splitters, receivers, signal processing, power supplies, etc., were kept in the same cabinet. This allowed the reference leg to be very short and the plasma leg to be very long. The differential path length from channel to channel was kept fairly constant in this manner. Because of the space considerations, the mechanical configuration of the vacuum vessel, and the insertion of the divertor coils within the vacuum vessel, the plasma path legs of the interferometer would be excessively long. It was decided to change the interferometer configuration such that the source, power supplies, and electronics would be separate from the power splitting, reference paths, and receiving systems. The former would be placed on a balcony while the latter would be placed next to the upper and lower ports on the vacuum vessel.

II. The Signal Source

The signal source cabinets are located on a balcony approximately at the same level as the upper port on the PDX vacuum vessel. These cabinets house the power supplies, the Extended Interaction Oscillator (EIO), the Automatic Frequency Control (AFC) system, the cooling unit, ramp modulator, and signal processing circuits. Figure 2 is a block diagram of the two signal sources, each supplying power to five channels. The output of each EIO is transmitted via overmoded guide to the upper enclosure opposite the upper vacuum port. Here the reference and plasma legs are separated and power split to feed each channel. Figure 3 is a photograph of one of the signal source cabinets.

The EIO power supply was built by Kilovolt Corporation and consists of several regulated power supply units in one cabinet. The following table

lists the voltage and current ranges out of each power supply:

Filament supply 0-12V @ 6 A max.

Cathode supply 0-10KV @ 100mA max.

Anode supply 0-8KV @ 5mA max.

Input power 115 VAC, 25A, 1 ϕ , 60 Hz.

A. AFC-System

As the EIO warms up, there is a slow drift in frequency and output power. Since the phase detecting system in the receiver is balanced with respect to amplitude changes, any change in frequency unbalances the amplitude each diode sees in the detector. It is therefore advantageous to incorporate some sort of frequency stabilizing system. The most straightforward system is shown in Fig. 4. It consists of a modified Travis^{8,9} discriminator connected to an instrumentation amplifier. Its output resembles the familiar discriminator S curve. The error signal is sent to a control amplifier in the power supply cabinet. The output of this amplifier is connected to the reference input of the cathode power supply pass tube control amplifier. When the frequency of the oscillator changes, an error signal is generated and amplified. This in turn is used to change the EIO cathode voltage to bring it back on frequency set by the Travis discriminator.

The Travis discriminator consists of two non-confocal-resonators¹⁰ which act as tuned filters. One is tuned above and the other tuned below the desired frequency. Some of the output power from the EIO is sampled by means of a 20 db coupler and split equally between the two resonators by an H plane tee. Each resonator is made up of two 2 inch diameter mirrors with a 4 inch radius of curvature. One of the mirrors in each resonator is fixed while the other is movable. The separation can be varied between 50 and 80 mm. A zero bias silicon detector is mounted on each of the movable mirrors. It is

important to note here that if a biased detector is used, there will be an additional offset problem with DC bias level changes that can produce an appreciable error signal in the zero crossing of the discriminator S curve. The output of each detector is fed to the input of an instrumentation amplifier. The output of this amplifier, when the rf frequency is swept, will show a typical discriminator S curve. The output is fed to a loop filter and amplifier that controls the cathode voltage of the EIO tube.

The system requirements are such that the AFC loop should hold the output frequency to ± 1 MHz over a cathode power supply variation of 600 volts (for this particular EIO, between 7.6 to 8.2 KV), and that the acquisition of lock be automatic. Referring to Fig. 4, the different gain parameters must be known. Figure 5 indicates the conditions under which the particular S curve parameters were derived. With a mirror separation of 56 mm, and 10 mW of power being split equally between the two resonators, the discriminator slope is 250 pV/Hz. From data obtained on both EIO's, the modulation sensitivity, i.e., oscillator gain, varies between 0.3 to 1 MHz/V. The instrumentation amplifier in Fig. 6 was designed to have a gain of 40 into a 50 ohm load. Its frequency response and CMRR are plotted in Fig. 7. The cathode power supply regulator gain was computed to be 60. The loop filter/amplifier makes up the remaining gain and filtering required in the loop. The circuit diagram is shown in Fig. 8. An AFC loop Bode plot shown in Fig. 9 indicates a min-max range resulting in a closed loop bandwidth of 2.5 to 4 rad/sec. The 10db variation is due to EIO tube gain variation with voltage.

When the AFC loop is closed, the requirement of automatic acquisition must be met. Since the discriminator has a peak separation of 80 MHz and the desired pull-in range is approximately 400 MHz, lock will not occur unaided. If a triangular sweep signal is introduced in the absence of lock, the EIO

will sweep through the discriminator operating frequency and lock will result. Referring to Fig. 8, the LM 308 is the loop integrator and the 741 is a Schmitt trigger set to threshold at ± 10 volts. With no input from the discriminator, the output voltage to the power supply would be a triangular wave of ± 10 Vpp amplitude. Since ± 5 V will sweep the EIO tube through 400 MHz, at some voltage during the sweep the discriminator will be activated. Since the discriminator error signal is much greater than the sweep signal, a stable operating point will result and the sweep will stop.

B. Cooling and Temperature Monitor Systems

The power dissipation of the EIO requires that an adequate cooling system be employed. The Varian EIO's are water cooled tubes. Distilled water is used as the coolant and a flow rate of at least 0.2 gal/min. is required to cool the tube. The body temperature should not exceed 176° F (80° C). In normal use, the body temperature has not exceeded 140° F (60° C). The cooling system is interlocked by means of a flow switch that trips when the flow rate drops below 0.1 gal/min. If the flow is reduced to almost 0.1 gal/min but not enough to trip the flow switch, the temperature of the EIO could rise to a dangerous level. For this reason, a temperature sensing system is incorporated into the interlock system.

The dual temperature sensing system uses an Omega Engineering Model 50 controller. The controller has a panel mounted thermometer that continuously monitors the body temperature. An Iron/Constantan Thermocouple is bolted to the body of the EIO. The temperature limit switch is set at 145° F. If this temperature is exceeded, the controller shuts off the high voltage to the EIO. A backup system uses a JP45J2 thermistor manufactured by Fenwal Electronics which is bolted to the body of the EIO. Referring to the circuit

in Fig. 10, the thermistor is part of a bridge circuit. The differential input of an instrumentation amplifier is connected across the bridge. As the temperature increases, the thermistor resistance drops causing the amplifier output to go negative. A negative reference voltage on the inverting input of the comparator is used as a trip point. If the amplifier negative - going output exceeds $-V_{REF}$, then the comparator output goes from 0 to + 4 volts triggering on the transistor relay driver. The relay activates and latches up until the over-temperature switch is pressed releasing the relay. Figure 11 is a diagram of the interlock system that ties in the over-temperature and water flow switches into the EIO high voltage power supply.

C. Modulator

As mentioned previously, the homodyne interferometer system requires that the oscillator be swept in frequency. With an average differential path length of 20 meters, the EIO frequency must swing 15 MHz to produce a phase shift of 2π radians. The EIO modulation sensitivity can be in the 0.3 MHz/V to 1 MHz/V range. The peak to peak ramp voltage has to be between 15 and 50 volts in order to obtain a 2π radian phase shift over the range of modulation sensitivities. A ramp modulator system was designed to be triggered from a master 1 MHz clock and have an output voltage that can be set between 0 to 80 volts peak to peak. The block diagram of the modulator is shown in Fig. 12. It consists of a ramp generator, a power amplifier, and the EIO modulation circuit.

The 1 MHz clock signal is transmitted via balance pair to a line receiver in the ramp generator. Referring to the ramp generator circuit in Fig. 13, the output of the line receiver triggers a multivibrator which momentarily turns VMP-1 on shorting out the 1000 pF charging capacitor. The 2N3906 in the

VMP-1 drain circuit provides a linear charging current for the 1000 pF capacitor. The potentiometer controls the peak voltage of the ramp signal. The ramp signal then goes through a line driver into the power amplifier.

The ramp amplifier shown in Fig. 14 is a linear amplifier with a gain of 13 and a 10 MHz bandwidth. Since the amplifier is powered by an 80 volt power supply, the quiescent point is set at + 40 volts. The ramp signal is centered plus and minus around this voltage. The amplifier output is capacitively coupled to the EIO circuitry. Incorporated are several protection circuits in the event of an arc-over in the tube or EIO power supply.

The ramp signal is coupled through a capacitor with a 10 KV rating to the cathode of the EIO tube as shown in Fig. 15. The cathode is decoupled by means of a trifilar wound ferrite choke. Since the ramp modulation has a frequency of 1 MHz, the choke is not large and bulky. The modulation signal sweeps the cathode voltage around a quiescent operating voltage thereby changing the output frequency of the EIO.

III. Power Splitting and Receiving Systems

The generated signal from each EIO source is transmitted by overmoded waveguide to the upper port enclosure containing the transmit power splitters, reference line connections, receive mixers, preamplifiers and their power supplies. From the upper enclosure, there are four overmoded waveguide runs connecting the upper enclosure receive/transmit systems to those in the lower enclosure opposite a lower vacuum port.

The general layout is schematically shown in Figs. 16 and 17. The ten channels are split up into five in the horizontal plane and five in the vertical plane. There are three additional channels in the vertical plane

that can be used by other diagnostic systems in the near future. In its present configuration, four transmit and six receive channel systems are housed in the upper enclosure, and six transmit and four receive channels are housed in the lower enclosure. The power from each signal source coming into the upper enclosure is split into two paths by a 10 db coupler. One group of five paths are the transmit lines to the plasma and the other five paths the reference lines to the receive mixers. The reference line is connected to a 20 meter long folded delay line. The delay line assemblies, one for each of five channel groups, are supported by a frame to the main support structure holding the enclosures. A photograph of the upper enclosure and delay line connections are shown in Fig. 18. Two attenuators are placed in the transmit line so that the receive systems can be adjusted. Under normal operation, the attenuation is completely removed. A phase shifter inserted after each delay line is incorporated in the reference line before this signal is split up. The phase shifter is used to align the interferometer. After the phase shifter, the reference signal is split five ways and transmitted to each receiver 3 db hybrid. As noted, there are two transmit and two reference waveguide runs that connect the upper and lower enclosures.

The lower enclosure receives part of the transmit and reference signals for the remaining channels coming through the lower port on the vacuum vessel. Figure 19 is a photograph showing the lower enclosure in place. The cover is partially off to show the waveguide network inside the box.

A. Magnetic Field Test Results

The upper and lower enclosures containing the transmitting and receiving networks are placed near a set of toroidal and poloidal coils. The magnetic field plots indicate that, depending on the position of the components in the

box affected by the fields, these components could experience magnetic flux densities up to 2 Kilogauss. Components that would be affected are Faraday rotation isolators, transformers, inductors, and possibly sensitive devices such as the rf detectors.

Several tests were conducted on the microwave detectors, the preamplifiers, the microwave isolators, and the power supplies. The power supplies are located to the rear of the upper and lower enclosures and here they can experience magnetic flux densities up to 500 gauss. The power supply output was connected to a load, and voltage and current were monitored. There was no change in voltage, current, or ripple with and without the external field on the power supply.

The receiver preamplifiers contained no transformer, inductors, or ferrite chokes. The amplifier was subjected to magnetic flux densities up to 3 Kilogauss. No effect was seen on the amplified signals or noise level while the field was switched on and off.

The main concern was the effect of the magnetic field on detector diodes and ferrite isolators. The latter had to be shielded; the question was with what material and how thick. The type of detectors are the GaAs Schottky barrier detectors. A modulated 140 GHz microwave source transmitted power to the detectors through attenuators. The detectors were placed between the pole pieces of an electromagnet and subjected to magnetic flux densities up to 3 Kilogauss. The detectors were placed in their E and H planes (TE_{10} mode propagating) while the magnetic field was applied transversely and longitudinally to them. Under all of the above conditions, there was no effect on the detected signal as the magnetic field was switched on and off.

The effect on the isolators was more pronounced. A similar test setup was used, namely, a modulated 140 GHz source fed power to the isolator and

detected. The isolator was placed in its E and H plane while in the magnetic field. In the first group of tests, the magnetic field was placed across the isolator. In the forward direction, magnetic flux densities up to 2 Kilogauss degraded the transmission through the isolator by as much as 1.9 db. In the reverse direction, the isolation was degraded by up to 10 db when the magnetic flux density approached 2 Kilogauss. The isolators were then placed longitudinally in the magnetic field. In the forward direction the transmission loss sharply increased to 26 db at 500 gauss. In the reverse direction, the isolation was degraded by as much as 4db beyond 500 gauss. When the isolator is placed longitudinally in field densities above 500 gauss, the magnet in the isolator reverses its field to align itself with the external field. Once the external field is removed, the isolator magnet retains its polarization. In order to restore the isolator back to its original transmission mode, the field of the isolator magnet has to be reversed.

As a result of these tests on the isolators, a shield had to be designed so as to allow the field inside the shield to not exceed 150 gauss when an external flux density of 2 Kilogauss was applied. A 1015 carbon steel was chosen since it is approximately 99% iron with traces of carbon, manganese, phosphorous, and sulphur. A shield $4\frac{1}{2}$ inches long with a 1 inch ID, and 1 $\frac{3}{4}$ inch OD was used. The $\frac{3}{8}$ inch thick wall shielded the isolator such that a 2 Kilogauss external flux density produced a 115 gauss flux density inside the shield.

B. Receiver-Preamplifier

Each receiving channel on the interferometer has a phase detector whose output phase is proportional to the phase difference between the plasma leg

and reference leg signals, and whose amplitude is proportional to the received signal level. These signals are amplified by a 50 db amplifier capable of driving a 50 ohm cable. The amplifier modules also contain the bias circuits for each diode. The schematic of the amplifier is shown in Fig. 20 and its Bode diagrams in Fig. 21.

The amplifier is shielded in that the case ground forming the outer shield is separated from the signal ground. This separation of two grounds is maintained into the tracking filter electronics. A transformer located in the source cabinet electronics couples the signal into the tracking filter providing the ground isolation. The only place both grounds are connected is at the diode video signal/bias connector.

Since the amplifier has high gain, early models tended to oscillate when an output cable was connected. A 6 db pad was inserted between output cable connector and the LH0002 driver IC. All cables between detector diodes and amplifiers, and between amplifiers and tracking filter electronics are triax cables. Twinax was tried with unsatisfactory results since there is capacitive coupling between the shield ground and the signal ground.

C. Ground Loop Isolation

The separation of signal and shield or case ground paths is one way to break up ground loops. There are other precautions taken. The support structure for the upper and lower waveguide circuit enclosures is isolated from the machine support structure, i.e., torque frame, braces, coil cases, etc. The waveguide runs to the vacuum ports have isolation breaks in them. The delay lines have an isolation break where connected to the waveguide in the upper enclosure. The waveguides feeding the signals to the upper box have high voltage isolation breaks. The waveguide networks inside each box and

between upper and lower boxes are isolated. The result is to isolate the upper and lower waveguide networks from the machine, the supports, and the source cabinets, thereby preventing induced current loops and alternate grounds paths.

IV. Vacuum Vessel Waveguide and Antenna System

A rather elaborate structure had to be made to support the waveguide runs and the antennas inside the vacuum vessel. There are a total of thirteen antenna pairs with their associated waveguide runs connected to the outside through vacuum windows. Ten of these paths are used for the interferometer while the other three are used for other diagnostic equipment. The biggest problem was to route these waveguide runs around the divertor coil structures. To do this, an elaborate bracing system was built to support the runs. Furthermore, to eliminate closed loops preventing eddy current paths from forming, any such loop had to be opened. Ceramic spacers were first tried on the waveguide support structure at these points of loop opening. In many cases the ceramic fractured, so another vacuum compatible material, Vespel, was tried. This is a tough machinable plastic with good insulation and low outgassing properties.

In order to reduce waveguide losses, overmoded transmission waveguide runs were used inside the vacuum vessel. In some cases where space requirements were tight, the run tapered down to dominant WR-8 guide. Most of the bends were overmoded H plane bends. A compromise was made as to the size of the overmoded guide. WR-90 guide has a loss of 0.3 db/m at 140 GHz and was our prime consideration. Preliminary mechanical layouts indicated that space requirements around the divertor coil structures would not allow installation of that size guide. WR-28 waveguide was chosen as a compromise since it could

be routed through the vacuum vessel internal structures. Its loss is 1 db/m at 140 GHz, and, while higher in loss than WR-90 guide, it is better than WR-8 dominant mode guide with a loss of 5.3 db/m.

The vacuum windows were made from alumina. They were inserted into the WR-28 overmoded guide as it comes through the main vacuum port. The window was made approximately a half wavelength thick at 140 GHz to minimize reflections. Typical window losses averaged 1 db.

All the antennas are horn radiators with the exception of two parabolic systems between the divertor coils. The transmitting antennas in these paths are parabolic mirrors and the receiving antennas are large aperture horns. With the exception of two horizontal channels that have dominant mode standard gain horns, the remaining antennas are overmoded horn radiators. Presently there are five transmit/receive paths in the horizontal plane and eight in the vertical plane. The half power beam widths and gains of the antennas and the direction of propagation were selected to reduce the negative effects of plasma refraction of the electromagnetic wave.

V. Conclusion

What has been presented is a description of a multichannel interferometer using a pair of stabilized EIO's. The measured dynamic range on all the channels of the interferometer was between 15 and 30 db. The interferometer has been used successfully on PDX to obtain data on density profiles. Further work has continued on monitoring detector performance, especially since there might be some negative effects due to vibration. Consideration is presently underway to look at beam lead Schottky diodes as a possible replacement of the pressure contact Schottky diode types now used on the system.

Acknowledgments

The authors wish to thank Dr. Gregory Schmidt for his suggestions and advice, and the many technicians who helped build and install the system on PDX.

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BLOCK DIAGRAM OF 10 CHANNEL INTERFEROMETER

(PPPL-804714)

Fig. 1. Block diagram of 10 channel interferometer.

BLOCK DIAGRAM OF SIGNAL SOURCE (One of Two Systems)

(PPPL-804707)

Fig. 2. Block diagram of signal source.

Fig. 3. Signal source cabinet. (PPPL-796465)

AFC LOOP BLOCK DIAGRAM

K_o = Osc. Gain = 0.3 to 1.0 MHz/V

K_d = Discr. Gain = 250 pV/Hz

K_a = Amplifier Gain = 40

K_p = Power Supply Gain = 60

$F(\omega)$ = Loop Filter Gain & Freq. Response

(PPPL-804708)

Fig. 4. AFC loop block diagram.

AFC DISCRIMINATOR AND ITS S-CURVE

(PPPL-804705)

Fig. 5. AFC discriminator and its S curve.

AFC DISCRIMINATOR AMPLIFIER

Note: Power Dissipation Rating
of Resistor are 1/4 W.
Unless Otherwise Noted

(PPPL-804713)

Fig. 6. AFC discriminator amplifier.

(PPPL-804710)

Fig. 7. Discriminator amplifier Bode diagram.

AFC LOOP FILTER AND ACQUISITION CIRCUIT

(PPPL-804711)

Fig. 8. AFC loop filter and acquisition circuit.

(PPL-804706)

Fig. 9. APC loop Bode diagram.

BACKUP TEMPERATURE SENSING CIRCUIT

* Prec. Res. 1/8 W.

Note: Power Dissipation Ratings
of Resistors are 1/4 W.
Unless Otherwise Noted

(PFI-604719)

Fig. 10. Backup temperature sensing circuit.

INTERLOCK SYSTEM BLOCK DIAGRAM

(FPPL-804704)

Fig. 11. Interlock system block diagram.

MODULATOR BLOCK DIAGRAM

(FPPL-804703)

Fig. 12. Modulator block diagram.

RAMP GENERATOR CIRCUIT

(PPPL-804717)

Fig. 13. Ramp generator circuit.

Fig. 15. EIO Modulator circuit.

UPPER VACUUM PORT MICROWAVE NETWORKS

Fig. 16. Upper vacuum port microwave networks.

(PPPL-804712)

LOWER VACUUM PORT MICROWAVE NETWORKS

(PPPL-804720)

Fig. 17. Lower vacuum port microwave networks.

Fig. 18. Upper port enclosure and delay line. (PPPL-796467)

Fig. 19. Lower port enclosure. (PPPL-796466)

RECEIVE PREAMPLIFIER CIRCUIT

(FFPL-804716)

Fig. 20. Receiver preamplifier circuit.

IP311-88-377-0

Fig. 21. Receiver preamplifier Bode diagram.