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**MILLIMETER RADIOMETER TECHNIQUES
FOR PLASMA TEMPERATURE DIAGNOSTICS**

BY

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**PLASMA PHYSICS
LABORATORY**

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Millimeter Radiometer Techniques
for Plasma Temperature
Diagnostics

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Radiometers have been employed in radio telescopes to measure stellar plasma temperatures. However, when electron temperature measurements are made on hot dense plasmas in thermonuclear fusion research, radiometry techniques are modified. This report discusses these modifications as they are incorporated in radiometers on the PLT device. Included is a list of proposed radiometer developments and techniques for the T, PDX, and TFTR devices.

I. Introduction

A radiometer is a receiver that is capable of measuring electromagnetic energy associated with thermal radiation.¹ The radiometer, the antenna system, and the recording system is the basic radio telescope used by the radio astronomers since 1933.² Many improvements on these radio telescopes were made as the state of the art progressed. Some of the techniques are directly applicable to electron temperature measurements in thermonuclear fusion experiments.

Radio astronomers employ gain stabilized radiometers which have long integrating times so that a very small change in signal power can be detected in the presence of large receiver noise.^{3,4} This technique limits the response of the radiometer to very slow amplitude changes in detected signal levels. On the other hand, the signal levels from laboratory confined hot plasmas greatly exceed the receiver noise and therefore measurement of plasma temperature fluctuations are possible. It is possible to build a switched radiometer in order to reduce gain fluctuations if ferrite switches were available that could switch at frequencies up to several MHz. This high switching speed is needed in order to realize the short integrating times to observe fast temperature fluctuations. However, since the signal level is much greater than the noise and gain fluctuations generated by the receiver, a total power radiometer is preferred over the switched radiometer system.

II. Radiometers for Plasma Diagnostics

The direct detection total power radiometer and the two channel* superheterodyne total power radiometer are two types of receiver systems employed to make plasma temperature measurements. An example of a direct detection receiver is the Putley Cell system shown in Fig. 1. Putley Cell cryogenic detectors operate in the upper millimeter to submillimeter wave region of the electromagnetic spectrum. Their frequency response lies between 100 GHz to 3 THz. The radiometer has been used to measure the higher harmonics of the cyclotron emission of the ATC and PLT experimental devices here at Princeton.⁵ Selection of received frequency is accomplished by passing the signal through a scanning band pass filter. This filter can be set of meshes at a fixed spacing in a Michelson Interferometer or a tunable Fabry-Perot resonator. Putley Cell receivers, however, must operate at temperatures between 2° to 3°K to achieve their maximum sensitivity.

When measurements of the fundamental and second harmonic cyclotron emission from present day tokamak hot plasmas are made, these frequencies fall within the millimeter wave range.^{6,7} The receiver commonly chosen is the superheterodyne total power radiometer. The receiver is tunable over a wide band of frequencies and recently has been successfully operated in a fast-scan mode.⁸ Since the radial plasma position is a function of the receiver frequency for a given

*Without preselection, a superheterodyne radiometer can receive both signal and image frequencies making up the two noise channels.

magnetic field on the tokamak, a three dimension plot of many radial temperature profiles is made during the plasma pulse. An example of a computer generated temperature profile plot is shown in Fig. 2.⁸ A block diagram of the receiver is shown in Fig. 3.

III. Design of Receiver Radiometers

There are various design parameters that must be considered when a radiometer system is to be rapidly swept in frequency. It is critical that all microwave and intermediate frequency components must have a wide bandwidth with flat response and a low noise figure. The detector should operate in the square law region and must have a wide video bandwidth. The post amplifier likewise must have a wide video bandwidth with adequate gain. These criteria will be examined in greater detail.

V. Antenna and Transmission Lines

Clearly the antenna should have a low sidelobe pattern relative to the signal received by the radiometer, i.e., antenna temperature is comprised of components from the antenna's main beam energy received by the antenna and its sidelobes. Reduction in sidelobe level increases the main beam energy received by the antenna and improves the spatial resolution of the radiometer system. For the case of an antenna "looking" at a hot plasma in a tokamak device, the range can be so short that to achieve the far field range of the antenna may be physically impossible. It is possible however, to focus the antenna into the Fresnel region while maintaining far field

performance. The trade-off is the depth of field reduction when close focusing is used. A lens corrected conical horn is one such antenna presently used on two radiometers on PLT. The focal range is 50cm, which places the "focal point" near the center of the plasma. The antennas are placed outside the vacuum vessel and "look" at the plasma through a vacuum window. A lens corrected horn antenna could be placed inside the vacuum vessel if the lens material was made from a ceramic dielectric.

With the antenna placement some distance from the radiometer, dominant mode wave guide transmission lines in the millimeter wavelength range become too lossy. Oversized waveguide operating in an overmoded fashion provide much lower loss at the expense of possible higher order modes being propagated. However, with proper launching of the dominant mode and careful positioning of quasi-optical bends, a high degree of mode control can be achieved over a wide bandwidth. The H plane bend is more tolerant of position and not as prone to generate higher order modes. However, there are some places where E plane bends have to be used. An E plane quasi-optical bend must be placed between several feet of straight over-moded guide in order to reduce the number of higher order modes propagating down the line. Fig. 4. shows what occurs when E and H plane bends are used in a transmission line run. A typical example of some loss figures at 140 GHz, for instance, follows:

dominant mode WR-8 Guide	5db/m
overmoded WR-90 guide	0.3db/m
dominant mode 90° E and H bends	0.3db
quasi-optical 90° bends	0.2db

At 70 GHz, measurements indicate the following losses:

dominant mode WR-15 guide	2db/m
overmoded WR-90 guide	0.18 db/m
dominant mode 90°E and E bends	0.2db
quasi-optical 90° bends	0.2db

3. Receiver Design

The receiver mixer and IF preamplifier determine the sensitivity of the radiometer. Since the radiometer is swept in frequency, the sensitivity must be maintained over the swept bandwidth of interest. These requirements present several unique design problems.

1. Mixer/IF Preamplifier

Mixers can be either single ended or balanced. The balanced variety uses a 3 db, 180° hybrid directional coupler which when designed and adjusted properly, will reduce the noise injected by the local oscillator (LO). The bandwidth over which this noise balance occurs is in reality only over about 10% of the full waveguide bandwidth. The single ended mixer, however, has no balancing provision and therefore allows LO noise sidebands to be injected over the full waveguide bandwidth of the mixer. In addition to LO noise, mixer diode noise is also added to the overall mixer noise. Since there is no low noise RF preamplifier used, the IF preamplifier noise influences the overall front end noise. Loss mechanisms such as isolators, switches, and transmission line attenuation affects the front end noise and therefore front end temperature. The front end noise can be represented in terms of an effective noise temperature as:

$$T_S = L T_O (F-1) + T_O (L-1)$$

where T_S = system front end temperature

F = system noise factor

T_O = ambient front end temperature

L = overall transmission line loss
(inc. isolators, etc.)

If antenna noise temperature, T_A , is to be included, then the overall system temperature is

$$T_S = T_A + L T_O (F-1) + T_O (L-1)$$

where T_A is defined as antenna temperature contributions from both external sources and internal sources to the antenna.

The mixer, whether single ended or balanced, must be flat within the bandwidth of interest. This criteria insures that the conversion loss be fairly constant with frequency so that the IF signal will be directly proportional to the RF signal and independent of frequency. The second criteria is that the LO injection be levelled across the entire bandwidth of interest so as not to change the conversion loss of the mixer.

The mixer diodes are made broadband by substituting absorbing loads for the adjustable reflecting backshorts. The compromise is wider bandwidth at the expense of higher conversion loss. Schottky Barrier diodes are preferred over silicon point contact diodes because the diode capacitance is very small (their high frequency limit is above 1THz). The use of GaAs over silicon in mixer diodes lowers the noise figure and conversion loss. Schottky Barrier mixers are usually operated with DC bias. This reduces the IF impedance, increases the IF output current, and reduces

the amount of LO drive required for a given mixer current.

2. IF Post Amplifier, Video Detection, and Video Amplifier

The choice of IF amplifier is a crucial point in radiometer design. As previously stated, the IF preamplifier noise figure is a critical factor in establishing the overall noise figure of the system. First, the overall IF amplifier gain must be high enough to establish the IF front end noise figure. Second, the gain must be such that the video detector is operating in the square law region. And third, the noise contributions of the video amplifier must be kept small. The IF amplifier bandwidth should be as wide as possible in order to increase the sensitivity of the radiometer and to reduce noise fluctuation contributions. However, the bandwidth determines the spatial resolution of the plasma temperature measurement. The noise sidebands of the LO can act as an incoming signal and mix with the LO carrier itself. This will generate a set of noise sideband in the IF passband. The $1/f$ noise of the mixer increases as the frequency is lowered. These two parameters will influence the lower cut-off frequency of the IF passband.

The detector and video amplifier must satisfy the following conditions: a) It has to operate in the square law region where the rectified output current of the detector becomes directly proportional to received noise power. b) The video bandwidth of the detector must be large enough to enable the detection of rapid noise fluctuations. c) The

video amplifier noise contribution should be low enough that there will be no significant contribution to the overall noise factor of the receiver. This requirement is usually satisfied, since the noise output of the IF amplifier is much greater than that of the video amplifier. d) The gain of the video amplifier must be large enough to obtain an acceptable voltage slope ($\text{mV}/^\circ\text{K}$). e) The output stage must also be capable of driving a low impedance cable into the control room.

3. Swept Levelled Local Oscillator

In broadband operation, the local oscillator injection should be maintained constant while it is being swept in frequency. For typical BWO's capable of wide tuning, the power output changes by an order of magnitude across the band. Such a change would alter the conversion loss and noise output of the mixer if it were not levelled.

There are two methods of power levelling a BWO oscillator. Both involve sampling the output using a broadband directional coupler and detector. However, as shown in Fig. 5a, the power control is achieved through a ferrite variable attenuator, or in Fig. 5b, by means of changing the anode voltage of the BWO tube. The former is preferred because it does not alter the frequency of the tube since the ferrite attenuator presents a constant impedance to the source. On the other hand changing the anode voltage as in Fig. 5b does introduce an additional frequency modulation while the oscillator is being swept.

There are several design problems with receivers that use BWO's as LO sources. The ramp modulator must supply up to 1 to 2 kilovolts peak ramp voltage in order to sweep the oscillator output across the band. This high ramp voltage must be added to the cathode power supply voltage. The rate of sweep is limited by how well the ramp modulator can drive the power supply capacitance with respect to ground. Sweep speeds up to 10 msec are in use on our present radiometers. There are ramp generators that can modulate the cathode voltage on BWO's up to 1 msec.

A second parameter to consider is the bandwidth of the level detector and its feedback amplifier driver system. The instantaneous power level changes that occur during a single sweep are much faster than the sweep speed. Unless the control element, albeit a variable ferrite attenuator or an amplifier driving a control electrode has the necessary bandwidth, the power out of the oscillator cannot be levelled properly.

IV. Radiometers on PLT

There are two radiometers in use on the PLT device. One is a total power radiometer that can operate on any fixed frequency between 130 and 140 GHz. This radiometer is used to observe the temperature and rapid fluctuations in temperature from the second harmonic cyclotron emission of the plasma. A second receiver, also a total power radiometer, operates between 60 and 90 GHz. It can be operated in either the swept mode or fixed frequency mode.⁸

A. 130 GHz to 140 GHz Radiometer

Fig. 6 shows a block diagram of the radiometer. A lens corrected horn antenna tapering down to WR-⁷ guide is connected to a taper that maintains the TE₁₀ dominant mode from WR-8 to WR-90 waveguide. The signal is transmitted to the receiver in overmoded guide.

The mixer is built as a quasi-optical beam splitter. The input signal port is in WR-90 guide dimensions. The quasi-optical beam splitter is operated as a single ended mixer. The diode mixer is a Schottky Barrier diode with 30% bandwidth. There is no attempt at levelling the LO. The power output of the Carcinotron local oscillator tube is adjusted by means of a variable level set attenuator. To change frequency the cathode voltage is changed, and the level set attenuator is adjusted to maintain the same mixer bias current.

The mixer output is connected to a bias box establishing the proper DC bias level to the mixer diode while coupling the IF signal power into the IF preamplifier. An IF attenuator controls the signal level and therefore IF gain. The IF post amplifier raises the signal level to where the video detector is operated in its square law region. A video amplifier/driver amplifies the video signal and transmits it to the control room via a coaxial cable driving a high voltage isolation safety break amplifier.

The specification of the system are as follows:

RF Frequency range:	130 to 140 GHz
Tuning:	Electronic tuning with cathode supply
Mixer:	Single ended
Sensitivity:	-75 dbm (S/N = 1)
IF passband:	200 to 600 MHz

B. 60 GHz to 90 GHz Radiometer

Fig. 7 shows a block diagram of the radiometer employed to measure fundamental cyclotron emission from the plasma. A lens corrected conical horn antenna receives the signal and is transmitted to the receiver via over-moded WR-90 waveguide. A mode transducer at the antenna changes the circular TE_{11} mode to rectangular TE_{10} mode. At the receiver a taper transitions back to the WR-12 components used in the receiver. A broadband isolator is used to reduce spurious responses from the LO re-radiation down the input line. A single ended mixer is used consisting of a 3db directional coupler and a broadband diode. The specifications of the radiometer are as follows:

RF Frequency range:	60 to 90 GHz
Tuning:	Swept L.O. @ 100 Hz Rate max.
LO injection levels:	1 mW + 1.5 db across band
Mixer conversion loss:	16.2 to 18.2 db across band
Sensitivity:	-72 dbm (S/N = 1)
Noise Figure, DSB:	23 db
IF passband:	200 to 600 MHz
IF gain max:	90 db
Normal operation IF gain:	70 db
Video output with - 50 dbm input signal	1 Volt peak
Video bandpass	DC to 30 KHz @ - 3 db point

The radiometer is built in modular form so that the RF, IF, and video sections can be removed for servicing. The LO and its associated leveling circuitry is in a separate module. The low voltage amplifier, meters, bias circuit, and video post amplifier are in a third module. BWO sweeper and power supplies are separate and can be removed for repair. Figure 8 is a photograph of the complete receiver.

The IF output from the mixer is amplified by a 30 db gain preamplifier. Following the attenuator are two 30 db IF post amplifiers and a video detector. The output of the video

detector is amplified by an amplifier/driver with a DC to 30 KHz bandwidth and a gain of 10. This amplifier is capable of driving a long 50 ohm cable to the control room through high voltage isolation safety breaks.

The LO is adjusted for the proper level across the band, with a bias of 0.5 ma on the mixer. The sweep voltage is generated by a Wavetek function generator that is triggered in its burst mode by the control room timer. A sample of the sweep voltage is sent back to the control room through the high voltage isolation safety breaks.

V. Proposed Radiometer Development

Besides two more radiometers to be built for PLT, a radiometer system is being built for PDX, and several are proposed for TFTR. Here is a listing of radiometry activity on the various experimental devices at PPL.

- PLT. 1. 60-90 GHz radiometer - presently in use for measuring fundamental cyclotron emission.
- 2. 130-140 GHz radiometer - presently in use for measuring second harmonic cyclotron emission.
- 3. 150-170 GHz swept radiometer - under construction, to measure second harmonic cyclotron emission.
- 4. 165-185 GHz swept radiometer - under construction, to measure second harmonic cyclotron emission.
- PDX. 75-115 GHz swept radiometer - under construction, to measure second harmonic cyclotron emission.
- TFTR. 75-170 GHz swept radiometer to cover fundamental cyclotron emission.

Further proposed development under the TFTR project include both development of an image rejection total power swept radiometer and a subharmonic mixer swept total power radiometer. Both of these radiometer developments are aimed

at reducing the noise generated by the receivers in order to increase sensitivity and expand the frequency bandwidth of the receivers. A future development commensurate with the above is to extend the present design to receive frequencies up to and beyond 300 GHz.

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SINGLE CHANNEL PUTLEY CELL RECEIVER

794951

Fig. 1. Single channel putley cell receiver.

Fig. 2. Computer generated profile plot.

786190

SUPERHETERODYNE SWEPT FREQUENCY TOTAL POWER RADIOMETER

Fig. 3. Superheterodyne swept frequency total power radiometer.

794955

TRANSMISSION THROUGH QUASI-OPTICAL BENDS
BETWEEN 70 GHz AND 80 GHz

H Plane 90° Bend Response
No Waveguide Runs Each Side of Bend

E Plane 90° Bend Response
No Waveguide Runs Each Side of Bend

H Plane 90° Bend Response
4 Ft. Waveguide Each Side of Bend

E Plane 90° Bend Response
4 Ft. Waveguide Each Side of Bend

794950

Fig. 4. Transmission through quasi-optical bends.

794953

Fig. 5. Power leveling systems.

130 TO 140 GHz SUPERHETERODYNE TOTAL POWER RADIOMETER

794952

Fig. 6. 130 to 140 GHz superheterodyne total power radiometer.

794954

Fig. 7. 60 to 90 GHz superheterodyne swept frequency total power radiometer.

Fig. 8. Photograph of the 60 to 90 GHz radiometer. 796141