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**A FAST-SCANNING HETERODYNE RECEIVER
FOR MEASUREMENT OF THE ELECTRON
CYCLOTRON EMISSION FROM HIGH-
TEMPERATURE PLASMAS**

BY

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A FAST-SCANNING HETERODYNE RECEIVER FOR MEASUREMENT
ELECTRON CYCLOTRON EMISSION FROM HIGH-TEMPERATURE PL

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We have developed a fast-scanning heterodyn receiver into a plasma diagnostic that measures fundamental cyclotron emission from the PLT plas and thus ascertains the time evolution of the electron temperature profile. The receiver scan 60-90 Ghz every 10 milliseconds and is interface to a computer for completely automated calibrate temperature measurements.

In recent years, there has been considerable interest in the measurement of the electron cyclotron emission from hot plasmas.¹⁻⁸ In hot dense plasmas, the intensity of the emission is observed to be at the black-body level for the second harmonic^{1,2,4,5,6} and recently for the fundamental electron cyclotron frequency^{2,3,7,8}, and thus the emission intensity is proportional to the local electron temperature.

In measuring this thermal emission, one can employ quasi-optical^{2,5,6} or microwave heterodyne techniques.^{1,4,7,8} Using microwave techniques, we have developed a fast-scanning heterodyne receiver that scans 60-90 GHz every 10 milliseconds and is interfaced to a computer system for completely automated calibrated temperature measurements of the Princeton Large Torus (PLT) plasma.^{7,8} In tokamaks, the toroidal magnetic field is inversely proportional to the major radius of the device (R) and thus the radiometer's receiving frequency corresponds to a unique cyclotron layer in the plasma.

The power (P) incident upon the microwave receiving horn is proportional to the cyclotron emission intensity

$$P(R) = K T_e(R) \Delta F (1 - e^{-\tau}) \quad (1)$$

where ΔF is the receiver bandwidth, τ is the optical depth of the emitting layer, K is Boltzman's constant, and $T_e(R)$ is the local electron temperature. τ is defined as

$$\tau = 2 \int k_I \cdot dR \quad (2)$$

where k_i is the imaginary part of the wave propagation for the mode of emission. The optical thickness is a function of electron temperature and density. For black emission $\tau \geq 2$, and the power measured by the radiometer

$$P = K T_E \Delta F$$

and thus the power is a function of electron temperature and other plasma parameter. When the vessel walls significantly reflect radiation, as appears to be the case in PLT, the black-body radiation intensity can be maintained at considerably lower values of τ .

Fig. 1 is a detailed block diagram of the microwave radiometer. This receiver is capable of scanning a frequency range 60-90 GHz every 10 ms. Under normal PLT conditions (toroidal magnetic field $B_0 \sim 32$ KG), this frequency range corresponds to the fundamental electron cyclotron emission from the region of the plasma between the center and outer edge. Presently, there are two microwave horns in the equatorial plane along the major radius of PLT: (1) located on the inside of the torus is oriented to receive ordinary mode emission, and (2) a horn located on the outside of the torus measures ordinary mode emission. The inside horn has a lobe width $\Delta\theta \approx 6^\circ$ and a central spot diameter of $d = 10$ cm. The outer horn has $\Delta\theta \approx 2^\circ$ and $d = 3$ cm.

The mixer is single-ended (Hughes 47355H-1100) with a response for the entire frequency range of the heterodyne

radiometer and a 11.5 dB conversion loss. The emission mixes with the output of a Siemens (RWO-80) backward-wave-oscillator (BWO) serving as the local oscillator. The BWO is electronically swept over the frequency range 60-90 GHz when provided with a 1 kV repetitive ramp signal. The BWO rate is merely that of the high voltage ramp. This ramp is generated in two stages. A Wavetr' function generator provides a 20 V ramp with the desired repetition rate to drive a Siemens high-voltage sweep amplifier. Unfortunately, the HV amplifier response time limits the sweep rate to 10 ms. Faster sweepers are available that enable the scan time to be 2 ms (Alfred).

A self-contained power-leveling feedback-loop (Hughes 44764H) is employed to level the BWO output power before it enters the mixer. A ferrite modulator provides the necessary attenuation. The attenuated BWO power is sampled by a broadband detector mounted in the side-arm of a 10 dB waveguide coupler. The detector signal is compared to a preset reference level by a comparator circuit which then commands the modulator to attenuate the BWO output power to the preset power level. This feedback loop has a 50 μ s response time and maintains a flat power level within 1 dB.

The mixer output signal is amplified by three 30 dB gain I.F. amplifiers (Avantek AK-500M) with 3 dB points at 250 and 500 MHz. A step attenuator, inserted between the first and second stages, provides the gain variability necessary to maximize the I.F. signal while keeping the video detector from saturating. The I.F. band-pass is kept far from the carrier in order to reduce spurious noise due to mixing of the BWO carrier and the carrier wings. The

instantaneous double-sideband bandwidth of the receiver ($\Delta F = 400$ MHz) establishes the spatial resolution of the system to be ~ 1 cm in a PLT plasma. A Schottky-barrier (Hewlett-Packard 8471A) detector with a 100 kHz response and -30 dBm minimum detectability measure the envelope of the I.F. signal. The final stage is a video amplifier-line driver (Burr-Brown 3342) with a 10 dB gain.

Calibration of the receiver is performed by two independent methods: a calibration is obtained from a comparison with Thomson scattering temperature measurements and the other absolute calibration relies on a microwave noise tube as a standard. The two calibration schemes agree within 10-15%. We measured the instantaneous noise figure of the receiver in the scanning mode of operation to be 23 dB, which corresponds to a 5 eV minimum detectable signal.

Computer data reduction of the raw output voltages is the only practical method of analyzing the 10,000 temperature measurements performed by the receiver for every PLT plasma discharge (~ 1 second duration). Essentially, there are two signals from the receiver: the raw temperature signal and the 20 volt ramp signal which is a function of the receiver scan frequency. These two signals are digitized and stored in a transient recorder (Le Croy 8212) and then transferred to a computer for analysis. The data analysis consists of transforming the two signals into a calibrated temperature for a specific location in the plasma. The actual temperature and position calibrations are contained in the computer program. Fig. 2 is a 3-dimensional computer plot of the time evolution of the electron temperature profile $T_e(r,t)$ measured by the receiver for a typical ohmically-heated PLT plasma

discharge. In this plot, the temperature at only 17 positions every 20 milliseconds is displayed while the receiver actually measured 100 positions along the profile every 10 milliseconds.

Fast scanning heterodyne radiometric measurement of electron cyclotron emission as a method of ascertaining the electron temperature of a plasma has an advantage over employing Thomson scattering by providing the entire time evolution of the electron temperature. This advantage was clearly demonstrated in plasma experiments designed to study the auxiliary heating of plasmas by injecting neutral beams.⁹ Fig. 3 is a computer plot of the electron temperature profile before, during and after injection of 2.1 MW deuterium neutral beams at time $t = 450 - 600$ ms into a low density ($\bar{n}_e = 1.8 \times 10^{13} \text{ cm}^{-3}$) hydrogen plasma. The observed peaking of the electron temperature profile 30 ms after the termination of injection can be explained by the heating of the electrons by the still energetic slowing-down ions and the removal of the power loss due to the thermalization of cold electrons coincident with the forming of beam ions.

In conclusion, the measurement of black-body electron cyclotron emission by swept heterodyne radiometry to ascertain the time evolution of the electron temperature profile is shown to be an important plasma diagnostic. This receiver can be built for any frequency range where oscillator sources and broadband mixers and waveguide components are available. There are two new broadband BWOs in the ranges 110-170 GHz (Siemens) and 320-400 GHz (Thomson CSF) that are suitable for fast-scanning local oscillators in a heterodyne receiver and in the near future; broadband sources will

be available up to 600 GHz. This source development will make the heterodyne receiver an attractive method of detection in the submillimeter regime. Although we are satisfied with the performance of our system, we are investigating the feasibility of a number of improvements: image-rejection mixer stages and harmonic mixing.

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FIGURE CAPTIONS

Figure 1. Detailed block diagram of the 60-90 GHz fast heterodyne receiver.

Figure 2. A computer plot of the time evolution of the temperature profile of a typical ohmically heated plasma discharge determined from the measurement of the ordinary-mode fundamental electron cyclotron emission by the fast-scanning heterodyne receiver. The graph easily visualizes the contours of the 3-dimensional temperature profile. Only seventeen radial positions of the temperature profile actually determined from the measurement are plotted.

Figure 3. A computer plot of electron temperature (K_e) from the cyclotron emission vs. plasma radius for four distinct times (ms) representing before and after (575 ms) and after (630 and 660 ms) the injection of 2.1 MW of deuterium neutral beams into a low-density ($\bar{n}_e = 1.8 \times 10^{13} \text{ cm}^{-3}$) hydrogen plasma.

Fig. 2. 786190

Fig. 3 783901

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