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ON THE DIII-D TOKAMAK**

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# **ECE RADIOMETER UPGRADE ON THE DIII-D TOKAMAK**

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## ABSTRACT

The electron cyclotron emission (ECE) heterodyne radiometer diagnostic on DIII-D has been upgraded with the addition of eight channels for a total of 40. The new, higher frequency channels allow measurements of electron temperature into the magnetic axis in discharges at maximum field, 2.15 T. The complete set now extends over the full usable range of second harmonic emission frequencies at 2.0 T covering radii from the outer edge inward to the location of third harmonic overlap on the high field side. Full coverage permits the measurement of heat pulses and magnetohydrodynamic (MHD) fluctuations on both sides of the magnetic axis. In addition, the symmetric measurements are used to fix the location of the magnetic axis in tokamak magnetic equilibrium reconstructions. Also, the new higher frequency channels have been used to determine central  $T_e$  with good time resolution in low field, high density discharges using third harmonic ECE in the optically gray and optically thick regimes.

## I. INTRODUCTION

Measurements of  $T_e$  from optically thick second harmonic electron cyclotron emission is an established technique in magnetic confinement experiments.<sup>1</sup> Particularly methods employing heterodyne radiometers, due to their low noise and high frequency resolution, have produced detailed pictures of plasma phenomena. In this paper we describe an upgrade to the DIII-D radiometer and how it has expanded and improved the range of electron temperature measurements.

## II. THE INSTRUMENT

The DIII-D multichannel ECE heterodyne radiometer has been installed on the machine since 1995. The instrument was originally built for and installed on the Advanced Toroidal Facility at Oak Ridge National Laboratory.<sup>2</sup> After being transferred to the DIII-D site, it has been modified at various times for improved operation. In its present configuration it has 40 channels with frequency selection by multiplexers and a filterbank. A layout of the device is given in Fig. 1. The original front end had a WR-10 one-to-one waveguide coupler that split the power in the 82–114 GHz band into two mixers, each one feeding a bank of sixteen channels. This year a second 3 dB coupler was added, after a WR-10 to WR-8 transition, to separate the power in the 98–130 GHz band and to feed an additional mixer in turn feeding 8 new channels. The three local oscillators are at 81, 96 and 112 GHz, giving mixer outputs of 2–18 GHz transmitted to each filterbank board, referred to as cards. In each card the IF power is amplified by a pair of 30–35 dB amplifiers separated by an adjustable thumbwheel attenuator. The output of the second amplifier is split into 4 bands with a quadruplexer, which is in turn split 4-ways or 2-ways with 4- or 2-channel power splitters. Frequency selection is accomplished with 40 individual bandpass filters leading into 40 Schottky barrier diode detectors. The bandpass filters are 1 GHz wide at frequencies 2.5–17.5 at 1 GHz steps, for the first two cards of 16 channels, and 1 GHz wide at frequencies 3.5–17.5 at 2 GHz steps, for the last 8 channels. Pad attenuators of 1–10 dB are used in front of the power splitters and detectors to level the outputs of the filterbank set to the same range of power.

The detector signals are amplified by low-noise video amplifiers that have two outputs, a slow one limited by an RC filter to a bandwidth of 800 Hz, and a fast one limited by the video amplifier design to 25 kHz. The two outputs are connected respectively to 40 channels of slow and fast CAMAC digitizers, sampling at 2 kHz and 100 kHz respectively. One of the improvements of the instrument was to increase the gain of the video amplifiers from 200 to 1000. Previously the output of the video amps had to be maintained below 200 mV to insure the Schottky detectors were running in the linear range below 15 mV output. The higher gain of 1000 allows full use of the 10 V/12-bit digitizer range, maximizing the volts/bit.

The front end of the radiometer is fed by a low-loss transmission line of 15 m leading from a long-horn antenna viewing the DIII-D plasma along a horizontal chord at the tokamak midplane. The loss of the transmission line is about 4 dB. At the end of the

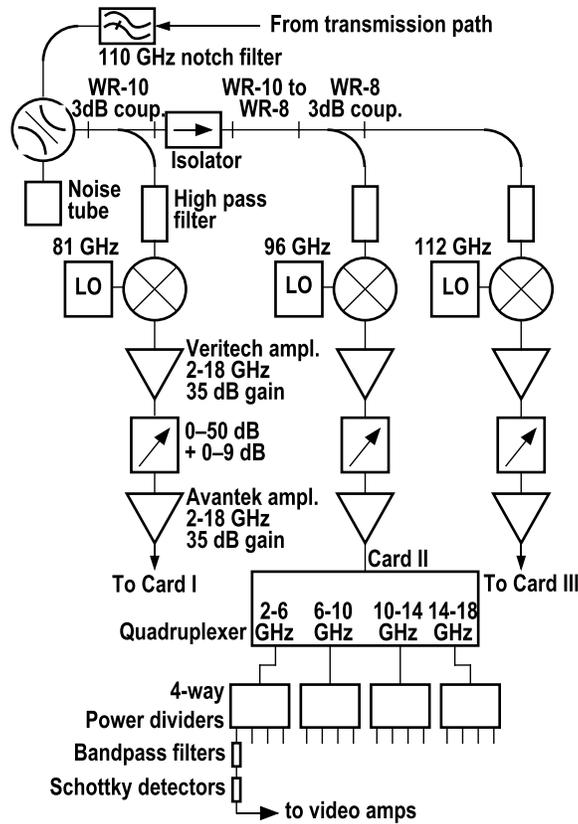


FIG. 1 Schematic of the DIII-D radiometer.

transmission line is a 110 GHz waveguide notch filter (Pacific Millimeter Waves Model N110). This bandpass filter provides at least 40 dB of attenuation between 109.75 and 110.25 GHz and is used to block power from a bank of 110 GHz gyrotrons used for electron cyclotron heating (ECH) and current drive (ECCD) in DIII-D plasmas. Without the notch filter, stray and unabsorbed power at 110 GHz would swamp the mixers and make that portion of the discharge useless for radiometer temperature measurements, or worse, would burn out the diode and render the mixer inoperable. With the notch filter, the radiometer has been able to provide in ECH and ECCD experiments measurements of  $T_e(r,t)$  which give the location and width of the EC power deposition in the plasma.

Just after the notch filter at the radiometer front end is a WR-10 baseball switch that is used to switch the input from the transmission leg to an F-band noise tube. The noise tube is used to check and characterize the radiometer. Comparing the signals from the noise tube and a room temperature load, the noise temperature of the radiometer has been determined to be about 5 eV. This matches well with the range and type of  $T_e$  measurements made on DIII-D. The instrument is not absolutely calibrated in stand-alone fashion. Instead it is calibrated by comparison with ECE spectra of plasma discharges from the DIII-D Michelson interferometer.

To ensure calibration stability across multiple DIII-D discharges and during a discharge, steps have been taken to maintain fixed sensitivity of the radiometer. The sealed instrument cabinet is air conditioned to provide an ambient temperature between 21°–25°C. Originally the local oscillators and IF amplifiers were outfitted with cooling fins to help maintain constant temperature. Subsequently the IF amplifiers were connected to thermal electric coolers (TECs) to maintain the temperature to within 0.5°C, since these amplifiers have temperature sensitive gain. The TEC elements are Melcor Model CP0.8-127-06L and the TEC controllers are Alpha Omega Instruments Model P37. Since adding the TECs, the calibration has been observed to remain stable for several weeks at a time.

### III. ELECTRON TEMPERATURE MEASUREMENTS

The additional channels of the radiometer have extended the operational range of the  $T_e$  measurements in DIII-D plasmas. At full field,  $B_T(0) = 2.15$  T, the second harmonic ECE frequency corresponding to the central magnetic axis is 117 GHz for a plasma with a typical major radius of 1.75 m. This frequency was not covered by the original range of the diagnostic, 83.5–113.5 GHz. With the new channels covering 115.5–129.5 GHz,  $T_e$  measurements at the magnetic axis and farther inboard are now possible. Figure 2 shows a  $T_e$  profile for a discharge at 2.10 T and details the improved coverage of the new channels.

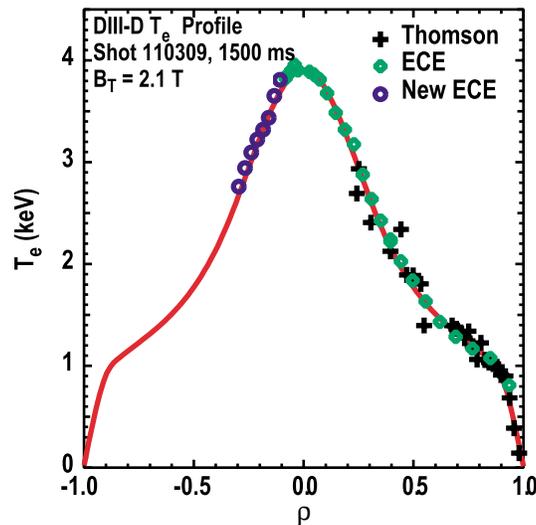


FIG. 2. DIII-D electron temperature profile for a discharge at 2.10 T showing new ECE radiometer channels covering the high field side of the magnetic axis. The curve is a spline fit to the data.

One of the common uses of ECE data on DIII-D is the determination of the magnetic axis location as an aid to the magnetic equilibrium reconstruction process. The flux contours in a DIII-D discharge are calculated by the EFIT code and one measure of the accuracy of the reconstructed equilibrium is the overlap of the low field side and high field side ECE  $T_e$  values near the center. Previously the Michelson interferometer data was the only means to look at this for fields of 2.0 T and higher. With the new high frequency channels it is now possible to use the radiometer data for this purpose.

The added radiometer channels have also opened up new possibilities at lower magnetic fields on DIII-D. Many experiments are done at fields of 1.60–1.00 T for low  $q$  and high

beta investigations. Also, for long pulse length experiments greater than 5 s, the B-field set point must be lower for constant magnetic field. The radiometer frequencies move far inboard at these fields and the higher frequencies fall into the regime of third-harmonic overlap. For example, at 1.60 T the central second harmonic frequency is about 86 GHz and frequencies above 98 GHz have both a second harmonic and a third harmonic resonance in the plasma. At this field the right-hand cutoff of the central frequency occurs at an electron density of  $n_e = 4.6 \times 10^{19} \text{ m}^{-3}$ , a value very often exceeded in H-mode discharges. Under these conditions it is not possible to measure central  $T_e$  with second harmonic ECE.

However, with the new ECE channels it is possible to measure emission from central third harmonic frequencies corresponding to fields at or less than 1.60 T. In addition, under many conditions the third harmonic ECE is optically thick or nearly so.  $T_e$  measurements from third harmonic ECE have been demonstrated on DIII-D and other plasma devices.<sup>3,4</sup> Using the method outlined in Ref. [3] central  $T_e$  has been determined in a discharge at 1.60 T where the emission at the central second harmonic frequency is cutoff. Using Thomson scattering central density and edge  $T_e$  data the radiation temperature signal at 129.5 GHz is adjusted for optical depth and absorption to give central  $T_e$  as a function of time. The result is shown in Fig. 3. The  $T_e$  values obtained are in good agreement with the central Thomson scattering measurements. For a given tokamak B-field the cutoff density for third harmonic ECE is a factor of 3 higher than for the second harmonic so this technique makes possible  $T_e$  measurements over a much broader range of operating conditions.

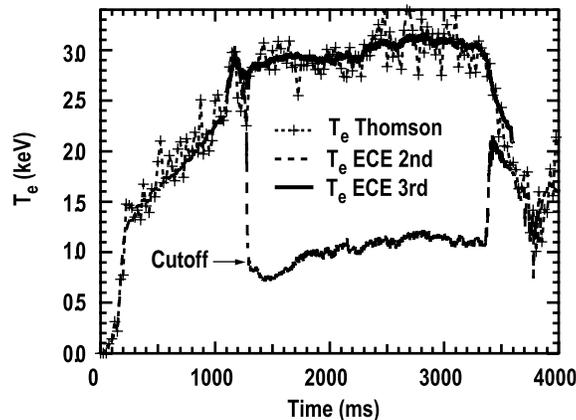


FIG. 3. Central  $T_e$  vs time in a DIII-D discharge with  $B_T = 1.60$  T. The long-dashed curve is from second harmonic emission at 90.5 GHz shown going into cutoff at 1200 ms. The solid curve is from central third harmonic emission at 129.5 GHz, corrected for optical depth. The short-dashed curve with markers is the core measurement from Thomson scattering.

## IV. SUMMARY

Several improvements have been incorporated into the DIII-D heterodyne radiometer. Higher gain video amplifiers have increased the sensitivity of the diagnostic while ensuring linear output of the detectors. Calibration stability has been enhanced with temperature control of the IF amplifiers using TECs. Additional channels at higher frequency permit second harmonic  $T_e$  measurements inboard of the magnetic axis at full field. Moreover, the added channels provide third harmonic  $T_e$  measurements at reduced field, in high density discharges, with good time resolution.

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