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D.P. Hutchinson
R.K. Richards
M.L. Simpson

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831-6004
(423) 574-4730

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WIDEBAND HETERODYNE QWIP RECEIVER DEVELOPMENT FOR THERMONUCLEAR FUSION MEASUREMENTS

R. K. Richards, D. P. Hutchinson, C. A. Bennett, and M. L. Simpson

Oak Ridge National Laboratory

P.O. Box 2008

Oak Ridge, Tennessee 37831-6004

and

H. C. Liu and M. Buchanan

National Research Council of Canada

Institute for Microstructural Sciences

Ottawa, Canada K1A 0R6

ABSTRACT

Oak Ridge National Laboratory (ORNL) has been developing heterodyne receivers for plasma diagnostic applications for over 20 years. One area of this work has been the development of a diagnostic system for the measurement of the energy of alpha particles created in a thermonuclear fusion reactor. These particles originate with an energy of 3.5 MeV and cool to the thermal energy of the plasma (around 15 keV) after several seconds. To measure the velocity distribution of these alpha particles, a Thomson scattering diagnostic is under development based on a high power CO₂ laser at 10 microns with a heterodyne receiver. The Doppler shift generated by Thomson scattering of the alpha particles requires a wideband heterodyne receiver (greater than 10 GHz). Because Mercury-Cadmium-Telluride (MCT) detectors are limited to a bandwidth of approximately 2 GHz, a Quantum Well Infrared Photodetector (QWIP) detector was obtained from the National Research Council of Canada (NRC) and evaluated for its heterodyne performance using the heterodyne testing facility developed at ORNL.

INTRODUCTION

ORNL has been developing heterodyne receivers for plasma diagnostic applications for over 20 years. One area of this work has been the development of a diagnostic system for the measurement of the energy of alpha particles created in a thermonuclear fusion reactor.¹ These particles originate with an energy of 3.5 MeV and cool to the thermal energy of the plasma (around 15 keV) after several seconds. It is this energy transfer between the alpha particles and the fuel which is needed to maintain ignition. The shape of the alpha particle velocity distribution gives an indication of this transfer. To measure the velocity distribution of these alpha particles, a Thomson scattering diagnostic is under development based on a high power CO₂ laser at 10 microns with a heterodyne receiver. Making use of the coupling between the ions and the electrons in a plasma, in collective Thomson scattering the Doppler shift in the scattered spectrum yields the ion velocity distribution. Because of the initial high energy alpha particles, the Doppler shift generated by Thomson scattering requires a wideband heterodyne receiver (greater than 10 GHz). This width is set by the expected Doppler spectrum of the scattered CO₂ laser radiation. An example of this spectrum expected in the proposed ignited fusion device the International Thermonuclear Experimental Reactor (ITER)² is given in Fig. 1. Note

SCATTERED POWER SPECTRUM FOR ITER

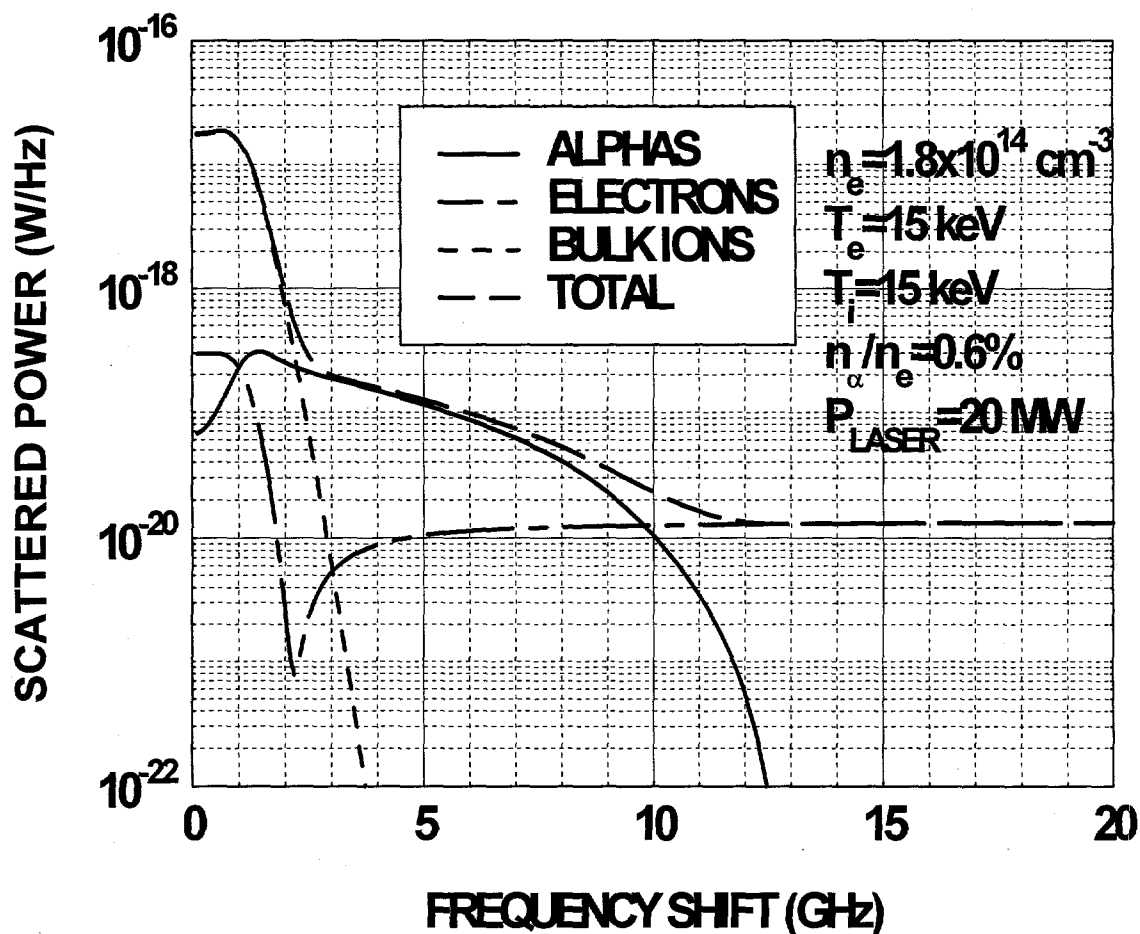


Fig. 1. Expected scattered power spectrum for the ITER tokamak.

that the contribution to the spectrum is dominated by the alpha particles for frequency shifts between 2 and 10 GHz (this is a double sided spectrum symmetric about the CO₂ laser line at 28,306 GHz.) Because MCT detectors are limited to a bandwidth of approximately 2 GHz, much less than the 10 GHz required for this measurement, the characteristically wideband QWIPs³ have been considered for detecting this radiation.

In addition to the bandwidth, the detector must have sufficient sensitivity to perform these small signal scattering measurements. The sensitivity of the detector is quantified by the signal-to-noise ratio (S/N). For a heterodyne receiver, this S/N is given by:

$$\frac{S}{N} = \frac{P_s}{P_s + NEP} \sqrt{B\tau + 1} \quad [1]$$

where P_s is the scattered power, NEP is the noise equivalent power, B is the receiver bandwidth, and τ is the integration time of the measurement for this application limited to the pulse length of the source laser. Note that for a large scattered power, the factor $P_s/(P_s + NEP)$ approaches unity producing little improvement in the S/N ratio. Under some conditions, the value of the scattered power may have an optimum for maximizing the S/N ratio. For a laser source of fixed energy, the trade off between the laser power and pulse length produces an optimum value when this factor is $\frac{1}{2}$ i.e. $P_s = NEP$. With reasonable sized pulsed CO₂ lasers it is possible to generate a scattered power for the alpha portion of the ITER spectrum around 10^{-19} W/Hz as illustrated in Fig. 1 for the case of a 20 MW source. Under these conditions (i.e. $P_s = NEP$) and with a 1 GHz bandwidth and a 1 microsecond laser pulse, then the S/N ratio has a value of 15.8.

RECEIVER TESTS

A QWIP detector has been obtained from the NRC for the evaluation of its heterodyne receiver performance. This detector consists of 32 GaAs wells. Its size is 40x40 microns and when tilted at 45° has a effective area of 40x28 microns. This testing was performed using the heterodyne testing facility developed at ORNL.⁴ This test facility makes use of the known emission from a blackbody source and compares the measured signal to the receiver noise in determining the noise spectrum. Fast f/1 optics are used to focus the combination of local oscillator and blackbody signals onto the detector. The local oscillator consists of a grating tuned waveguide CO₂ laser set on the 10P(20) line at 10.6 microns (28,306 GHz). The optimum local oscillator power has been determined to be approximately 10 milliwatts. The signal generated from the detector is amplified using a combination of broadband low noise pre-amplifiers followed by power amplifiers (several were needed to cover this bandwidth) and the resulting signal is measured with a spectrum analyzer. Using the output from the spectrum analyzer to select a frequency shift, the results were recorded as an AC signal (giving the contribution from the blackbody source) and a DC signal (giving the noise). Results from that test are shown in Fig. 2 indicating a flat heterodyne response over 7 GHz and a heterodyne noise level below 1×10^{-18} W/Hz.

QWIP NEP

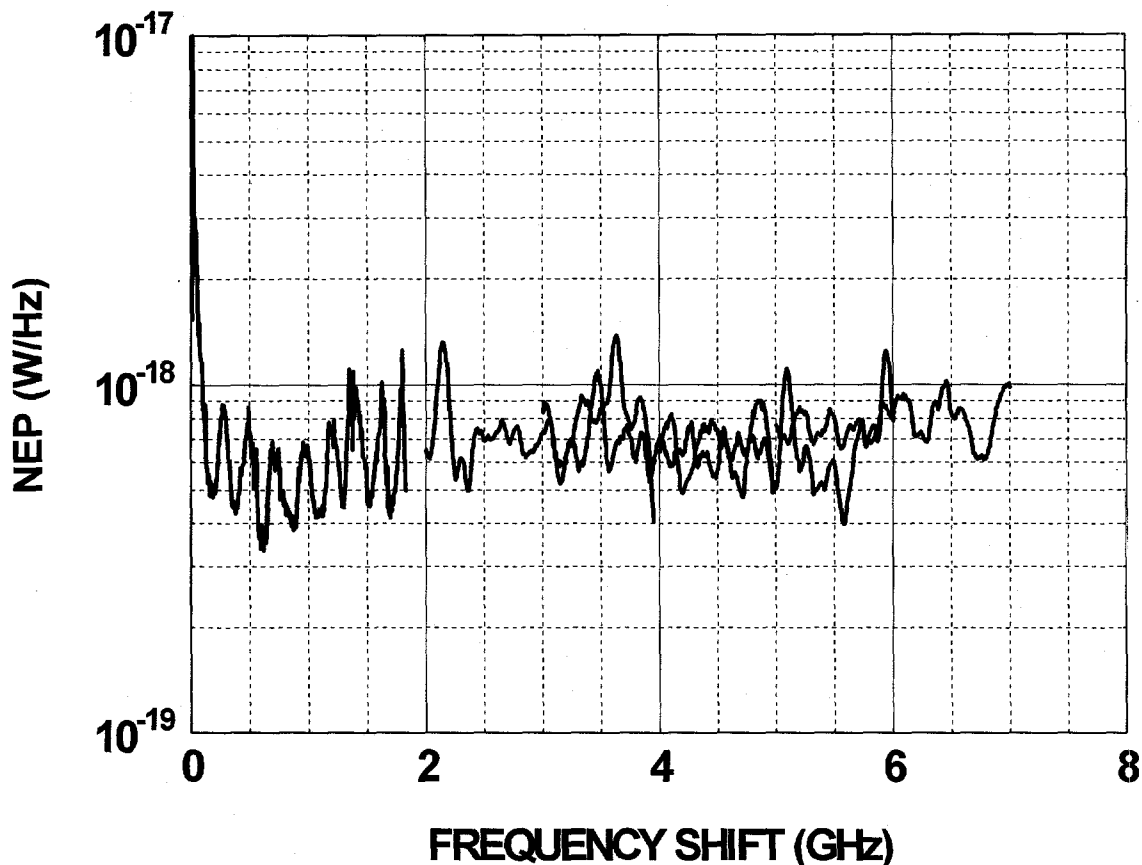


Fig. 2. Measured heterodyne noise spectrum for a QWIP detector. The different curves are for combinations of amplifiers and spectrum analyzers indicating the detector noise is below 10^{-18} W/Hz.

CONCLUSIONS AND FUTURE WORK

Although this noise level is sufficient for testing, the low density of alpha particles in an ignited fusion reactor will require a much lower noise, approaching the quantum limit of 4×10^{-20} W/Hz. Work has begun with the NRC in developing a lower noise heterodyne receiver. Improvements are expected from three areas. First, an anti-reflection coating will be added to the detector. With the high index of refraction, an-antireflection coating should provide a nearly 30% reduction in the NEP. The second step is to increase the number of wells to improve the photon absorption, and the third is to increase the doping in the detector wells to also increase the absorption, which happens to increase the dark current. Normally, the increase in dark current is associated with a decrease in sensitivity, however, for heterodyne detection where the dominant form of detector current is generated by the local oscillator, increasing the detectors' dark current does not degrade the sensitivity.

At present the receiver system is being design to perform Thomson scattering measurements on the JT-60U tokamak.⁵ Although this is not an ignited plasma experiment producing the energetic alpha particles at 3.5 MeV, high energy neutral beams are used in testing the heating of the plasma. With particle energies approaching

500 keV and particle fluxes near 10 amperes, this beam heating produces an energetic ion tail which can be used to simulate the general shape of the expected alpha particle spectrum. The expected scattered spectrum for JT-60U is shown in Fig. 3. Note the

SCATTERED POWER SPECTRUM FOR JT-60U

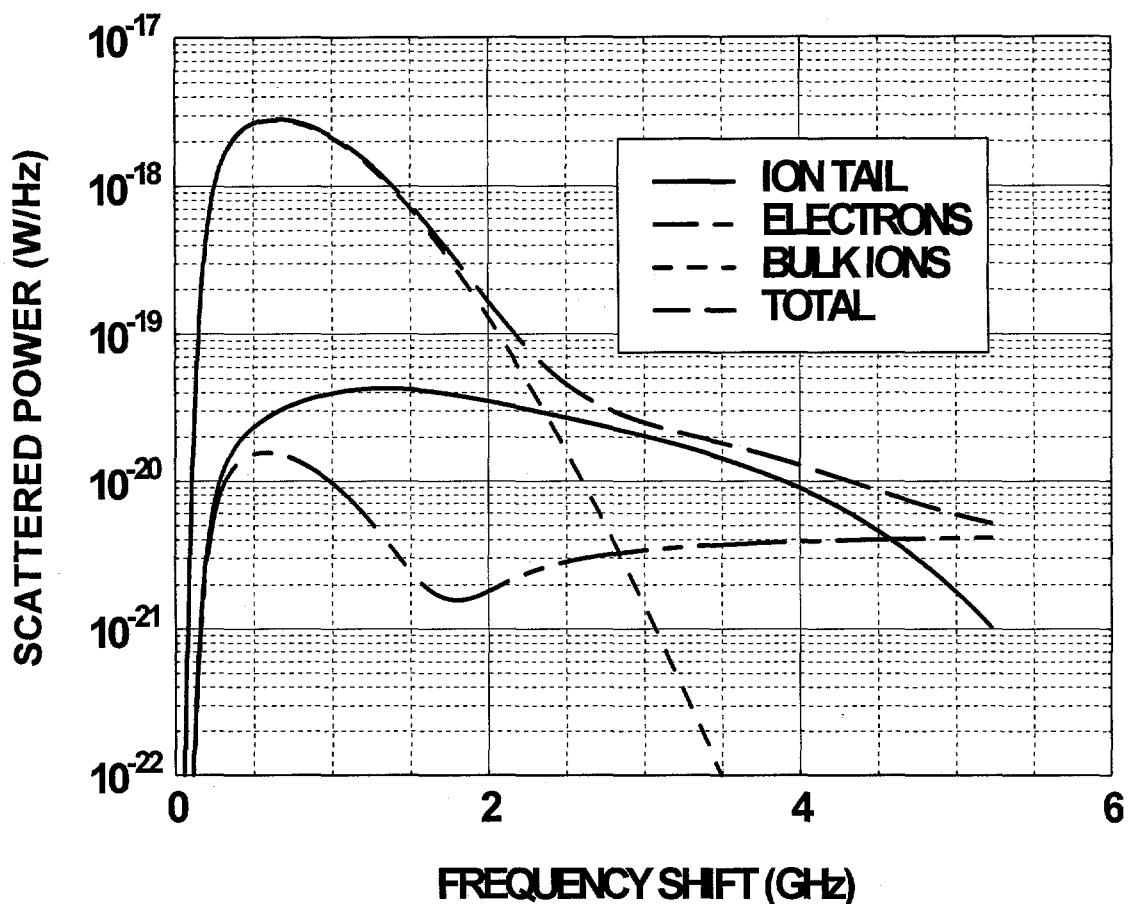


Fig. 3. Expected scattered power spectrum for the JT-60U tokamak.

contribution to the total signal is dominated by the ion tail from approximately 2 to 5 GHz. However, to measure this part of the spectrum will again require a detector with a low noise level, in this case approaching the noise limit of 4×10^{-20} W/Hz. With higher receiver noise, the S/N ratio will be reduced. For example, setting a minimum level for S/N at 5 to perform these measurements and taking the expected value of the scattered power to be 2×10^{-20} W/Hz, requires a value of NEP to be less than 1.07×10^{-19} W/Hz. Although this is nearly an order of magnitude lower than 10^{-18} W/Hz, the noise for the first detector tested, it is still well above the noise limit and the three modifications are expected to yield the next version with this required noise level.

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