A Heterodyne-Detection System for Measurements in Collective HCN-Laser Scattering from Thermonuclear Plasmas

O. GEHRE

Abstract—Collective HCN-laser scattering may become a useful diagnostic for waves and fluctuations in plasmas in the parameter range of Tokamak and Stellarator. Conditions for the measurement of the scattered spectrum are given and a resulting detection system, using a whisker detector in a heterodyne mode of operation, is described.

I. INTRODUCTION

SCATTERING of electromagnetic radiation from a plasma is a well-known nondisturbing diagnostic method. For values of the scattering parameter α

$$\alpha = \frac{1}{\lambda_D \cdot |\boldsymbol{k}|} = \frac{\lambda_0}{\lambda_D \cdot 4\pi \cdot \sin \theta/2} \tag{1}$$

where

- $\boldsymbol{k} = \boldsymbol{k}_s - \boldsymbol{k}_0$;
- $\boldsymbol{k}_0$ incident wave vector;
- $\boldsymbol{k}_s$ scattered wave vector;
- θ scattering angle;
- λ_0 incident wavelength;
- λ_D Debye length.

For α larger than one the spectrum is dominated by the collective effects. The measured Doppler shifts in the scattered light give the k spectrum of waves and fluctuations in the plasma and the corresponding density-fluctuation amplitudes and damping mechanisms can be estimated. Collective microwave-scattering experiments [1],[2] have shown strong enhancements in scattered intensity into certain directions when the density fluctuations grow overthermal. This coherent scattering represents a sort of reflection [3] of incoming radiation from plasma waves in the scattering volume.

We are interested in the use of coherent scattering as a diagnostic for turbulence and wave-conversion phenomena in HF-heated plasmas with densities $N_e = 10^{11} - 10^{14}$ cm^{-3} and temperatures $T_e = 10$ eV to some keV, which includes present Tokamaks and Stellarators. Such experiments should lead to a better understanding of anomalous resistivity effects in these machines. Due to a lack of suitable sources and detectors at higher frequencies, up to now this diagnostic has been only usable for laboratory plasmas at low densities and temperatures.

Manuscript received May 6, 1974.
The author is with the Max-Planck-Institut für Plasmaphysik, Garching, Germany.

II. CHOICE OF THE SCATTERING SOURCE

For collective scattering from the previously mentioned plasmas the optimum wavelength lies in the far infrared (FIR). This is easily found from scattering theory, taking into account two important conditions for an experiment.

1) The spectrum of detectable plasma waves should include short wavelengths. The smallest value measurable in backward scattering is fixed by scattering theory to half the source wavelength.

2) A wide range for the scattering angle θ should be available keeping α within the collective regime for different scattering geometries.

To match these conditions the HCN laser with a strongest line at 337 μm seems a good choice. Plasma waves down to a 0.17-mm wavelength can be measured with this laser, and for a plasma with $N_e = 10^{14}$ cm^{-3} and $T_e = 1$ keV, for example, the whole range from forward to backward scattering can be used at $\alpha > 1$.

For first experiments two HCN lasers have been developed at our laboratory. One delivers a maximum output power of 100 mW CW and is described in detail in [5]; the other is similar to the one described by Sharp and Wetherell in [6] and should deliver some 100 W in a pulsed mode.

III. THE DETECTION PROBLEM

The maximum output power available from present HCN lasers is far below the values known from high-power scattering sources in the visible and near-infrared range. A scattering experiment in the FIR will only be feasible if the small scattered light intensities can be detected. In Table I a signal-to-noise (S/N) analysis is shown from which we can find the conditions for a detection system. The average power into a 100-kHz frequency interval has been calculated for scattering from a plasma in thermal equilibrium. From this value we get the necessary detector sensitivity and can evaluate S/N for video detection, taking into account background noise from walls and plasma. The important parameters are given in Table I. The results show that at our laser powers video detection is impossible for scattering from a thermal plasma.

The situation improves if we consider coherent scattering from overthermal density fluctuations. In this case the scattered radiation will be concentrated into a rather narrow frequency peak for certain scattering angles. Its value can be calculated following the expression [3],[4]

TABLE I
SIGNAL-TO-NOISE ANALYSIS FOR HCN-LASER SCATTERING

Scattering source	CW-HCN Laser 100mw	Pulsed HCN-Laser 1kw	Coherent enhancement factor ($\tilde{n} = 10^9\ cm^{-3}$)
Scattered power to detector	$4,3 \cdot 10^{-18}$ W	$4,3 \cdot 10^{-14}$ W	x 10^6
Noise of walls and windows	$\sim 2 \cdot 10^{-17} \frac{W}{HZ}$		
Plasmanoise	$\sim 2 \cdot 10^{-18} \frac{W}{HZ}$		
necessary Detector sensitivity (Frequencywindow 100 KHz)	$4,3 \cdot 10^{-23} \frac{W}{HZ}$	$4,3 \cdot 10^{-19} \frac{W}{HZ}$	x 10^6
$\frac{S}{N}$	$\sim 2 \cdot 10^{-6}$	$\sim 2 \cdot 10^{-2}$	x 10^6

Note: H_2 plasma, $T_e = T_i = 10^6$ K; $N_e = 10^{13}$ cm^{-3}. Scattering volume: 1 cm^3, T_{Wall}: 1000 K, detector field of view: 0.1 sr.

$$P_s = \lambda_L^2 \cdot \tilde{n}^2 \cdot \sigma_{\text{Th}} \cdot L^2 \cdot P_L \tag{2}$$

where P_s is the scattered power, P_L is the laser power, λ_L is the laser wavelength, $\tilde{n}$ is the density-fluctuation amplitude, σ_{Th} is the Thomson cross section, and L is the length of the scattering volume.

The increase with λ_L^2 partly compensates for the low output (LO) power of the HCN laser. With a value of 10^9 cm^{-3} for the turbulent density-fluctuation level, which already has been measured in heating experiments, we get an increase of six orders of magnitude in scattered power. This reduces the necessary detector sensitivity and improves S/N by the same amount, as shown in Table I. Even then video detection may only be possible for strong enhancement factors and at the highest laser powers available.

A more convenient way is the use of heterodyne detection which has already become a standard technique for microwave-scattering experiments. This method offers two main advantages.

1) The problem of background noise and thermal-detector noise, which is the main limitation of detectors in the FIR, can be overcome by increasing the LO power P_{LO} until it dominates all other noise sources. The gain in the minimum detectable signal as compared to video detection is then given by $C \cdot P_{\text{LO}}/P_s$ (C is a detector constant), and an increase in sensitivity of many orders of magnitude can be obtained.

2) The scattered spectrum can be easily measured at the lower IF using commercially available low-noise amplifiers and spectrum analyzers. No information is lost by the conversion process.

From the possible detectors usable for heterodyne detection at FIR frequencies, at the present time whisker diodes seem to be the most hopeful approach to our requirements in sensitivity and bandwidth. Their response time allows them to follow IF frequencies of many gigahertz. This makes them superior to other types as they will easily resolve spectra with maximum Doppler shifts of some 100 MHz, typical in collective HCN-laser scattering. Calculations on the basis of a heterodyne NEP of 10^{-18} W/Hz at millimeter waves show that they should be able to detect at least 10^{-16} W/Hz at 337 μm, considering a $1/f^2$ roll off in sensitivity. Up to now they have not been commercially available for the infrared, but laboratory models have already been used during the last years for frequency measurements of infrared laser lines. From these experiments only few exact and reproducible values for detector NEP are known.

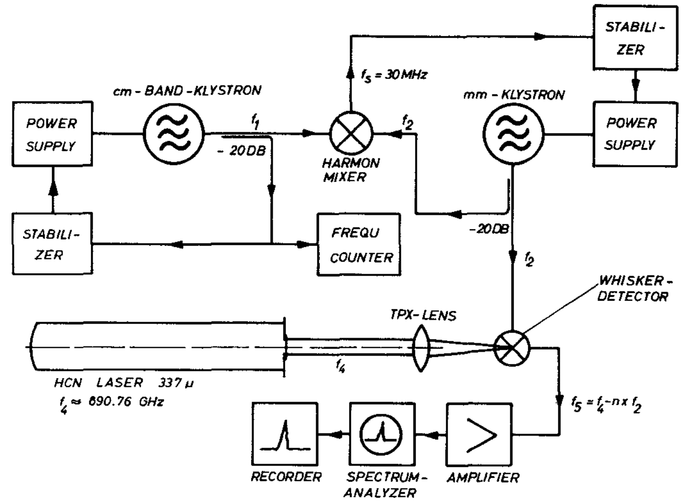

Fig. 1. Heterodyne-detection system for HCN-laser radiation.

IV. EXPERIMENTS

A. The Heterodyne-Detection System

The heterodyne-detection system, which was developed for our experiments, is shown in principle in Fig. 1. Radiation from a CW HCN laser working at a 337-μm wavelength in the fundamental mode is focused on the detector. The radiation is linear polarized in a horizontal direction by means of a grid polarizer in the laser resonator. For the heterodyning a LO klystron in the millimeter range is used, as there were no higher frequency LO sources available. The IF signal is formed by the mixing of the laser frequency with a harmonic of the LO excited in the point contact due to higher order terms of its nonlinear characteristic. The millimeter LO klystron is frequency stabilized by using a double phase-locked system. IF spectra with center frequencies of some megahertz to some gigahertz can be measured by using different amplifiers and a spectrum analyzer and recorder.

B. The Whisker Detector

A main problem with whisker detectors in the FIR is the stability of the contact. Due to the junction capacitance, the incoming radiation field is short circuited at higher frequencies and the sensitivity decreases. To compensate for this effect, infrared diodes use very thin wires for the whisker, allowing small contact areas to keep the capacitance low. This only allows small contact pressures and the detector becomes sensitive to vibration and shock.

Considering these points, we have machined the main part of our detector out of a solid block of brass. All important parts like whisker mount, flat electrode mount, differential screw for contacting, and LO microwave feed are integrated into this block to avoid internal vibrations between different parts. The detector can be positioned in three room directions and turned around a vertical axis which coincides with the inner conductor of a rigid coaxial line for the IF signal. The mount of the whisker directly fits into the inner conductor through a hole in the surface of the block.

The whisker is fabricated at the laboratory from a 25-μm-diam tungsten wire. After soldering to the mount it is bent to an L shape and pointed by standard electrolytic etching. A length of 1 mm for the vertical part and around 2.5 mm for the active horizontal part is used for good spring action and efficient coupling of infrared radiation. To find the best material for the flat electrode chip, different semiconductors and pure metals have been compared for harmonic mixing efficiency. From semiconductors (Ge, Si) single-crystal Si has shown the best results. For any metal measured (Mo, W, Cu, Ms) the sensitivity was at least 20 dB lower than best semiconductor results. The best crystals were taken out of millimeter-wave mixer diodes and left on their mount to avoid additional contact noise problems. Before use, the surfaces of the crystals were cleaned and brought to optical quality using diamond grinding and polish paste. Only then a reproducible contact with good NEP was possible.

To reach good coupling of the LO, the whisker was arranged in the field maximum of a standing wave of the millimeter radiation. A sample from the LO klystron is fed to the whisker by means of a waveguide feed fixed to the detector block. A small reflector on the opposite side forms the standing-wave pattern. The polarization of the microwave is kept parallel to the whisker front part independent of its orientation to the laser polarization by using a flexible dielectric waveguide in the LO line.

C. Measurements

Compared to other FIR whisker detectors our detector has shown good reliability. A contact normally could be used for weeks without change in sensitivity, even when vibrations or shocks to the bench or detector block did happen. A change of the whisker and recontacting could be done in a minute and measurements would be reproducible.

1) Video Detection: Some measurements of the video response were made when the detector was turned around its vertical axis to find the best coupling angle of infrared radiation. The front part of the whisker acts as a long-wave antenna for 337 μm and shows a typical antenna diagram (Fig. 2), similar to the one measured in [9].

The best responsivity for optimum coupling was 30 V/W. Good results only were possible at low contact pressure and high contact impedance as compared to rather high pressure and low impedance in heterodyning.

2) Heterodyne Detection: For the first measurements LO klystrons with different frequencies in the 4-mm range were used allowing harmonic mixing at the thirteenth to the eleventh harmonic. The fundamental power of the LO delivered to the detector was increased to 100 mW. The

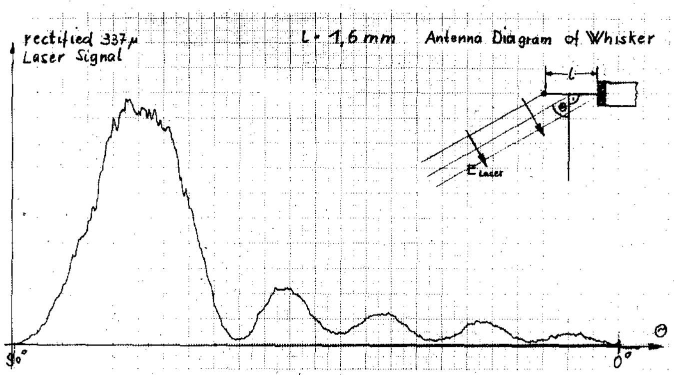

Fig. 2. Antenna diagram of the whisker.

contact did stand this power without burnout, but current noise from the LO and its harmonics limited the increase in NEP. The measured values ranged from near 10^{-11} W/Hz for the thirteenth harmonic to near 10^{-12} W/Hz for the eleventh harmonic. For the same contact and constant LO power, a transition from the twelfth to the eleventh harmonic did improve the NEP by 8 dB. Measurements were made with different bandwidths in the IF range 30 MHz–3GHz, showing no evidence for a decrease in NEP at the higher frequencies.

The measurements were continued with a 2.5-mm klystron which could deliver around 50 mW to the whisker. The higher fundamental frequency allowed mixing between the seventh harmonic of the LO and the laser. A typical result is shown in Fig. 3. The upper trace shows the IF spectrum obtained for 5 mW of 337-μm radiation focused on the whisker. The signal was measured in a bandwidth of 100 kHz and the center frequency was 40 MHz. The lower trace shows the signal 50 dB down near to the noise level, when the laser power to the detector is decreased by 55 dB with a calibrated attenuator. Because of the stable narrow-band LO line, the mixing spectrum directly gives the line shape of the free running laser. The linewidth of around 200 kHz is determined by the loaded Q of the laser resonator and additional short-time fluctuations of the line center introduced by refractive index changes of the active medium in the laser discharge.

The NEP calculated from the measured data is 10^{-13} W/Hz. The use of a reverse bias to the detector only brought an increase in the IF signal for contacts which

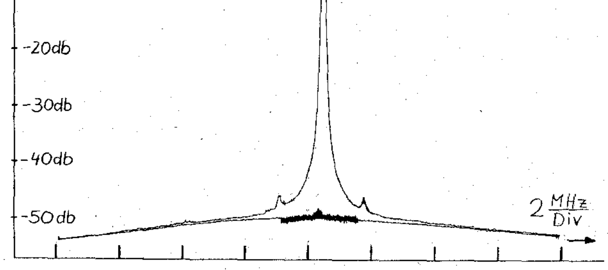

Fig. 3. IF spectrum for mixing of the HCN laser with the seventh harmonic of a 2.5-mm klystron.

were not set to their best sensitivity at zero bias. When the signal had vanished after extensive contact pressure a short current pulse across the barrier could bring back almost full sensitivity. It is thought that this effect is due to welding of the contact and formation of a depletion layer.

V. FUTURE IMPROVEMENTS

As a result of our measurements, the main limitation for an improvement in NEP seems to be the harmonic-mixing process. The high-harmonic conversion loss cannot be overcome by a further increase in LO power because of LO current noise and burnout of the contact. Higher LO frequencies are necessary to come to low harmonic orders or even to fundamental mixing. It seems unreasonable to use microwave sources like carcinotrons which are extremely expensive and hard to handle at these frequencies. Moreover, the stabilization of LO frequency will become a main problem.

A possible method, now under test at our laboratory, is the use of a second smaller HCN laser as an additional LO delivering some milliwatts at the 311-μm transition. The difference between 337 and 311 μm corresponds to a frequency near 75 GHz from where the spectrum can be converted down by mixing with a stable 4-mm klystron in the same contact. This process needs no harmonic conversion and should lead to sensitivities near the calculated limit. In addition, the development of infrared lasers to higher output powers is still going on. In the near future this should allow FIR collective scattering to become a useful diagnostic for fusion plasmas.

REFERENCES

[1] V. Arunasalam, M. A. Heald, and J. Sinnis, "Microwave scattering from unstable electron plasma waves," *Phys. Fluids*, vol. 14, pp. 1194–1203, June 1971.
[2] C. B. Wharton, D. S. Prono, and F. Sandel, "Turbulent heating studied by microwave scattering," Cornell Univ., Ithaca, N.Y., Rep. CU 3958-2, May 1969.
[3] O. Gehre, H. M. Mayer, and M. Tutter, "A model for coherent scattering of electromagnetic waves from spacially bounded plasma waves," IPP Lab. Rep. IV/48, Jan. 1973.
[4] C. M. Surko, R. E. Slusher, D. R. Mohler, and M. Porkolab, "10.6 μm laser scattering from cyclotron-harmonic waves in a plasma," *Phys. Rev. Lett.*, vol. 29, pp. 81–84, July 1972.
[5] O. Gehre, "An HCN laser source for coherent scattering from waves in stationary plasmas," IPP Lab. Rep. IV/39, July 1972.
[6] L. E. Sharp and A. T. Wetherell, "High power pulsed HCN laser," *Appl. Opt.*, vol. 11, pp. 1137–1141, Aug. 1972.
[7] L. M. Matarrese and K. M. Evenson, "Improved coupling to infrared whisker diodes by use of antenna theory," *Appl. Phys. Lett.*, vol. 17, pp. 8–10, July 1970.

Submillimeter Spectroscopy of Weak Antiferromagnets in Magnetic Fields Up To 300 kOe

E. G. RUDASHEVSKY, A. S. PROKHOROV, AND L. V. VELIKOV

***Abstract*—The dynamic properties of antiferromagnets with Dzyaloshinsky interaction were investigated at wavelengths 0.3–14 mm, in magnetic fields up to 300 kOe and temperature 4.2–400 K. The problems of impurities, field induced phase transitions, types of spin oscillation, etc., for different types of antiferromagnets with Dzyaloshinsky interaction are discussed. Based on the investigation results, a new approach to the physics of magnetic phenomena, using the complete rational basis of invariants and avoiding potential series expansion, has been developed.**

DESPITE the fact that antiferromagnetism has been known for a long time [1] and up to today over 300 antiferromagnetic insulators have been discovered, there is an increasing interest in studying this phenomenon by resonance methods. The main reason for this is that inherent oscillation frequencies of the above classes of materials fall in the submillimeter and the far-infrared ranges of electromagnetic radiation (200 μm–2000 μm). It is worthwhile noting that the interest in these materials is explained by the following two reasons. First, the present active conquest of this range from both superhigh frequencies (vacuum electronics) and from optics (lasers); the sources of coherent radiation of the above range have become available. Second, the necessity of finding substances for practical applications over this range.

A variety of antiferromagnets have greatly differing properties and, as a rule, have nonlinear and very complicated dependences of resonance frequency upon magnetic field, temperature, and orientation. Of special importance is the insight into the fundamental properties of antiferromagnets in order to investigate their use in practice and to predict the properties of newly synthesized crystals.

Though there are many known antiferromagnets, antiferromagnetic resonance (AFMR) has been observed for relatively few of them (about 30), and the number of

Manuscript received May 10, 1974.
The authors are with the P. N. Lebedev Physical Institute of the Academy of Sciences of the USSR, Moscow, USSR.