A 300 GHz collective scattering diagnostic for low temperature plasmas[a)]

Robert A. Hardin,[1,b)] Earl E. Scime,[1] and John Heard[2]
[1]*Department of Physics, West Virginia University, Morgantown, West Virginia 26506-6315, USA*
[2]*Department of Physics, Clarion University, Clarion, Pennsylvania 16214, USA*

(Presented 13 May 2008; received 9 May 2008; accepted 21 May 2008; published online 31 October 2008)

A compact and portable 300 GHz collective scattering diagnostic employing a homodyne detection scheme has been constructed and installed on the hot helicon experiment (HELIX). Verification of the homodyne detection scheme was accomplished with a rotating grooved aluminum wheel to Doppler shift the interaction beam. The HELIX chamber geometry and collection optics allow measurement of scattering angles ranging from 60° to 90°. Artificially driven ion-acoustic waves are also being investigated as a proof-of-principle test for the diagnostic system. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2953460]

I. INTRODUCTION

Collective scattering is a nonperturbative method capable of directly measuring fluctuations in plasmas. Recent experiments in helicon plasma sources have employed collective scattering diagnostics in the microwave to millimeter wavelength ranges.[1,2] Using enhanced backscattering of microwaves at the upper hybrid resonance layer, ion-acoustic-like waves were observed by Altukhov *et al.* Ion-acoustic waves were also observed with a 140 GHz millimeter-wave based scattering diagnostic by Kwak *et al.*, similar to the system described here. Interferometers employing millimeter-wave sources have been installed on experiments ranging from a fusion class device[3] (DIII-D) to a low temperature helicon plasma.[4]

The initial focus of the scattering experiments is to measure the "trivelpiece-gould" (TG) wave,[5] or slow wave, which is believed by some to be responsible for the high rf absorption efficiency of helicon sources operating near the lower hybrid frequency.[6–9] The collective scattering experiments are to be performed for source parameters found to perpendicularly heat ions near the plasma edge[10] and that are also consistent with theoretical predictions for strong slow wave damping in the plasma edge. For the source operating near the lower hybrid frequency, the TG wave driven at the primary rf frequency is dominantly electrostatic with $k_\perp \gg k_\parallel$. Assuming that the ions were heated by damping of the slow wave on the ions, the ion heating provided indirect evidence of the existence of the slow waves in the plasma edge. However, due to the short perpendicular wavelength of the slow wave ($\lambda \sim 1$ mm), probe measurements are problematic and the development of a diagnostic capable of directly measuring the slow wave is required for the confirmation of slow wave propagation in the edge of helicon source plasmas.

II. HELIX DESCRIPTION

The hot helicon experiment (HELIX) vacuum chamber (Fig. 1) is a 61 cm long Pyrex tube 10 cm in diameter connected to a 91 cm long stainless-steel chamber that is 15 cm in diameter. The stainless-steel chamber has one set of four 6 in. crossing ports in the center of the chamber and four sets of four $2\frac{3}{4}$ in. crossing ports on either side for diagnostic access. The opposite end of the stainless-steel chamber opens into a 2 m diameter space chamber. Ten electromagnets produce a steady-state axial magnetic field of 0–1200 G in the source. The source gas is argon at neutral pressures of 1–10 mTorr, regulated with a mass flow controller and fed into the source chamber at either a port on the stainless-steel section of the chamber or from the far right end of the source chamber (as shown in Fig. 1). rf power of up to 2.0 kW over a frequency range of 6–18 MHz is used to create a steady-state plasma with a 19 cm, half-wave, right-handed helix antenna. The right handedness of the antenna is relative to the magnetic field direction and is designed to launch the $m=+1$ helicon wave. A common electrical ground is used for the vacuum chambers and the rf amplifier. The characteristic electron temperature and density in the steady-state plasma are $T_e \approx 4$ eV and $n \sim 1 \times 10^{13}$ cm^3, as measured with a rf compensated Langmuir probe.[11]

III. 300 GHz DIAGNOSTIC DESCRIPTION

The homodyne scattering system, which is basically a quasioptical interferometer, consists of three beam paths: an "interaction" beam path, a "scattered" beam path, and a "reference" beam path. ZEMAX™, an optical design program with Gaussian beam propagation capabilities for each beam path, was used for the design. All optical component dimensions were designed so that their radii are at least a factor of 2 larger than the beam waist. Another feature emphasized during the design was that the system had to be portable. Thus all optical components, except the vacuum collection mirror, fit on a 36 by 36 in.^{2} vertically oriented optical table. For diagnostic beam access, extensions were added to two of

[a)]Contributed paper, published as part of the Proceeding of the 17th Topical Conference on High-Temperature Plasma Diagnostics Albuquerque, New Mexico, May 2008.
[b)]Electronic mail: rhardin@mix.wvu.edu.

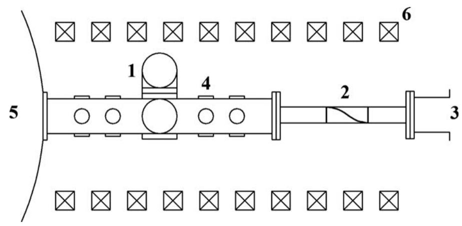

FIG. 1. Schematic of the HELIX plasma source: (1) injection and collection ports for the millimeter–wave system, (2) fractional helix antenna, (3) pumping station, (4) retractable rf compensated Langmuir probe, (5) space chamber, and (6) magnetic field coils.

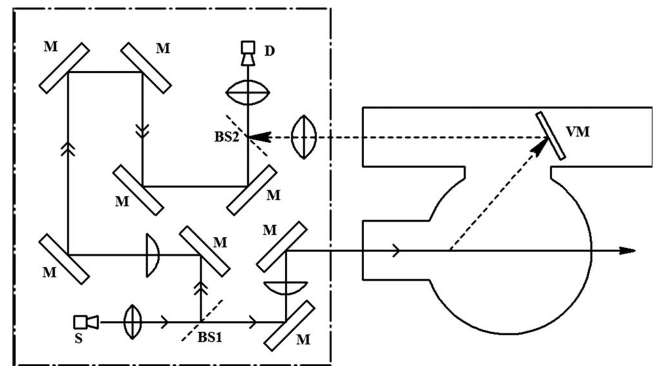

FIG. 2. Schematic of the millimeter–wave system: (S) is the millimeter-wave source, (D) is the detector, (M) are mirrors, (VM) is the adjustable vacuum mirror, and (BS1) and (BS2) are the beam splitters.

the four 6 in. ports. One extension is a 4 in. diameter stainless tube along the interaction beam path. A 4 in. diameter stainless "T" tube was added to the scattered beam path so the scattered radiation could pass from vacuum to air at a normal incidence.

The source is a frequency tripled Gunn oscillator, manufactured by Radiometer Physics GmbH of Mechenheim, Germany, with a tunable frequency range of $\sim\pm1$ GHz and an output power of $\sim$3.3 mW at 300 GHz. The source uses a "potter horn" antenna to produce a linearly polarized cylindrically symmetric Gaussian beam. The 300 GHz beam is directed into the plasma with the polarization direction parallel to the magnetic field of HELIX. Quasioptical propagation is used due to the large losses associated with waveguides at 300 GHz.

The millimeter-wave design was chosen because typical collective scattering diagnostic lasers need several watts of power to yield observable scattered powers. For coherent fluctuations, the scattered power is proportional to the square of the incident wavelength, $P_s=1/4P_0r_e^2\tilde{n}^2L_V^2\lambda_0^2$.[12] P_s is the scattered power, P_0 is the incident power, r_e is the classical electron radius, $\tilde{n}$ is the density fluctuation amplitude, L_V is the scattering volume length, and λ_0 is the incident wavelength. For the same incident power, fluctuation levels, and scattering volume, a 1 mm wavelength (300 GHz) beam will produce a scattered signal nearly 10 000 times larger than a 10.6 μm CO_2 laser.

The detector is a Schottky diode detector mixer centered at 300 GHz, with a sensitivity of 600 mV/mW and an output intermediate frequency (IF) bandwidth of approximately 500 MHz. The detector is enclosed in a $\frac{1}{4}$ in. thick copper box with a battery-powered analog module 322-12 voltage amplifier providing 60 dB of gain. The copper box and battery-powered amplifier are used to minimize rf noise pickup. Only the detector's potter horn protrudes from the copper box. Sub miniture A (SMA) and bayonet nut coupling (BNC) bulkhead connectors are used for the dc bias and IF output. Data acquisition of the IF signal is performed using either a spectrum analyzer or a 100 MHz digitizer. The spectrum analyzer has a noise floor voltage of approximately 450 nV. Given the detector sensitivity, the scattered power detection threshold is approximately 750 pW.

The lenses are fabricated from high density polyethylene (HDPE). Hyperbolic and ellipsoidal lens surfaces are used to produce and maintain a planar phase front and correct any phase lag. HDPE windows are also used as vacuum interfaces for the interaction and scattered beams since standard viewports heavily attenuated the 300 GHz signal. The windows have a 2.5° wedge cut into each face, relative to the surface normal, to minimize direct reflections.

Beam splitting is accomplished with stretched Mylar sheets. In Fig. 2, BS1 is a 76.2 μm thick Mylar sheet that yields 90-10 (transmission-reflection) ratio. The 10% reflection creates the local oscillator reference beam, while the remaining power is directed into the plasma as the interaction beam. The scattered and reference beams are recombined at BS2, a 127 μm thick Mylar sheet. The 127 μm thickness was found to produce the optimal scattered beam reflection while minimizing transmission losses.

The mirrors on the optical table are constructed from mirrored stainless-steel sheets attached to aluminum plates with retaining rings. The two mirrors in the reference path are mounted on a single linear stage for a correction of the reference leg path length relative to the combined interaction and scattered path lengths. The translating mirror system maintains the overall optical path length difference between the reference and scattered paths to within a single wavelength (1 mm).

In the vacuum chamber, a flat mirror (VM), designed to maximize signal detection, is used to direct the scattered radiation from the vacuum chamber to the optical table. The mirror is oval in shape to allow linear translation and rotation in the 4 in. diameter vacuum tube while maximizing the reflective surface area. The translation, via two shafts mounted on a linear stage, allows for scanning the collection volume across the plasma column. Radial scanning across the plasma is critical since we expect the slow wave to be largest near the plasma edge. The mirror pivots by sliding along a fitting attached to the end of one shaft, while the relative position of the other shaft controls the angle of the vacuum mirror through a micrometer and an inline ball joint. Rotating the mirror changes the angle of collection and thereby selects the wave number to be observed. The measurable scattered angles in the HELIX range from 60° to 90°, corresponding to fluctuation wave numbers of 63 to 89 rad/cm via the Bragg condition, $k=2k_0\sin(\theta_s/2)$, where k_0 is the incident wave number, k is the fluctuation wave number, and θ_s is the scattering angle.[14] The radial location of the collection volume depends on the angle and location of the collection mirror. Observable radii for 60° scattering are from $r=-5$ to

−1.5 cm, while for 90° scattering the observable radii range from −1.5 to +5 cm. Future measurements with improved spatial resolution will employ an off axis parabolic mirror, with the focal point fixed in the waist of the incident beam.

The lenses in the interaction beam path are designed to focus and collimate the primary beam, which is designed to achieve a Rayleigh length longer than the plasma column diameter and a beam waist of approximately 17 mm on the HELIX axis. The collection lenses are designed to match the scattered beam and the reference beam sizes at the mixer (BS2), as well as to form a beam waist nearly identical in size to the interaction beam waist. The beam, after mixing, is focused into the detector's potter horn with a final set of focusing HDPE lenses.

For incident and collection beam waists of 17 mm, an incident power of 1 mW, a collection solid angle of 1.1×10^{-3} sr, and a scattering volume length of twice the beam waist (34 mm), the scattered power equation becomes $\tilde{n} = 2.0 \times 10^{16} \sqrt{P_s}$, where $\tilde{n}$ is the density fluctuation amplitude in cm^{-3} and P_s is the scattered power in watts. Given our scattered power detection threshold of 750 pW, a density fluctuation amplitude of $5.5 \times 10^{11}\ \mathrm{cm}^{-3}$ is required for an observation of an electrostatic wave, a 5% density fluctuation for a peak density of $10^{13}\ \mathrm{cm}^{-3}$. Therefore, in the plasma edge, where the plasma density is typically one order of magnitude smaller, a 50% density fluctuation is required to detect the TG wave with this diagnostic.

IV. OBSERVATIONS

A rotating diffraction grating wheel was constructed to test the diagnostic before installation on the plasma source.[13] The aluminum wheel is 6 in. in diameter, with a 1 in. wide face containing 320 triangular teeth separated by 1.49 mm. Light pulses passing through a hole in the wheel and detected with a photodiode provide an absolute measurement of the wheel rotation frequency. The Doppler shift from a rotating diffraction grating[14] is $\nu_D = 2\pi m f_r R / d$, where R is the radius of the wheel, f_r is the rotational frequency of the wheel, d is the groove spacing, and m is the diffraction order. Figure 3 shows the Doppler shifted frequency spectra measured with the mixer for $f_r = 41$ and 50 Hz. Visible in the signal are diffraction orders $m=1$ and 2 for both wheel frequencies. The signals at 22 and 44 KHz are ambient noise seen in all measurements.

After the proof-of-principle tests demonstrated that the system was optically aligned and that the mixer functioned as intended, the full system was installed on the plasma source. At this time, no scattered signals at the primary rf frequency or in the ion-acoustic range of frequencies have been observed. In an effort to directly excite finite $k_\perp$ electrostatic waves propagating perpendicular to the magnetic field that can be detected with this diagnostic, an antenna designed to launch electrostatic ion-cyclotron waves has been built and installed in HELIX. Similar spontaneously occurring waves were reported by Kwak *et al.* in their helicon source microwave scattering experiment. At the magnetic field strength of HELIX, the wave dispersion of such waves is essentially that of an ion-acoustic wave.[2]

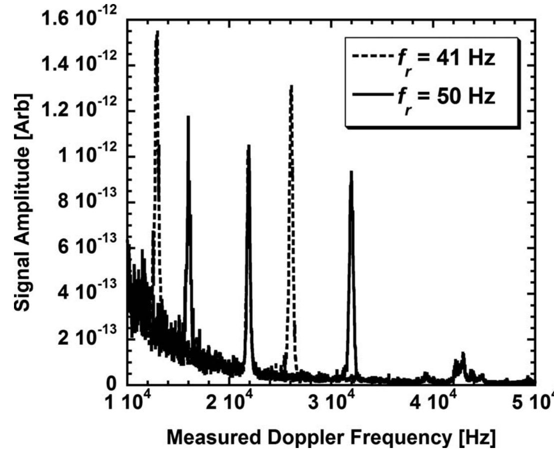

FIG. 3. Frequency spectrum from the spectrum analyzer using the rotating grating wheel to test the millimeter–wave system.

ACKNOWLEDGMENTS

The authors thank Carl Weber, Doug Mathess, and Tom Milam for help in designing and manufacturing many of the components for the diagnostic system. We also thank Ralph Zimmermann of Radiometer Physics GmbH and Thomas Crowe of Virginia Diodes Inc. for helpful discussions. This work is supported by the Department of Energy Laboratory Partnership EPSCoR Program and NSF Award No. PHY-0611571.

[1] A. B. Altukhov, E. Z. Gusakov, M. A. Irzak, M. Krämer, B. Lorenz, and V. L. Selenin, Phys. Plasmas **12**, 022310 (2005).
[2] J. G. Kwak, S. J. Wang, S. K. Kim, and S. Cho, Phys. Plasmas **13**, 074503 (2006).
[3] L. Porte, C. L. Rettig, W. A. Peebles, and X. Ngyuen, Rev. Sci. Instrum. **70**, 1082 (1999).
[4] M. Kramer, B. Clarenbach, and W. Kaiser, Plasma Sources Sci. Technol. **15**, 332 (2006).
[5] A. W. Trivelpiece and R. W. Gould, J. Appl. Phys. **17**, 1784 (1959).
[6] K. P. Shamrai and V. B. Taranov, Phys. Lett. A **204**, 139 (1995).
[7] K. P. Shamrai and V. B. Taranov, Plasma Sources Sci. Technol. **5**, 474 (1996).
[8] G. G. Borg and R. W. Boswell, Phys. Plasmas **5**, 564 (1998).
[9] D. Arnush, Phys. Plasmas **7**, 3042 (2000).
[10] J. L. Kline, E. E. Scime, R. F. Boivin, A. M. Keesee, and X. Sun, Phys. Rev. Lett. **88**, 195002 (2002).
[11] I. D. Sudit and F. F. Chen, Plasma Sources Sci. Technol. **3**, 162 (1994).
[12] J. Sheffield, *Plasma Scattering of Electromagnetic Radiation* (Academic, New York, 1975).
[13] D. Veron, in *Infrared and Millimeter Waves*, edited by K. J. Button (Academic, New York, 1979), Vol. 2, pp. 69–135.
[14] J. Howard, Appl. Opt. **31**, 1419 (1992).