

Multichannel microwave interferometer for the levitated dipole experiment

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(Received 5 January 2009; accepted 16 February 2009; published online 6 April 2009)

A four-channel microwave interferometer (center frequency: 60 GHz) has been constructed to measure plasma density profiles in the levitated dipole experiment (LDX). The LDX interferometer has a unique design owing to the unique geometry of LDX. The main design features of the interferometer are: (1) the transmitted beam traverses the plasma entirely in O-mode; (2) the interferometer is a heterodyne system employing two free-running oscillators; (3) four signals of data are received from just on transmitted beam; (4) phase shifts are detected in quadrature. Calibration tests demonstrate that the interferometer measures phase shifts with an uncertainty of approximately 5°. Plasma densities in LDX corresponding to phase shifts of up to 5π are routinely and successfully measured. © 2009 American Institute of Physics. [DOI: 10.1063/1.3095684]

I. INTRODUCTION

The levitated dipole experiment (LDX) is a new and innovative nuclear fusion experiment run jointly by Massachusetts Institute of Technology (MIT) and Columbia University and located at MIT's Plasma Science and Fusion Center.^{1,2} LDX has been built to explore the physics of plasmas confined by a dipole magnetic field and to investigate whether this magnetic geometry might one day be suitable for confining fusion-grade plasmas. In order to eliminate particle losses along field lines, the dipole field is produced by means of a magnetically levitated superconducting current-loop.

The LDX facility consists of a large, oblate vacuum chamber with an equatorial diameter of 5 m. The central dipole magnet is a doughnut-shaped superconducting coil 1.2 m in diameter. The dipole coil is levitated in the middle of the LDX vacuum chamber by attraction to a second magnet located on top of the vacuum chamber. A dynamical feedback system between the two magnets maintains the floating, dipole coil in position, and limits any vertical excursions to just a few millimeters. The dipole coil remains floating for intervals of approximately 3 h—an interval determined by how long the coil can remain at superconducting temperatures. Steady-state plasmas are produced by electron cyclotron-resonance heating (ECRH) at 3 frequencies: 2.45, 6.4 and, recently, 10.5 GHz. Total ECRH power is 15 kW.

A microwave interferometer (Fig. 1) has been built to measure the density profiles of LDX plasmas as functions of both radial position and time. Because the geometry of LDX is so unique, the design of the LDX interferometer must likewise be unique. LDX, in contrast to other plasma experiments, is physically a very large device ($R \sim 5$ m) that operates at relatively low densities ($n \sim 10^{11}$ particles per cm^3) in an unusual magnetic geometry. The LDX interferometer, when operated as a single-channel instrument, was based primarily on a device described in Ref. 3. However as a multi-

channel device, the LDX interferometer is distinct from most multichannel interferometers found in the literature, which generally employ sophisticated optics or laser sources.^{4,5}

Our goal was to build an interferometer that could measure the density over a wide swath of the vacuum chamber and also over a reasonably wide range of densities. In addition we wanted the interferometer to be simple, robust, reasonably inexpensive, and readily upgraded from one to multiple channels. The LDX interferometer has proven to be very successful and is currently one of the chief diagnostics on the experiment.

II. INTERFEROMETER DESIGN

A. O-mode propagation

One advantage of operating in a dipole magnetic geometry is that in the equatorial plane the magnetic field is mainly vertical. This allows the interferometer beam to traverse the plasma entirely in O-mode ($\mathbf{k}_{\text{wave}} \perp \mathbf{B}_{\text{external}}$ and $\mathbf{E}_{\text{wave}} \parallel \mathbf{B}_{\text{external}}$). The cold-plasma dispersion relation for O-mode waves is particularly simple in that it is a function of only the electron density of the plasma (and not the magnetic field in addition). This simplification remains valid in LDX even if the field deviates somewhat from vertical since the field decays rapidly with increasing radius.⁶

If the interferometer frequency f is selected such that the electron density of the plasma n_e is always much less than the cutoff density of the interferometer beam n_c , then the O-mode dispersion relation simplifies to a linear relationship between phase shifts (which can be measured) and the line-integrated plasma density (which we desire to know)

$$\int n_e d\ell \approx \frac{-n_c c}{\pi f} \Delta\phi. \quad (1)$$

Here c is the speed of light and $\Delta\phi$ is the phase shift in radians measured by the interferometer.

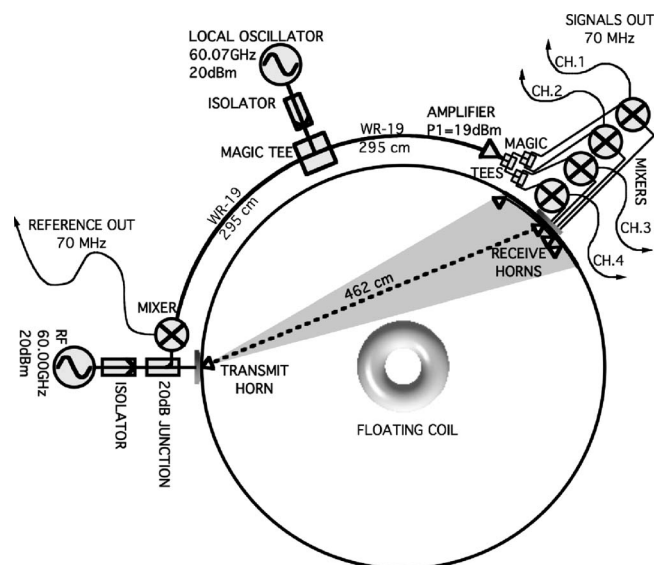


FIG. 1. Top view schematic of the LDX interferometer. The large, outer circle denotes the outline of the LDX vacuum chamber. Most of the power from the transmit horn spreads out into a cone of about 10° (shaded gray). The beam is received at four different locations at the far wall of the vacuum chamber.

By considering the frequencies of the ECRH sources, it was predicted that LDX plasmas would have densities on the order of 10^{11} particles per cm^3 —a prediction that was confirmed by subsequent measurements. Consequently, the operating frequency of the LDX interferometer was chosen to be 60 GHz since the cutoff density for this frequency is $4.5 \times 10^{13} \text{ cm}^{-3}$ and the condition $n_e/n_c \ll 1$ is well satisfied.

B. Heterodyne operation

Like any interferometer, the LDX interferometer consists of two beam paths: (1) a signal path that runs through the plasma and (2) a reference path that runs along the outside of the vacuum chamber and that has no contact with the plasma. In general, it is necessary that the signal and reference path-lengths be equal to within a few wavelengths of the beam in order that any phase noise from the frequency-source be subtracted away. At 60 GHz, where the wavelength is 5 mm, equal path lengths are impossible on a device as large as LDX. The path-length problem is solved by using a heterodyne system, that is, two separate frequency sources: a “radio frequency” (RF) and a “local oscillator” (LO). The RF and LO are offset from each other by an “intermediate frequency” (IF). The main advantage of heterodyning is that it averages the phase noise such that the signal and reference paths need only be equal to within a few wavelengths of the IF. Heterodyning does not compromise the precision of the measured data provided that the frequencies can be arranged such that $f_{\text{RF}} \gg f_{\text{IF}} \gg f_{\text{signal}}$.

For the LDX interferometer, the IF was chosen to be 70 MHz corresponding to a wavelength of 4.3 m. In fact, the LDX interferometer is designed with uneven signal and reference legs (Fig. 1). The signal legs are longer than the reference leg by the length of their path across the vacuum chamber. This compromise in symmetry was necessary in order to maximize the available power from the LO source.

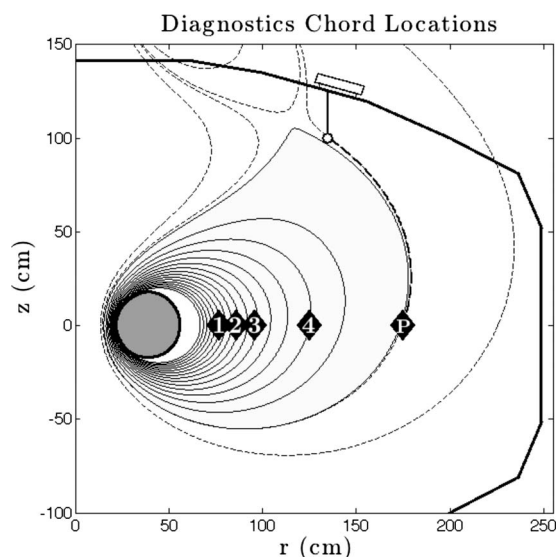


FIG. 2. Cross-sectional view of the right-half of LDX. The outline of the vacuum chamber is delineated with a heavy black line. The floating dipole coil is shown as a dark gray circle. The plasma (light gray) occupies a volume defined by the first and last closed magnetic field lines. The four channels of the interferometer have radii of tangency of 77, 86, 96, and 125 cm (numbered black diamonds). A Langmuir probe is located on a field line that crosses the equatorial plane at 175 cm (denoted by “P”). Data from these five locations can be inverted to obtain an approximate radial profile of the plasma density.

However the difference in path lengths is only about one wavelength of the IF and so the noise level of the interferometer is affected only minimally. Because 70 MHz is a sufficiently high IF, the two 60 GHz oscillators can be left free-running (i.e., not phase-locked) without any effect on the overall phase noise.³ The two oscillators are linked by a drift compensation circuit (similar to a phase-locked loop), which allows the interferometer to operate for the duration of plasma experiments, which last most of a day without needing to be tuned.

C. Multiple channels from one transmitted beam

An important feature of the LDX interferometer design is that the same transmitted beam is received at multiple locations thus allowing line-integrated density information to be measured along multiple chords. The transmitting antenna and the four receiving antennas are all pyramidal standard gain horns. The power transmitted from a standard gain horn spreads out into a cone of about 10° that, due to the geometry of the setup, illuminates about 20° of the far side of the vacuum chamber wall (Fig. 1). By contrast the receiving horns, due to their large distance from the transmitter, subtend less than 0.5° . Consequently, the wave impinging upon the receiving horns will be planar to a good approximation. On account of this, the LDX interferometer can achieve multichannel operation without the need for complicated optics and with only slight modifications of its single-channel design. In this respect, the LDX interferometer is similar to a device described in Ref. 7.

The locations of the four receiving antennas correspond to chords with tangential radii of 77, 86, 96, and 125 cm (Fig. 2). These four interferometer measurements, along with

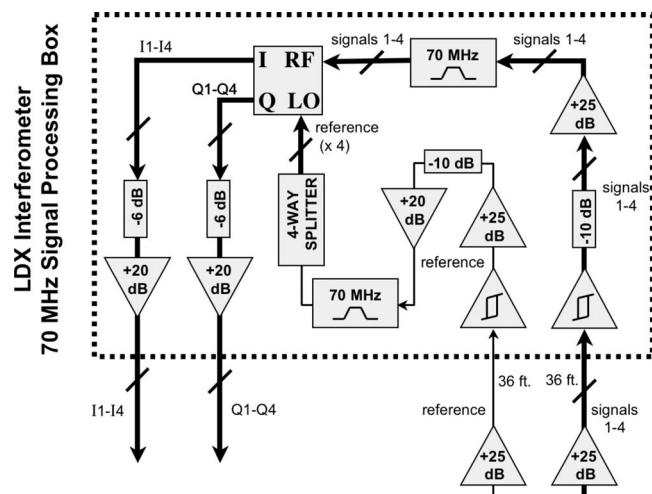


FIG. 3. IF (70 MHz) signal processing block diagram.

a Langmuir probe near 175 cm, can be Abel-inverted to obtain an approximate radial density profile. Although the spatial resolution and accuracy are limited, the resulting radial density profiles are sufficient to answer basic questions about the dynamics of LDX plasmas: What is the approximate value of the plasma density; is the density increasing or decreasing; is the density profile becoming more broad or more steep? Measurements from the interferometer have proven essential in characterizing the nature of LDX plasmas under a wide range of experimental conditions.⁸

D. Phase detection by quadrature

Mixing the 60 GHz RF and LO signals results in five signals at the 70 MHz IF: four signals modulated by density information and one signal that serves as a reference. Each of these five IF signals is passed through a comparator stage, which eliminates any amplitude modulation and then through a 70 MHz bandpass filter, which eliminates the higher harmonics added by the comparators. These signals are then amplified and fed into off-the-shelf quadrature demodulators (Mini-Circuits ZFMIQ-70D). There are four demodulators in total—one for each data channel—and each takes two inputs: the IF reference signal, now called “LO,” and one of the IF signals modulated by density data, now called “RF.” Each of the four demodulators outputs two signals: “*I*” proportional to the cosine and “*Q*” proportional to the sine of the phase shift between the 70 MHz RF and LO signals. The advantage of quadrature detection is that with two outputs instead of one there is no ambiguity as to whether the phase is increasing or decreasing. In total, eight signals are digitized: *I* and *Q* for each of the four data channels. The phase shifts are unfolded from the digitized *I*s and *Q*s with a simple computer program. A diagram of the IF signal processing is shown in Fig. 3.

E. Power and reflections

The LDX interferometer employs two, free-running 60 GHz Gunn diodes (Quinstar QTV-60200V) with output powers of 20 dBm (100 mW). There are five 60 GHz mixers (Millitech MXP-15), each of which must be driven with at

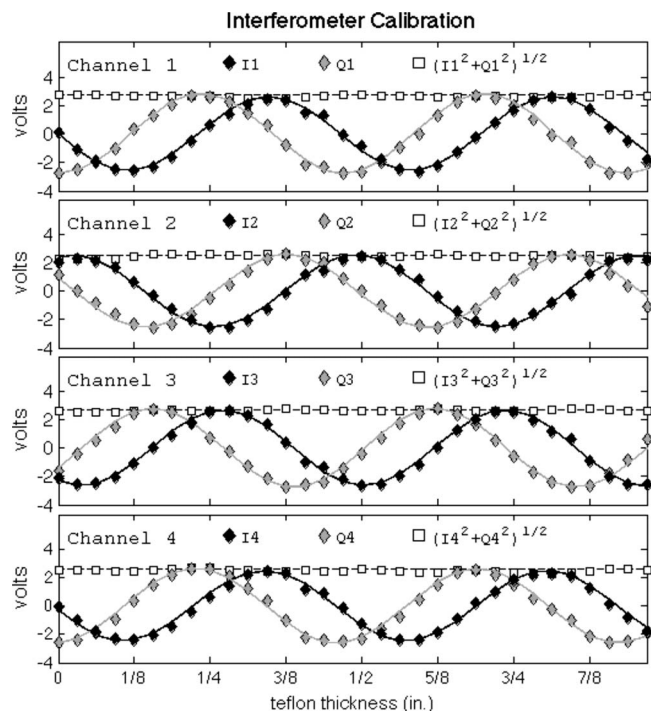


FIG. 4. Calibration test results of the LDX interferometer. Teflon slabs of increasing thicknesses were placed in the path of the interferometer beam. The *I* and *Q* signals for each of the four interferometer channels exhibit the expected sinusoidal behavior.

least 10 dBm of LO power. Because these mixers are so far from the LO source (nearly 10 ft), it was necessary to over-mode the LO waveguide run along the circumference of the vessel. Upon being upgraded from single-channel to multi-channel operation, it was necessary to add a 60 GHz amplifier (Terabeam-HXI HHPAV), along with additional magic Tees, near the location of the four far mixers (Fig. 1).

The large size of the LDX vacuum chamber is however an advantage when dealing with reflections of the transmitted beam inside the vacuum chamber. Although the stainless steel vacuum chamber is highly reflective, each 4 m pass across the chamber reduces the beam power by 80 dB. Consequently any reflected beams are attenuated to near or below the noise threshold and the receive horns measure predominantly the main beam. The effect of reflections was measured—and shown to be small—by moving reflective objects inside the vacuum chamber near the path of the main beam, while data from the interferometer were recorded.

III. CALIBRATION AND OPERATION

In order to establish that the phase shifts measured by the interferometer correspond in the expected way to changes of density, 32 different slabs of Teflon—increasing in thickness up to a maximum of one inch—were placed inside the vacuum chamber and directly in the path of the transmitted beam. The measured *I* and *Q* signals for each of the four data channels exhibit clean, sinusoidal curves (Fig. 4) corresponding to linear phase shifts with the expected slope.

The phase errors of the LDX interferometer can be calibrated by measuring the phase stability and signal balance for the four pairs of *I* and *Q* signals. The phase stability,

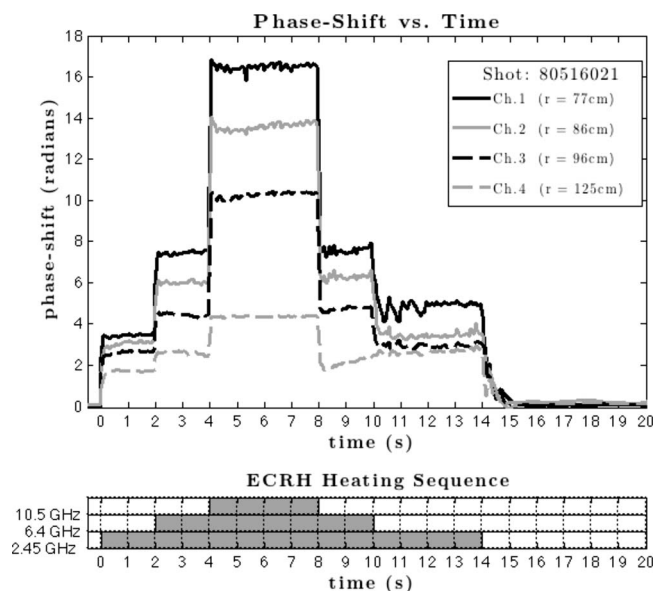


FIG. 5. Phase shifts vs time as measured by the interferometer for an especially high-density LDX plasma discharge. The peak phase shift of over 5π translates to a peak density of approximately 8.0×10^{11} particles per cm^3 . The lower chart indicates the times during which an ECRH source was on (gray shading) or off (no shading).

which is the noise level on the I and Q signals, is found to be between 1° and 2° on each of the four channels of the interferometer. The signal balance is a measure of the deviation of $(I^2 + Q^2)^{1/2}$ from a constant value over the course of a plasma discharge and results from either an amplitude or phase offset on pair of I and Q signals. The phase errors resulting from signal imbalance are measured to be between 3° and 4° . A combination of these two sources of phase uncertainty results in a total phase error of approximately 5° for each of the four interferometer channels.⁸ This instrumental uncertainty of the interferometer is just a few percent of the phase shifts measured for LDX plasmas, which can be as large as 5π (Fig. 5).

The total uncertainties of the corresponding line-integrated density measurements can, however, be signifi-

cantly larger. This is because the simple relationship of Eq. (1), which assumes the interferometer beam traverses straight-line paths through the plasma, is not always valid. The densities of LDX plasmas are sufficiently low that any refraction through the bulk-plasma is small, as can be confirmed with a ray-tracing program. However, refraction from glancing-angle scattering off a density gradient is an important effect. This is especially evident on the outermost interferometer channel (radius of tangency: 125 cm), which sometimes behaves erratically. Even so, as the LDX vacuum chamber becomes cleaner and the plasma volumes become larger during the course of an experimental campaign, the phases measured by the outermost interferometer channel become as well-behaved as the phases measured by the three inner interferometer channels.

IV. CONCLUSION

Dipole-confinement devices such as the LDX present both advantages (e.g., simple magnetic geometry) and challenges (e.g., large physical size) for microwave diagnostics. The success of the LDX interferometer has demonstrated that excellent density measurements can be made from an instrument with a straightforward and robust design.

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