AIP | Review of Scientific Instruments

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Citation: Review of Scientific Instruments **78**, 113503 (2007); doi: 10.1063/1.2805193
View online: http://dx.doi.org/10.1063/1.2805193
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/78/11?ver=pdfcov
Published by the AIP Publishing

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Y. G. Li, and X. T. Ding
Southwestern Institute of Physics, Chengdu 610041, China

(Received 8 May 2007; accepted 14 October 2007; published online 16 November 2007)

A new multichannel HCN interferometer has been developed on HL-2A tokamak, which is characterized by two techniques: (1) the wave-guide HCN laser with cavity length of 6 m to increase the optical resource power and (2) high response room temperature waveguide Schottky diode detectors to obtain good beat signal. The space resolution is 7 cm by the use of focusing metal mirrors mounted on the vacuum chamber and a compensated optical system. In the 2006 experiment campaign, this new interferometer has been applied for plasma density profile and density sawtooth measurement. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2805193]

I. INTRODUCTION

HL-2A is a middle size tokamak with a closed divertor and begins to operate for study of divertor plasma physics, plasma transports, and plasma profile control.[1] The understanding of plasma density behavior and realization of density profile control require detailed information on the density distribution. Interferometers operating in the wavelength region of infrared or far infrared have been regarded as a basic diagnostic tool for the measurement of plasma electron density in tokamak.[2–6] Though interferometer technique has been developed for many years, there are many problems to be resolved such as how to increase measurement precision and reliability, estimation of the lifetime and performance of the in-vessel optical element, etc.

A single-channel HCN laser interferometer routinely operated on HL-2A to measure the line density for several years.[7] To obtain the density profile and realize density feedback control, a new multichannel interferometer was developed recently. In this paper, a new interferometer implementation with various improvements is described in detail. Some preliminary results of the interferometer are also presented.

II. HIGH POWER HCN LASER

High power source of radiation is beneficial for getting good signal-to-noise ratio signal in an interferometer. Considering the mechanical vibration effect and the beam refraction caused by the plasma density gradient, the HCN laser at 337 μm is a good compromise for diagnosis density on HL-2A, so a high power cw HCN long cavity laser has been designed and constructed.

As HL-2A operates 8 h/day, 6 days/week, laser power stability and reliability are very important for the interferometer. The laser long cavity increases the laser output power. However, decreases the difference between the frequency of each two longitudinal modes, reducing power stability. This can be solved by improved laser stability on mechanical vibration, environment temperature, and power supply.

The laser waveguide tube, gas puffing, and pumping system are set on three pneumatic isolator optical benches which should insulate vibration frequency above 2 Hz. Two 3 m Pyrex-glass tubes are conjunct to form a 6 m discharge tube. According to the Belland scaling law,[8] the HCN laser tube is designed with inner diameter of 68 mm, discharge length of 5.6 m, and straightness accuracy of 0.5‰/m. The laser discharge chamber is surrounded by an oil jacket to prevent polymer deposition the inner tube wall. The temperature of the silicon oil flowing through the oil jacket is maintained at about 140 °C and controlled with two thermostats. The laser cavity consists of an axially movable plane mirror and an inductive metal mesh output coupler. High temperature during laser discharge can extend glass and make laser mode frequency transfer; therefore, four superinvar rods of 25 mm in diameter are used to fix the length of laser cavity.

A kind of hollow LaB6 cathode with graphite coat is used to increase electron emissivity. Two parallel thin metal wires of ⌀50 μm spaced by 30 mm are stretched in the front of the plane mirror to fix the direction of the beam polarization. The output window is sealed with *X*-cut crystal quartz plate, which thickness is chosen to minimize the reflection loss. Work gases (CH_4, N2, and He) with an appropriate ratio are injected into discharge tube by two flow meters.

A 15 kV A high power steady-current switch power sup-

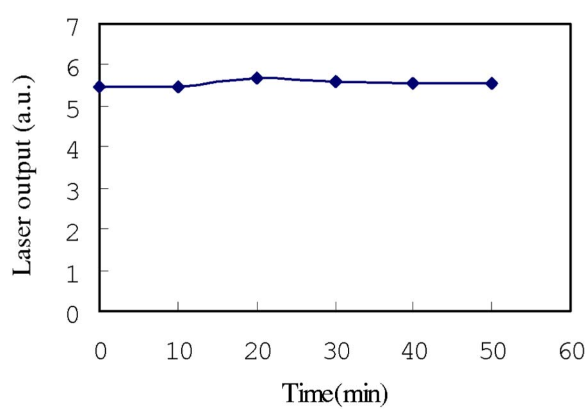

FIG. 1. Laser output power as a function of time.

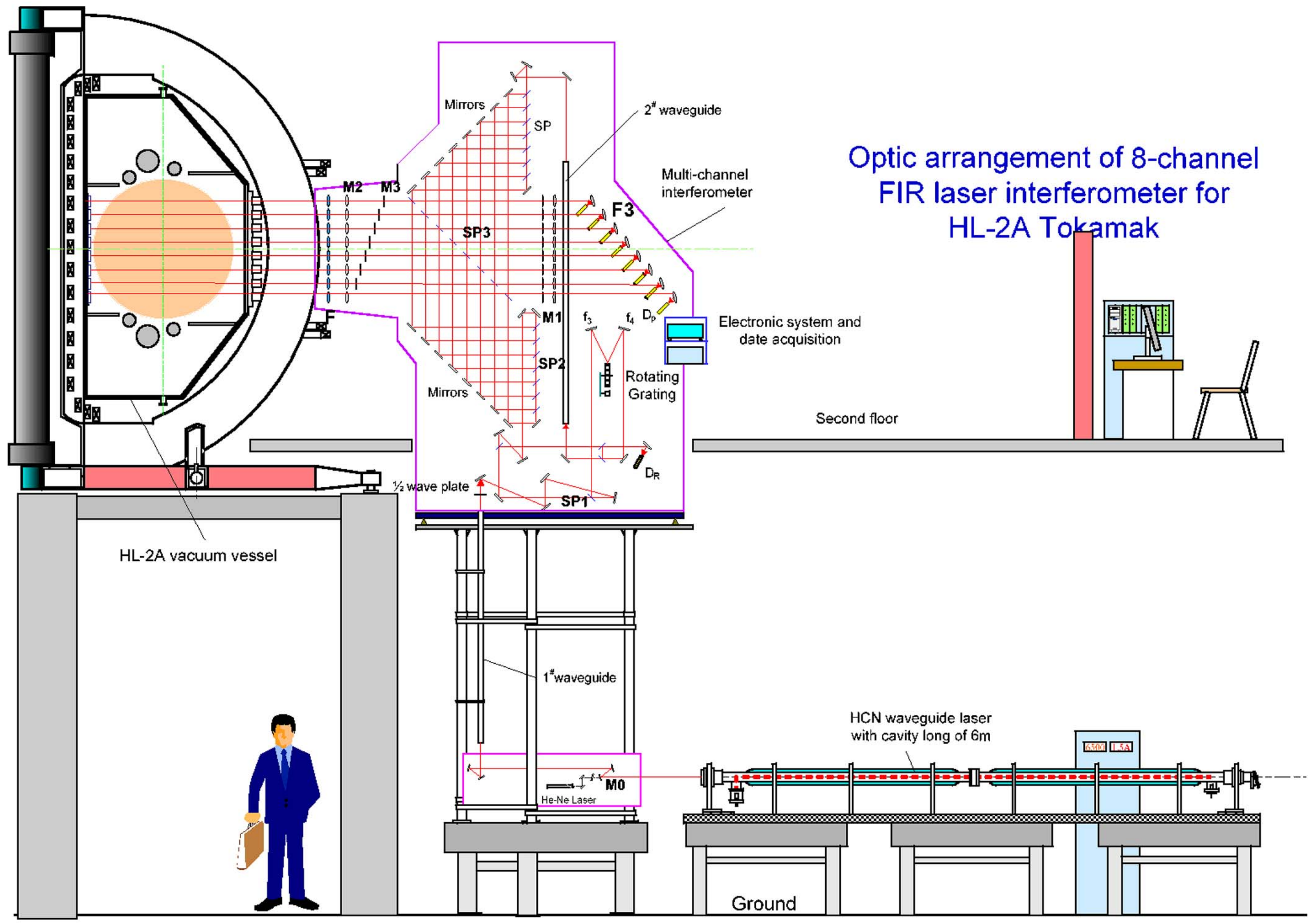

FIG. 2. (Color online) Schematic drawing of multi-channel interferometer

ply is employed for steady discharge. Up to now, the output power of the laser is over 300 mW with discharge current of 1.5 A and voltage of 6.7 kV.

Figure 1 shows a typical time evolutions of the laser output power for 50 min after 1 h from the start of discharge. The long term power stability for 50 min is about 2%.

III. OPTICAL SYSTEM CONFIGURATION

A. Beam transfer and compensated optical system

The schematic diagram of the multichannel Michelson-type interferometer system constructed for the HL-2A tokamak is shown in Fig. 2.[9] To prevent low-frequency vibration from device basement floor, a special vibration isolation frame, which is independent from the machine, is used to sustain all interferometer optical elements. Gaussian beam theory of propagation is applied to design the optical parts of the interferometer.

HL-2A tokamak is a double null closed divertor device, in which triplet multipolar magnetic field coils are set in the divertor chamber; this does not allow vertical probing channel. The eight interferometer chords spaced 7 cm to each other are arranged horizontally.

The laser beam propagates 4.7 m from laser output window to the HL-2A second floor by a Pyrex-glass waveguide of 60 mm diameter. The laser beam is split into a probing beam and a reference beam by a crystal quartz beam splitter SP1. Several spherical mirror optical beam transforms have been used instead of common telescopic arrangement. The eight probing beams enter the vacuum chamber through eight ⌀50 mm windows. The 13 mm probing beam waists are fixed in the center of the plasma by focus mirror F transform; the beam diameter on diagnostic windows is 18 mm.

We set the eight beam waists in the same median plane of the plasma to obtain the best spatial resolution. Quartz beam splitters SP2 are used to feed each channel with beams of equal intensity, but the distances of the eight channels from SP2 to the median plane are different. As a compensation optical system, we installed plane mirrors M2 and M3 to make the path length of each channel equal between SP2 and plasma median plane.

At the highest HL-2A density (10^{20} m^{-3}), the maximum value of refractive angle is 0.01 rad and the beam displacement at the window is 7.5 mm, so the beam refraction at the window is not a big problem for the system. In fact, we have not observed the probing beam completely off the windows or detectors even in pellet injection discharge.

B. In-vessel focus mirror

Eight focus copper mirrors which are directly mounted on the inner wall of the vacuum chamber make incidence

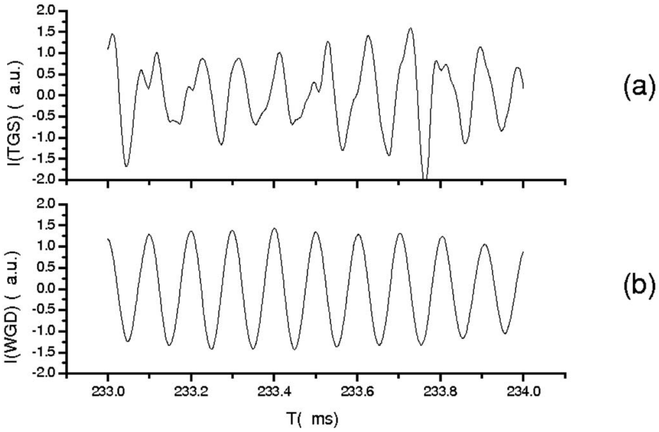

FIG. 3. Beat signal obtained by DLATGS (a) and by waveguide detector (b).

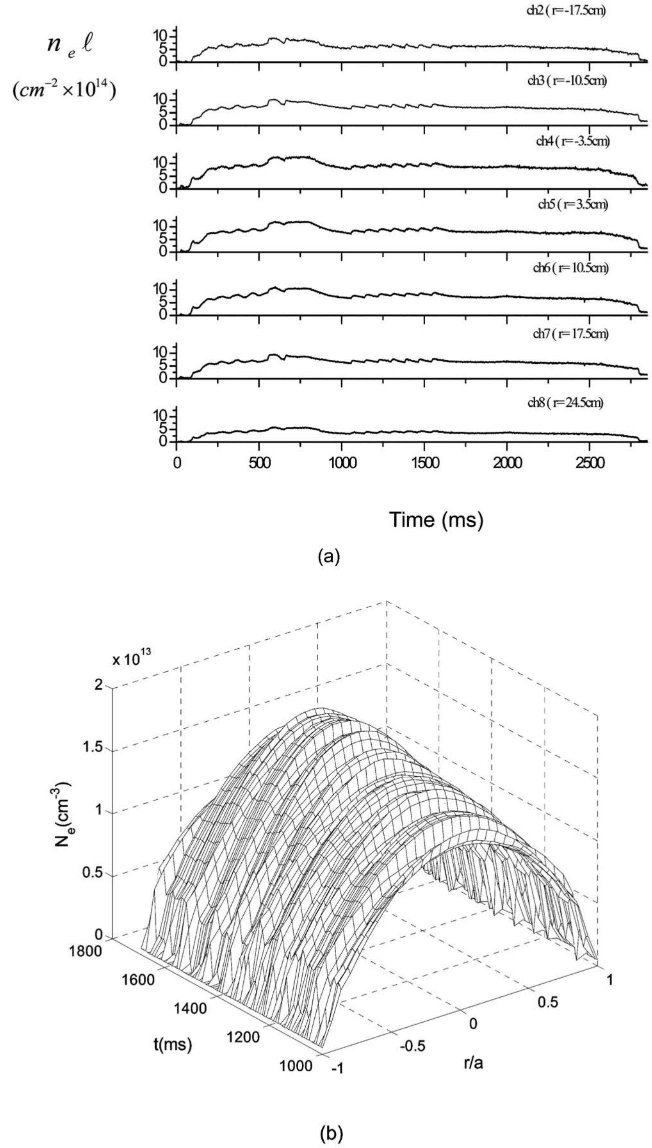

FIG. 4. Typical measurement results by interferometer. (a) Temporal waveforms of line density in different position. (b) Time behaviors of density profile by Abel inversion.

beams returning to the interferometer. In plasma discharge and wall processing, impurity particles can erode and deposit on the mirror and reduce the mirror optical characters. To increase the optical lifetime of the reflector in vacuum chamber, an especial shield cup is used to resist deposition particles,[10] by that the mirrors can obtain longer lifetime (1 yr or longer). Nonmagnetic material and steady structure are also requirements for mirror frame long term stability. During shots there is no obvious reduction of interference signals when toroidal field is stabilization, which means that the mirrors do not tilt during plasma discharge.

As alignment purpose, a 10 mW He–Ne visible laser (6328A) is included to adjust all optical elements. The He–Ne laser beam goes through a hole on mirror M_0 into the far infrared (FIR) laser from the output end of HCN laser. The visible beam is allowed to expand from the FIR laser reflector to the main body of the interferometer to simulate the HCN beams. The alignment of the optical components is made with an accuracy of 1 mm. As HL-2A vacuum chamber opened once a year, if the reflectors mounted on the inner wall is tilted by vibration, we can adjust the M2 and M3 to align the probe beam and preserve good interference signals. In fact, the focalizing mirrors have not been tilted obviously during about 1600 shots.

IV. DETECTOR

In order to obtain density information from the phase shift directly, a rotation grating (diameter of 176 mm, number of grooves of 1320) is used to produce 10–50 kHz Doppler shift (at present, we use 10 kHz). The Doppler shift beam is matched with the probing beam at SP_3. Then the beat signals will be explored by detectors.

We employ the room temperature deuterated L-lanine doped triglycine sulfate (DLATGS) detectors (type P5243) for both the reference and probing signals. These detectors give a response (responsivity of $\sim$400 mV/mW, noise equivalent power of $\sim 6 \times 10^{-10}$ W/$\sqrt{\text{Hz}}$) at 337 μm when the beat signal frequency is under 3 kHz. As optical beam aligned error and transmission loss, sometimes the signal-to-noise rate of ch8 is low with DLATGS, so another new high response room temperature waveguide detector (Schottky diode detector, noise temperature of $<$6000 K, video responsivity of $\sim$400 mV/mW) has been applied. Though the responsivity of Schottky diode detector and DLATGS detector is the same in the lower frequency range ($<$3 kHz), in the 10–50 kHz frequency range the DLATGS detector's responsivity decreases faster, but the Schottky diode detector keeps its performance because it has a better high-frequency response. Using a circular feed horn waveguide as an antenna and adding a dc bias on the diode to obtain the lowest conversion loss, the Schottky diode's optical beam receiving efficiency and noise are improved. Figure 3 shows the results of ch8 beat single (10 kHz) by DLATGS and that by waveguide detector in the same input beat signal and same amplifier. When signal amplitude is 3 V, the noise amplitude of DLATGS and waveguide detector are 0.024 V, and 0.006 V, respectively. It is obvious to see that the new Schottky detector signal is very clear and the single to noise ratio has been improved about two to four times.

Due to the long HCN wavelength and the small fre-

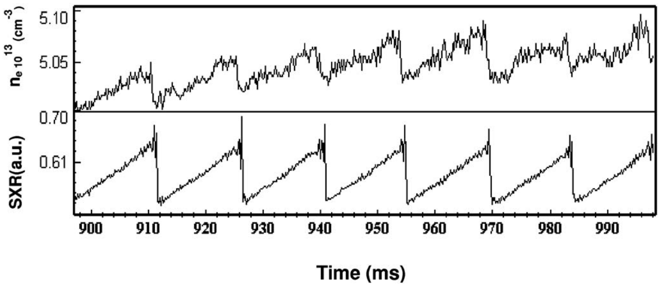

FIG. 5. Density sawtooth measurement by interferometer (top trace) and soft x-ray sawtooth (bottom trace).

quency shift (10 kHz) of the reference beams, in 0.1 ms, one fringe (correspond with average line density of 0.41×10^{13} cm^{-3}) can be measured by the system. For example, in large pellet injection situation, because the fast change of density is more than 0.41×10^{13} cm^{-3} in 0.1 ms, we observed the fringe losses. By using of the high-frequency performance of waveguide Schottky detector, the system can operate in high frequency shift (50 kHz) for solving the fringe jump problem.

V. TEMPORARY VESSEL DISPLACEMENT COMPENSATING

The HL-2A device is reconstructed based on original ASDEX main components. In ASDEX: "the high mechanical stability of the experiment, no measurable wall movement occurred during discharges and a compensating interferometer was not necessary,"[11] so that the compensating interferometer was not taken into account in the system design. However, in the 2006 HL-2A experiment, the displacement of vacuum chamber was found. This displacement is especially high during the change of the toroidal magnetic field. At present, we set a reflector at the ch1 diagnostic window; the probing beam reflects by the reflector and goes to the detector. Because the mechanical vibration of the reflector is similar to that of inner wall mirrors, we choose the beat signal of ch1 as the reference signal of the interferometer.

The problem of HL-2A device mechanical displacement is temporarily solved by reference channel compensating. Because the mechanical displacement in low field side is somewhat different from that in high field side, the measurement densities have a nonzero value after the discharges. The typical line density measurement error (nonzero value) is about 2×10^{14} cm^{-2}. In order to wipe off the mechanical displacement phase shift absolutely, a He–Ne laser interferometer is being developed for correction of the vibration.

VI. PRELIMINARY EXPERIMENTAL RESULTS

In the 2006 HL-2A experiment campaign, the multichannel interferometer has been first tested in experimental environment. A typical measurement result performed with the interferometer is shown in Fig. 4, in OH discharge, where $I_p = 188$ kA and $B_T = 1.5$ T. Seven supersonic molecular beam[12] pulses are injected into the plasma after $t = 1000$ ms; seven density peak value undulation on the line density [Figs. 4(a)] and on Able inversion density profile [Fig. 4(b)] appears. In Fig. 5 we can see the waveform of the central channel density and soft x-ray sawtooth during Ohmic discharge with electron cyclotron resonance heating. It means that the interferometer can be used to study the density fluctuation and transport in the core plasma. The noise amplitude of the density sawteeth is of the order of 1.7×10^{11} cm^{-3} (corresponding to a minimum density change), which corresponds to a minimum measurable phase shift of 1/33 fringe.

VII. CONCLUSION

A new multichannel interferometer with high power HCN laser has been installed, which has undergone 1600 shots. It has been proven to be of great utility for measuring line density and density profile in Ohmic and wave heating discharges. The phase resolution is about 1/33 fringe and the time resolution is 0.1 ms. The interferometer will be an ideal tool for real time density-feedback control on HL-2A device.

Considering the long HCN wavelength and small window size, several spherical mirror optical beam transforms instead of common telescopic arrangement have been used to keep a reasonable beam waist in the median plane of the plasma, so the beam refraction at the window is not a big problem for the system. A new waveguide Schottky detector has been used in the system. This kind of detector has high response at high frequency. The fast transient density phenomena during pellets injection or hard disruption should be observed at the higher modulation frequency (>50 kHz).

ACKNOWLEDGMENTS

The authors wish to acknowledge and express their appreciation for the contribution of HL-2A team, Dr. K. Kawahata, Dr. W. X. Ding, and Dr. X. Gao. This work has been supported by the Chinese Nature Science Funds No. 10575032 and 10675043.

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