Bench Test of the Vibration Compensation Interferometer for EAST Tokamak∗
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Abstract A visible laser-based vibration compensation interferometer has recently been designed for the EAST tokamak and the bench test has been finished. The system was optimized for its installation on EAST. The value of the final optical power before the detectors without plasma has been calculated from the component bench test result, which is quite close to the measured value. A nanometer level displacement (of the order of the laser’s wavelength) has been clearly measured by a modulation of piezoelectric ceramic unit, proving the system’s capability.

Keywords: vibration compensation, system design, tokamak diagnostic

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(Some figures may appear in colour only in the online journal)

1 Introduction

Long-pulse tokamak operation requires an accurate, time-resolved diagnosis of the internal magnetic field, current density, and electron density profiles. A multichannel far-infrared laser-based POlarimeter-INTerferometer (POINT) system has been developed on the EAST tokamak [1,2], which can measure the density and Faraday angle profile information, contributing to the plasma control [3−6]. The density measurement of the system is carried out using the interferometer, where the line integrated electron density is proportional to the phase shift between the reference beam and the plasma beam. In the POINT system, retro reflectors are attached to the inner wall of the vacuum chamber to make a double optical path through the plasma. This will introduce a sensitivity to the vessel movement and an additional term in the phase difference, which is a system error in the density measurement (especially in the low density plasma case) [7]. A compensating interferometer is then motivated, trying to measure the phase shift due to mechanical vibration and to compensate for it. In addition, during the design of polarimeter systems with either poloidal, vertical, or toroidal viewing geometry, the method that uses a shorter wavelength laser as a subsystem to compensate the vibration has been taken into consideration in many tokamak machines, for instance DIII-D [8], KSTAR [9], as well as ITER [10]. Recently, we designed a second laser (wavelength at 0.532 µm) interferometer as a sub-system for the EAST POINT system [7]. The system’s concept design was carried out in early 2014. The bench test has recently been finished. This paper is organized as follows. In section 2, the principle of the vibration compensation interferometer is introduced. In section 3, the design on EAST tokamak is described. In section 4, the components test of the system is presented; meanwhile, the measured and calculated values of final optical power before the detectors in two channels are given. In section 5, a nanometer level displacement applied has been clearly measured. In the last section, an overall summary and a discussion of relevant issues are described.

2 The principle of the system

According to the principle of interference, the line integrated electron density is measured by the phase shift between the reference channel and the plasma channel [7], which is shown as follows:

$$\varphi = \varphi_p = 2.82 \times 10^{-15} \lambda \int n_e dl.$$ (1)
In Eq. (1), \( \varphi_p \) (rad) is the phase shift by plasma, \( n_e \) (m\(^{-3}\)) is the local plasma density, \( \lambda \) (m) is the laser wavelength. During a plasma discharge, a vibration especially from the retro reflectors, as expected, will bring another phase shift. Then, Eq. (1) should be amended to Eq. (2) which includes the additional phase shift,

\[
\varphi = \varphi_p + \varphi_v = 2.82 \times 10^{-15} \lambda \int n_e dl + \frac{2\Delta L}{\lambda} \times 2\pi. \tag{2}
\]

The second part in Eq. (2), \( \varphi_v \) (rad) means the phase shift by vibration \( \Delta L \) (m) is the vibration amplitude, \( \lambda \) (m) is the wavelength of the laser. To evaluate the ratio between \( \varphi_p \) and \( \varphi_v \), a coefficient \( k \) has been introduced:

\[
k = \frac{\varphi_v}{\varphi_p} = \frac{2\Delta L \times 2\pi}{2.82 \times 10^{-15} \lambda \int n_e dl} = \frac{4.46 \times 10^{15}}{\lambda^2} \frac{\Delta L}{n_e dl}. \tag{3}
\]

As Eq. (3) shows, the value of \( k \) depends on the wavelength of laser and the vibration amplitude in the case of the same plasma density and the plasma does not produce a significant phase change in the short wavelength beam. Therefore, a solid-state laser (green) interferometer (wavelength at 0.532 \( \mu \)m) measures only the machine vibration, and this information can be used to correct the EAST POINT system measurements (wavelength at 432.5 \( \mu \)m), which are sensitive to both the plasma and the machine vibration.

In addition, the electron line-integrated density resolution of EAST POINT system is less than \( 5 \times 10^{16} \text{ m}^{-2} \) \[^{[1]}\]. According to Eq. (1), the corresponding path length difference is \( \sim 4.19 \mu \text{m} \). Hence, any vibration amplitude \( \Delta L \) larger than 2.095 \( \mu \text{m} \) is hoped to be compensated. Because the solid-state laser (green) vibration compensation interferometer operates at 1 MHz \[^{[7]}\], the time resolution of the vibration measurements will be good.

3 The system design

The layout of the vibration compensation system is presented in Fig. 1. The system settles on a vertical optical board, which is 50 mm thick, in front of the EAST window. The front panel of the board is used for the 10 channels POINT system \[^{[11]}\]. Therefore, there is little room left for the vibration compensation system. The rear panel of the board is currently considered as a location for the vibration compensation system. A hole with diameter of about 3 cm must be drilled at an appropriate place to let the visible light penetrate to the front panel, and then through the EAST window into the vacuum vessel. Such an arrangement assumes that the vibration mainly comes from the retro reflectors and is identical for all of the channels POINT system. After compensated by \( \varphi_p \) measured by the vibration compensation system, \( \varphi_v \) measured by HCOOH interferometer will give a more realistic and accurate density information.

The system mainly occupies the upper position of the vertical board, as shown in Fig. 1, the space leftover could be used for future system upgrade. All of the components including one laser, two Acoustic Optical Modulators (AOM), eight beam splitters, five mirrors and two detectors, are mounted on the board by brackets designed by the EAST FIR team to reduce the vibration on the panel. There are four beams in the optical design, including two reference beams and two plasma beams. A pair of mirrors has been used to conduct one plasma beam from the rear panel to the front panel and then back in the same optical path after propagating through the plasma. The optical layout is double pass by applying molybdenum retro-reflectors mounted on the inner vacuum vessel wall. The beam is reflected back by the retro-reflector while carrying the vibration information, which also goes through the hole by beam turning device adjustment, and is then made collinear with another probe beam before the detector.

4 The bench test of the system components

The laser power before the detectors should be high enough for the detectors’ response. This is also one of the fundamental criterions for the system. Therefore, an optics test is needed. The main components for the vibration compensation interferometer system are a laser, AOMs, beam splitters, retro-reflector, detectors. This section describes the detail of the bench test of these components.
4.1 Laser

The system uses a circularly polarized, solid-state green laser with a wavelength of 532 nm as the optical source. The full power of the laser is 19.8 mW. Since the wavelength is quite short, the power attenuation in the air must be taken into consideration. At different distances from the source \(d\) (m), the laser power has been measured (seven times repeated). The attenuation \(\eta(\%)\) of the power with the distance can be fitted by the function of

\[
\eta = 0.097 \times d^2 - 1.9 \times d + 100,
\]

as shown in Fig. 2. At a distance of 7 m, the power will decay to 91%. In the system, the longest distance from one component to another is the distance from the EAST window to retro-reflector, which is about 2.716 m and the laser power will decay to about 97% at this distance. The beam size is another important parameter which should be taken into consideration during system design. The diameter of the output beam size of the laser is 6.2 mm, and it will increase by about 1 mm per meter. The hole in the vertical board should be large enough for the beam to pass through. However, the final beam size is larger than the detector active area. A lens should be used to focus the beam before the detectors.

![Fig.2 The fitting curve of laser's power attenuation](image)

4.2 Acoustic optical modulators (AOMs)

The Acoustic Optical Modulators (AOMs) are important components in the system. Two AOMs are applied to get the 1 MHz intermediate frequency (IF), which has been described in Ref. [7]. However, the power loss of AOMs is quite large. The AOMs are mounted on the mechanical modulators. When \(\theta\) is near the Bragg angle condition, the AOMs will work, and the input beam will be diffracted into several output beams with different orders, see Fig. 3. By rotating the modulator, \(\theta\) can be varied slightly around the Bragg Angle, to allow the diffracted +1\(^{\text{st}}\) order beam which enters the system to be as strong as possible. In the bench test, AOM-A’s transmittance is 42.35±0.38% and AOM-B’s transmittance is 42.92±2.82%, respectively. They are closed and quite high. In the optical design, an aperture will be used to only allow the +1\(^{\text{st}}\) order beam to pass through while blocking the other beams to avoid light interference.

![Fig.3 Operating principle of the Acoustic Optical Modulators (AOM)](image)

4.3 Beam splitters

The system has two reference channels and two plasma channels. The laser power before the detectors needs to be nearly equally distributed to all channels. This is accomplished by the combination of several kinds of beam splitters. They are made of quartz, 25 mm in width, 36 mm in length and 1 mm in thickness. These beam splitters can divide the input beam into two beams in two directions. One is transmitted beam and another one is reflected beam. When the beam incidents in different angles, the ratio of the transmitted power and the reflected power varies. In the optical design, the angle \(\alpha\) between the incident beam and the beam splitters is 45°, but there will always be a small deviation during installation. Therefore, we measured the range of three different beam splitter’s transmittance when the incident angle is between 40°-50° in the bench test, as described in Table 1. The measured values are closed to the theoretical values. Another function of beam splitters is to combine two beams. We only use this function to make two channel beams collinear before the detectors.

![Table 1. The theoretical and measured transmittance of three kinds of beam splitters](image)

4.4 Retro-reflector

Due to the double pass optical layout, the retro-reflector mounted on the inner vessel wall in EAST is necessary for this system and the whole POINT system. The retro-reflectors, 55 mm in diameter, 61.2 mm in height, can withstand 350 baking temperature and
1000 s discharge duration. The power loss on the retro-reflector \((89.51\pm0.21\%)\) is the largest one among all the components, which has a great impact on the beam power. The reason may be that there is an anti-reflection film for HCOOH laser covering the surface of the retro-reflector, which has a relatively strong absorption of visible light. The retro-reflector can be protected from dust by using a shutter when the EAST device needs lithium coating, cleaning, etc.\[11\].

4.5 Detectors

A Model APD110A2 detector (APD110 Series, Thorlabs Company) has been selected as the system’s detector. It uses a Silicon Avalanche Photodiode with a detector active area diameter of 1 mm, operating in the 200-1000 nm wavelength range. Its maximum power density is 4 W/cm\(^2\), and the optical damage threshold is 1 mW. The output voltage \(V_{\text{out}}(V)\), which is a function of the incident light power \(P_{\text{in}}(W)\), detectors responsivity \(R_{\lambda}(A/W)\), the multiplication factor \(M\) and the transimpedance gain \(G(V/A)\), can be calculated by

\[
V_{\text{out}} = P_{\text{in}} \cdot R_{\lambda} \cdot M \cdot G = 1.70 \times 10^6 P_{\text{in}}. \tag{5}
\]

The responsivity \(R_{\lambda}\) is \(\sim 0.34 \text{ A/W at 532 nm.}\) The multiplication factor \(M\) is factory set to 50 at 23°C ambient temperature which is acceptable for the system. The amplifier’s transimpedance gain \(G\) is 100,000 V/A. Since the active area is quite small, the lens should be used to focus the beam to make the detectors capable of access of the entire laser spot.

In addition to the optical components described above, the EAST window and mirrors have also been tested. The EAST window is made of quartz, with a thickness of 8 mm, and its transmittance is \(\sim 91.85\%\). There are five mirrors with diameter of 2 inch \((\sim 5 \text{ cm})\) used in the system, and their reflectance is about \(\sim 99.3\%\).

4.6 Beam power before the detectors without plasma

After the system design, the last and most important step is to certify that the beam can reach the detectors and the beam power is large enough for the detector response. There are four beams in the system, plasma channel (A), plasma channel (B), reference channel (A), and reference channel (B). The power loss of one plasma beam which will go through the plasma and be reflected by the retro-reflector is the largest among the four beams. Then the four beams’ power before the detectors has been calculated and measured to prove the feasibility of the system design. The results that are summarized in Table 2 show that the measured and the calculated values are close and they are both enough for detector response. These results fully demonstrate the feasibility of the system design.

### Table 2. The measured and calculated value of beam power without plasma before the detectors in four beams

<table>
<thead>
<tr>
<th>Channels</th>
<th>Measured/ calculated power ((\text{mW}))</th>
<th>Measured/ calculated total power ((\text{mW}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference channel (A)</td>
<td>0.05/0.08</td>
<td>0.12/0.13</td>
</tr>
<tr>
<td>Reference channel (B)</td>
<td>0.06/0.05</td>
<td>0.10/0.14</td>
</tr>
<tr>
<td>Plasma channel (A)</td>
<td>0.06/0.10</td>
<td></td>
</tr>
<tr>
<td>Plasma channel (B)</td>
<td>0.03/0.04</td>
<td></td>
</tr>
</tbody>
</table>

5 Measurement of an applied nanometer level displacement

The components test in section 4 proves that the 1 MHz intermediate frequency (IF) signal can reach and be detected by the detectors. The next step is to demonstrate that a small vibration (within the order of the laser wavelength) could be distinguished and calculated by the system. The vibration is modulated by a nanometer level displacement modulation of a piezoelectric ceramic unit which has a spatial resolution of 1 nm. The experiment setup is shown in Fig. 4. (The right part shows the optical arrangement and the left part shows the mirror mounted on the displacement platform of the piezoelectric ceramic unit.) The displacement platform is fixed on a lifting table which can adjust the height through the interface board. The mirror mounted on the displacement platform can make flexible three-dimensional adjustments to make the incident beam and reflected beam collinear, playing the role of retro-reflector. The displacement is controlled by customized software. After setting the displacement \(\Delta L\) in the software, the mirror will move such a distance, and the optical path will change \(2\Delta L\). Meanwhile, the phase shift between the reference and plasma channel will also change due to the optical path change, which can be measured by voltage variation \(U\) from the phase meter. The IF of the phase meter is 1 MHz, which is fast enough for EAST and performs well during the bench test. When the phase shift is \(2\pi\), the voltage variation is 5 V. The relationship between the applied displacement \(\Delta L(\text{nm})\) and the voltage variation \(\Delta U(\text{V})\) can be described as,

\[
\Delta U = \frac{2\Delta L}{\lambda} \times 5. \tag{6}
\]

![Fig.4](image-url) The setup of the applied displacement measurement
The experimental laser is a solid-state laser, with wavelength at 532 nm. If the optical path length change is within $\lambda$, there is no need to consider the fringe counting during the experiment. According to Eq. (6), when the piezoelectric ceramics gives a movement at 0.025 $\mu$m (0.05 $\mu$m, etc.), optical path length will change 0.05 $\mu$m (0.10 $\mu$m, etc.), equivalent to about $0.1\lambda$ ($0.2\lambda$, etc.). The voltage given by the phase meter will also change about 0.47 V (0.94 V, etc.). The result is shown in Fig. 5.

Afterwards, the applied displacement value $\Delta L$ (m) can be measured by the phase shift signal which can be obtained from the converted voltage signal, too. The relationship between the measured displacement $\Delta L'$ (m) and the voltage variation $\Delta U$ (V) can be described as,

$$\Delta L' = \frac{\Delta U}{s} \times \lambda \times \frac{1}{2}$$  \hspace{1cm} (7)

Fig. 6 shows that the fitting curve of the applied displacement $\Delta L$ versus the measured displacement $\Delta L'$ is linear, and the calculated deviation is less than 1.1%. It indicates that the system is able to accurately measure the vibration of the order of microns.

6 Discussion and summary

This paper presents the bench test of the vibration compensation for EAST. However, several issues should be discussed. First, only one channel has been designed for the vibration compensation currently. This is based on the assumption that the vibration comes mainly from the retro-reflectors and is identical for all HCOOH interferometer channels. However, the system may well be upgraded to multi-channels in the future. Second, the bench test has been finished under conditions without plasma. In fact, the plasma will have a great impact on the plasma beam. When the beam goes through the plasma, the laser power will be lost. If the power loss is significant and beyond the detector response range, a larger power laser should be considered as the light source. At the same time, the detection beam will be divergent, and some concave mirror or lens should be used to focus the beam. Third, the wavelength of visible light (532 nm) chosen is short since it is sensitive to the mechanical vibration. Therefore, a much longer wavelength, $\sim$10 $\mu$m (CO$_2$ laser) will be considered if the visible 532 nm interferometer cannot work well for compensation.

In conclusion, the vibration compensation interferometer on the EAST tokamak has been designed to compensate the phase shift due to the machine vibration for the POINT system. The lasers’ power attenuation characteristics have been studied and the transmittance of different kinds of optical components used in the system has been measured in the finished bench test. The calculated and measured beam power before the detectors are closed and both are enough for detector response. Finally, an applied nanometer level displacement has been accurately measured. In summary, the bench test results fully demonstrate the feasibility of the system design.

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