J Fusion Energ
DOI 10.1007/s10894-014-9750-1

ORIGINAL RESEARCH

Improvement of the Laser Beam Pointing Stability for EAST Thomson Scattering Diagnostic

Hui Chen · Jun Yu Zhao · Qing Zang ·
Shu Mei Xiao · Ai Lan Hu · Xiao Feng Han ·
Teng Fei Wang

Abstract Thomson scattering diagnostic, measuring the spatial profiles of the electron temperature and density in fusion plasma, is one of the most important diagnostic on tokomaks. The accuracy of its results could be strongly impacted by the stability of the laser beam passing plasma. However, the stability of the laser beam pointing is influenced by many factors. On experimental advanced superconducting tokamak (EAST), the laser beam of Thomson scattering diagnostic (1,064 nm wavelength, 10 ns pulses, 10–50 Hz repetition rate) traverses a network of 7 mirrors approximately 35 m before enters the vacuum chamber. To ensure that the laser beam transports stably and accurately, vibration isolation platforms and a remote supervisory and control system for laser alignment are built. The vibration isolation platforms could mitigate the impact of external vibrations in the beam path. And by using the remote supervisory and control system, misalignments will be found and corrected in time. With these renovations, the beam pointing stability of EAST Thomson scattering diagnostic can be improved from about 120 to 10 μrad successfully.

Keywords Thomson scattering diagnostic · Infrared laser · Vibration isolation platform · Webcam · Laser beam alignment

Introduction

Thomson scattering diagnostic is a standard diagnostic on tokomaks. It measures the spatial profiles of the electron temperature and density in fusion plasma which are of great importance for plasma physics research. On EAST, the 90° Thomson scattering diagnostic system has operated for several years [1, 2]. Figure 1 shows the schematic diagram of the Thomson scattering diagnostic system on EAST. This system employs Nd: YAG lasers with output energy up to 6 J/pulse. During experiments, the laser beam emits from the laser and traverses a network of 7 mirrors approximately 35 m, and then enters the vacuum chamber vertically from a fixed position. It is focused onto the center of the vessel's cross section by a focusing lens (f = 6 m). In the fusion plasma, the laser is scattered at various angles by electrons and the scattered light is imaged on the twenty five 1.55 × 4.5 mm fiber optic bundles by the collective lens. Then the scattered light is communicated to the polychromators to analyze the signals. The raw data acquired is inputted into computers for further analysis. The spatial locations corresponding to the top of each fiber are established by the laser beam entering the vacuum chamber and measured before experiments. At last, the spatial profiles of the electron temperature and density in fusion plasma are obtained.

H. Chen · J. Y. Zhao · Q. Zang (✉) · S. M. Xiao · A. L. Hu · X. F. Han · T. F. Wang
Institute of Plasma Physics, Chinese Academy of Sciences, P.O. Box 1126, Shushanhu road 350, Hefei 230031, Anhui, China
e-mail: zangq@ipp.ac.cn

H. Chen
e-mail: yhchen2010@163.com

J. Y. Zhao
e-mail: zhaoj@ipp.ac.cn

S. M. Xiao
e-mail: smxiao@ipp.ac.cn

A. L. Hu
e-mail: ailanhu@ipp.ac.cn

X. F. Han
e-mail: hxf@ipp.ac.cn

T. F. Wang
e-mail: wtf@ipp.ac.cn

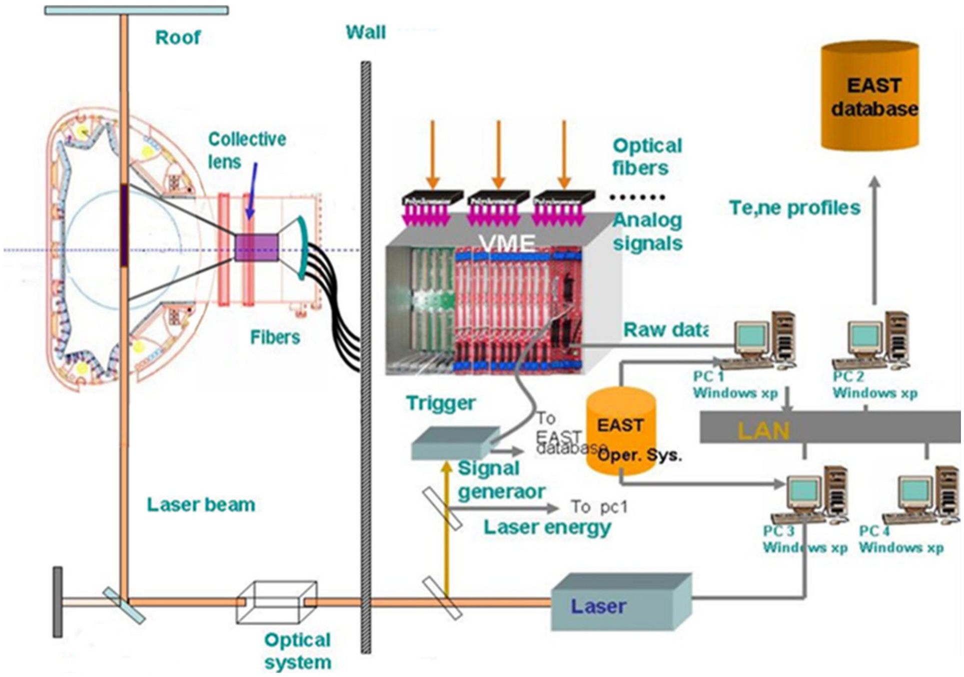


Fig. 1 Schematic diagram of the Thomson scattering diagnostic system on EAST

The electron temperature is dependent on the amount of scattered light frequency shifts and the electron density is proportional to the total amount of the scattered light. So the reliability of the results is highly affected by the alignment of the laser beam crossing the plasma, in particular density data. Even slight deviations of the laser beam crossing the plasma will lead to considerable deterioration of the accuracy. Therefore the stability of the laser alignment is a major concern for the Thomson scattering diagnostic system.

For the Thomson scattering diagnostic system on EAST, before entering the vacuum chamber, the laser beam traverses a network of 7 mirrors approximately 35 m and the maximum misalignment is designed to be about 2 mm. Moreover, many factors could influence the laser beam pointing stability, such as mechanical vibrations of optical devices, temperature variations in the environment, air convection in the beam path, instabilities in the laser cavity, etc. Thus, in order to improve the laser beam pointing stabilization, some renovations are carried out for EAST Thomson scattering diagnostic system, including vibration isolation platforms to reduce mechanical vibrations of optical devices together with a remote supervisory and control system for laser alignment to discover and calibrate the deviations in time. They will be detailed in the following sections.

Vibration Isolation Platforms

There are numerous external vibrations in the environment of the EAST Thomson scattering diagnostic system that may cause vibrations of the optical instruments for laser transporting. And then they will lead to shifts of the laser beam. In order to reduce these impacts, several vibration isolation platforms are designed and constructed. The lasers, mirror mounts and other optical instruments are all put on the vibration isolation platforms to become more stable. Then the laser beam pointing will be more stable, too. The vibration isolation platform to put lasers (P1) will be described in this article, while the others will be introduced in other papers.

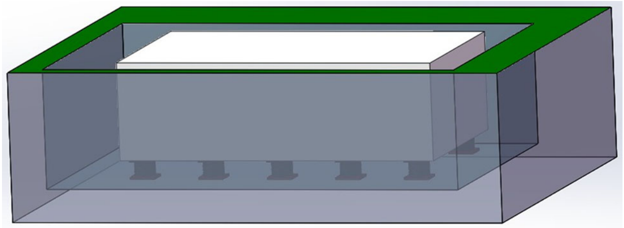


Fig. 2 The rendering of the vibration isolation platform to put lasers

Design of Vibration Isolation Platform to Put Lasers

Figure 2 displays the rendering of P1. This is a passive vibration isolation system, comprised of a heavy concrete block and ten vibration isolation components. Five vibration isolation components are placed along each longer side of the concrete block. Based on the vibration isolation theory and taken into account the environment and construction cost, the natural frequency of this system is intended to be $4*1/\sqrt{2} = 2.82$ Hz.

The mechanical model is presented in Fig. 3. This is a single-degree-freedom system. In Fig. 3, k is the stiffness of the system, c is the damping and m is the weight consisting of the concrete block and the loads on it. The loads are lasers and optical tables, weighting about 8 tons. Generally, the mass of the concrete block should be >6 times of the loads, and it'll be better to be >10 times. So the mass of the concrete block is conceived to be about 100 tons.

The structure of the vibration isolation components is illustrated in Fig. 4. In order to adapt the system, the vibration isolation components are designed with large damping and excellent carrying capacity (range of load 4,500–15,600 kg; vertical stiffness 300 kg/mm; original height 382 mm; minimum height 340 mm). Then, in theory, the natural frequency of the passive vibration isolation system is 2.5 Hz with the designed loads, which meets the design requirements.

The effect of the vibration isolation system is usually represented by vibration isolation coefficient η and vibration isolation efficiency E. η and E can be expressed as:

$$\eta = \frac{A_2}{A_1} = \sqrt{\frac{1 + (2\xi\lambda)^2}{(1 - \lambda^2)^2 + (2\xi\lambda)^2}} \tag{1}$$

$$E = (1 - \eta) \times 100\,\% \tag{2}$$

where A_1 is the amplitude of the vibration source, A_2 is the vibration amplitude after vibration isolation, ξ is the damping ratio and λ is the frequency ratio.

Fig. 3 The mechanical model of the vibration isolation platform to put lasers

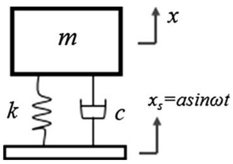


Figure 5 indicates the vibration transmissibility of the single-degree-freedom system. In this system, ξ is designed to be 0.12–0.18 and assumed to be 0.15 in computational procedures. When the natural frequency of the passive vibration isolation system is 2.5 Hz with the designed loads, the vibration isolation efficiency E is about 85 % for the excited vibration of 8 Hz and is more than 90 % for more than 10 Hz. The stability of the lasers and other optical instruments on it can be enhanced effectively.

Test of Vibration Isolation Platform to Put Lasers

This platform has been tested as soon as it was constructed. The schematic diagram of the test system is given in Fig. 6. The physical quantity to be tested is the natural frequency of this vibration isolation system. Because according to the design theory, when the natural frequency meets the design

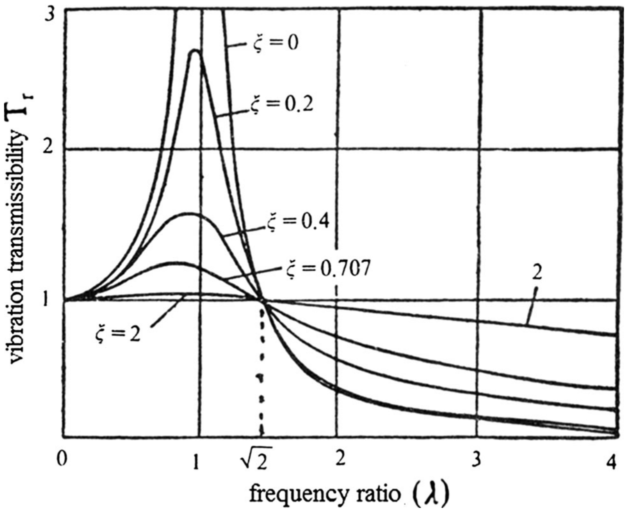


Fig. 5 The vibration transmissibility of the single-degree-freedom system

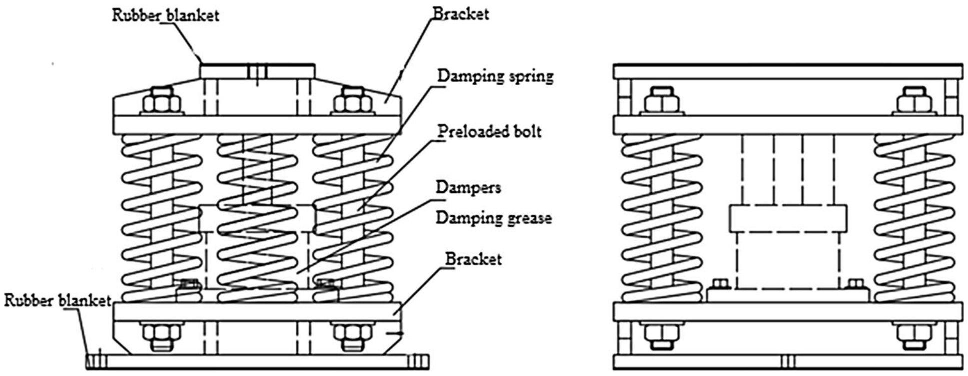


Fig. 4 The structure of the vibration isolation components

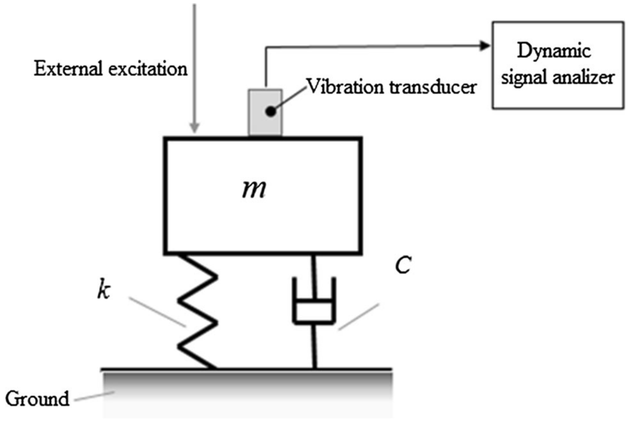


Fig. 6 Schematic diagram of the test system

requirements, the isolation efficiency will be guaranteed. The vibration transducer (CA-YD 159) used here is a low-frequency acceleration sensor with high sensitivity, produced by Chinese Lianneng Company. Photon II of Danish B & K Company serves as the dynamic signal analyzer.

During the test, a transient external excitation is applied on P1 to make it vibrate freely. The vibration sensor detects the vibration signals and inputs the signals to the dynamic signal analyzer. The test system collects the vibration signals of the vibration isolation platform in time domain and turns them into frequency domain. So the inherent frequency of the vibration isolation system can be identified easily.

Averaging method is employed in order to reduce the interference of ambient vibration and improve the test accuracy. The average number is ten. The frequencies to be analyzed range from 0 to 100 Hz with a frequency resolution as 0.002 Hz. Figure 7a reveals responses of the vibration isolation system in time domain under transient ambient excitation. It can be observed that the responses gradually attenuate over the time. Figure 7b sets out the responses in frequency domain. The inherent frequency of the vibration isolation system can be told as 2.747 Hz easily, which means the design specifications are fully reached.

Remote Supervisory and Control System for Laser Alignment

Though optical instruments for laser transporting are more stable with the vibration isolation platforms, there are still other factors influencing the laser beam pointing stability, such as air convection in the beam path, ambient temperature variations and so on. Consequently, the operators are obliged to check the alignment and align the beam manually every once in a while, which is a tedious and time consuming task. Meanwhile, during experiments, the operators can't always be permitted to enter the experimental hall to adjust the mirror mounts. To address these issues, a remote supervisory and control system is fitted. It can assist in finding misalignments in time and correct the drifts in the laboratory.

Experimental Setup

Figure 8 illustrates the laser path's schematic diagram of the EAST Thomson scattering diagnostic system. The complex laser beam path with 7 mirrors and one focusing lens is about 35 m. Besides, on the top of EAST, there is also one mirror reflecting the laser beam to reduce the stray light. The eight mirrors are numbered from 0 to 7. Only the mirror 0 is located in the laboratory. Thus, one camera is placed in front of each mirror from mirror 1 to mirror 7 recording scattered light from its optical surface to visualize the beam pattern of the laser [3, 4]. The amount of scattered radiation depends on the substrates surface quality, the surfaces cleanliness and the laser energy density. By observing the laser spot position on the mirror 6 and 7, the position and orientation of the laser passing through the plasma could be informed.

One more camera is mounted on the vibration isolation platform near the mirror 6 to monitor the shutter in the bottom vertical neck tube, marked as camera 8 in Fig. 8. The switch of the shutter can be controlled in the laboratory. This camera observes whether the laser beams enter into the tube completely when the shutter is open, and visualizes the laser beam pattern substituting camera 7 when the shutter is close. During experiments, mirror 7 and camera 7, which are fixed on top of EAST, will waggle causing by the EAST shaking. Then the laser spot position recorded by camera 7 will change when it doesn't virtually. This can be prevented by using the camera 8.

In this system, the Hikvision camera DS-2CD6412FWD is chosen. It is a network digital camera to ensure the signal quality in long distance transmission, equipped with a progressive-scan CMOS sensor with the highest resolution of 1,280 × 960 pixels. A major advantage of this camera is that it can be separated into two parts: the head and the tail. The head is laid before the mirror to capture images and send them to the tail. Its volume is quite small (25 mm × 37 mm × 26 mm). The tail is put several meters away from the mirror and transmits the data to the computer. So the camera can adapt to the narrow space of the laser path and refrain from being damaged by the laser of misalignment or during the alignment procedure more easily.

Fig. 7 The test results

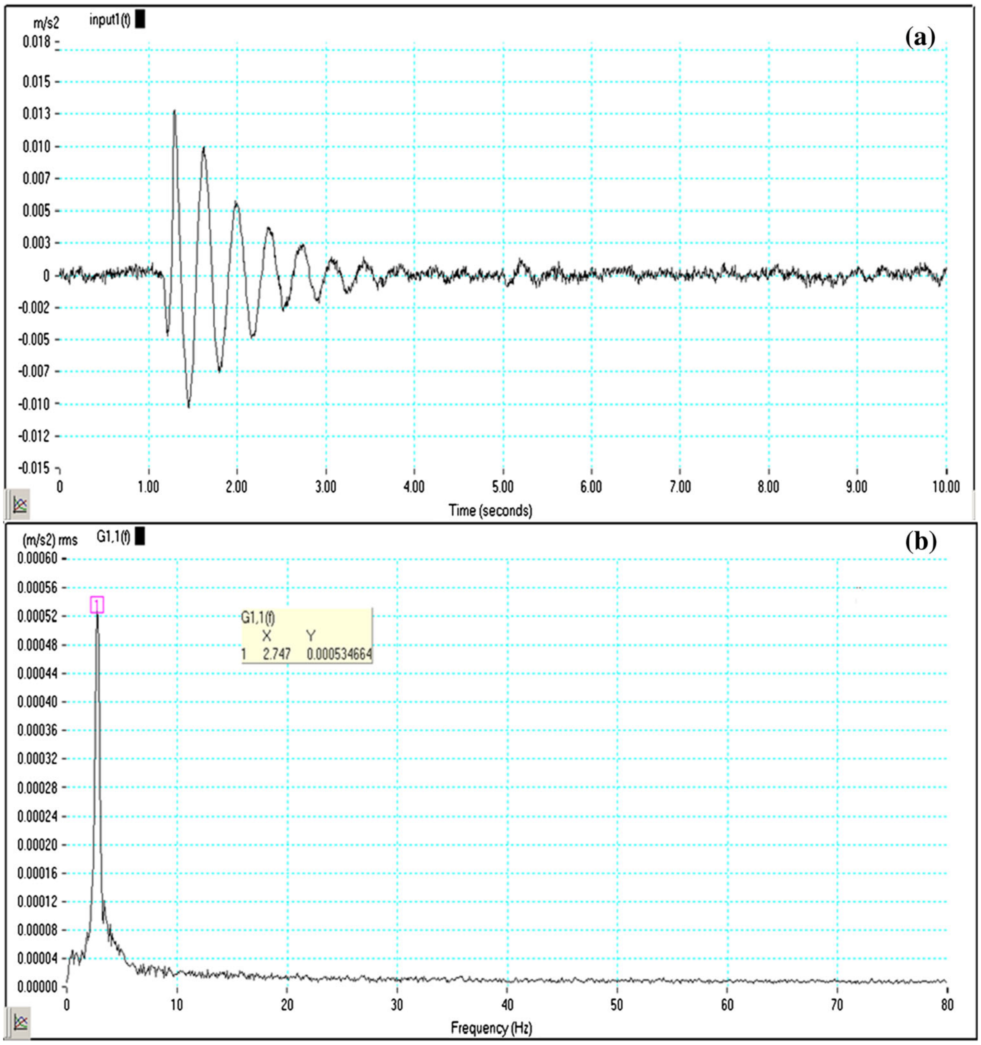
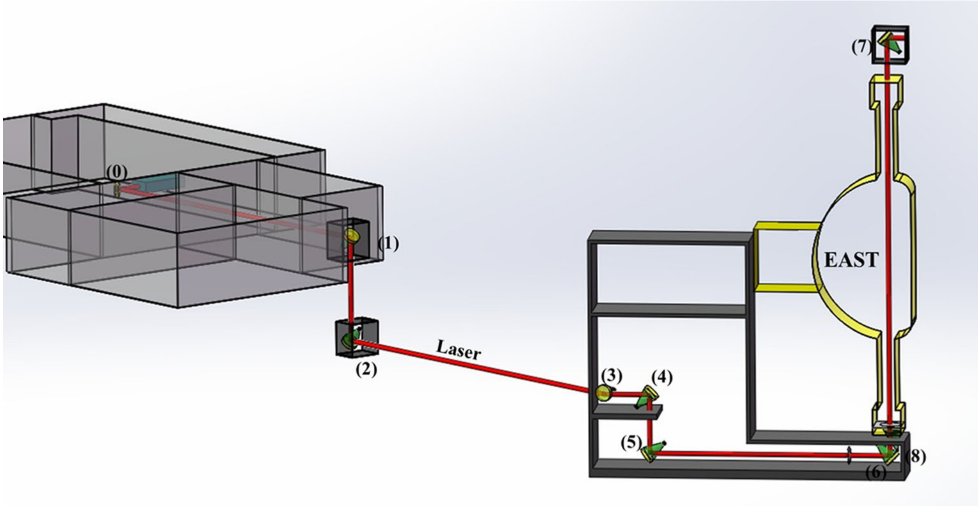
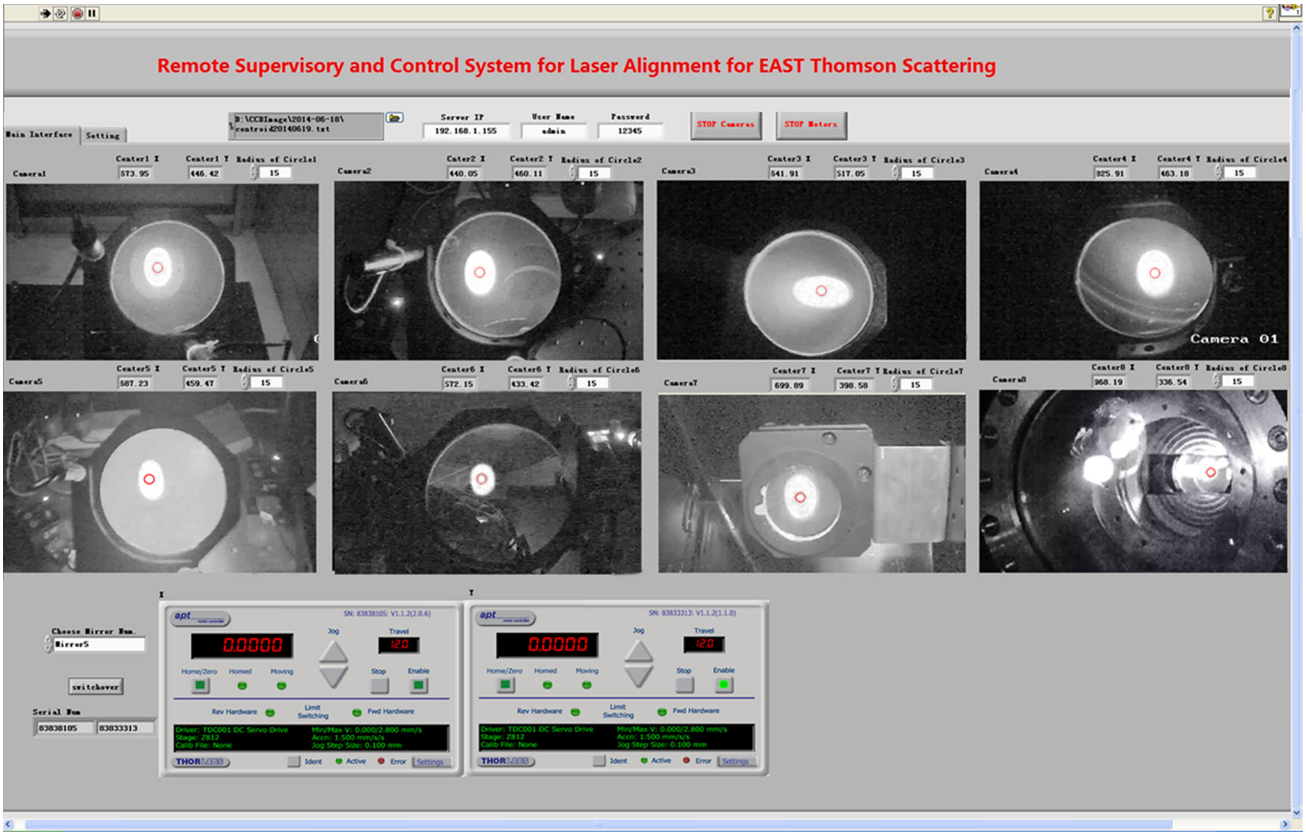


Fig. 8 Schematic diagram of laser path laser path of the EAST Thomson scattering diagnostic system



Another use of the cameras in front of mirrors is checking whether the mirror is damaged when the lamps near the mirrors are on. In order to turn on and off the lamps along the laser path conveniently, every lamp is designed to be controlled by two switches. One is arranged near the lamps using an ordinary switch and the other is



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Server IP: 192.168.1.155
User Name: admin
Password: 12345

Camera1: Center1 X 573.95; Center1 Y 446.42; Radius of Circle1 15
Camera2: Cater2 X 440.05; Center2 Y 460.11; Radius of Circle2 15
Camera3: Center3 X 541.91; Center3 Y 517.05; Radius of Circle3 15
Camera4: Center4 X 825.91; Center4 Y 463.18; Radius of Circle4 15
Camera5: Center5 X 587.23; Center5 Y 459.47; Radius of Circle5 15
Camera6: Center6 X 572.15; Center6 Y 433.42; Radius of Circle6 15
Camera7: Center7 X 699.89; Center7 Y 398.58; Radius of Circle7 15
Camera8: Center8 X 968.19; Center8 Y 336.54; Radius of Circle8 15

Choose Mirror Num.: Mirror5
Serial Num: 83838105 83833313

SN: 83838105: V1.1.2(2.0.6)
0.0000
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Driver: TDC001 DC Servo Drive
Stage: Z812
Calib File: None
Min/Max V: 0.000/2.800 mm/s
Accn: 1.500 mm/s/s
Jog Step Size: 0.100 mm

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Stage: Z812
Calib File: None
Min/Max V: 0.000/2.800 mm/s
Accn: 1.500 mm/s/s
Jog Step Size: 0.100 mm

Fig. 9 The screen shot of the software main interface

placed in the laboratory employing an intelligent switch. Intelligent switches can be operated both by manual and software.

Four motorized mirror mounts are fixed along the beam path to align the laser beam in laboratory [5]. They are employed severally by mirror 1, 2, 5 and 6. Two motorized mirror mounts are exploited by mirror 1 and 2. The reason is that the isolation efficiencies of vibration isolation platforms with them putting on are not very good on account of the size and the installation restricted by space conditions. The other two are applied by mirror 5 and 6 due to the key role they played in determining the position and orientation of the laser ripping into the vacuum chamber.

The motorized mirror mount is composed of a high-stability mirror mount (Thorlabs, KS4) with angular adjustment range of ± 4° and two DC servo motor actuators (Thorlabs, Z812). The motor actuator is managed by a single channel servo motor controller (Thorlabs, TDC001) that can operate in both standalone operation and PC operation mode. In this case, it is operated in the PC operation mode to set the parameters via software. The minimum resolution of motor actuator is 29 nm, provided by an encoder. The minimum repeatable incremental movement set by program is 0.2 μm. So by using these motorized mirror mounts, the requirements of high precision adjustments are satisfied.

Software Design

A computer is destined to work as a server with all the network cameras, motor controllers and intelligent switches linked to. The software is developed in the LabVIEW platform to display the real-time images from all the cameras and control all the motorized mirror mounts. It uses a Call Library Function Node to call the relevant DLL and the extensive ActiveX programming environment supplied by the manufacturers. The screen shot of the software main interface can be observed in Fig. 9.

The reference positions of the laser spot after the initial alignment are written as a text file and marked with red circles on the main interface by the software to find the laser drifts in time. In order to be more reliable, the reference positions are the average of the centroid locations of several laser spot images. The centroids are found out by a program developed using a Vision Development Module [6]. In this case, fifty images taken consecutively are utilized to get the reference data. The markers will remain

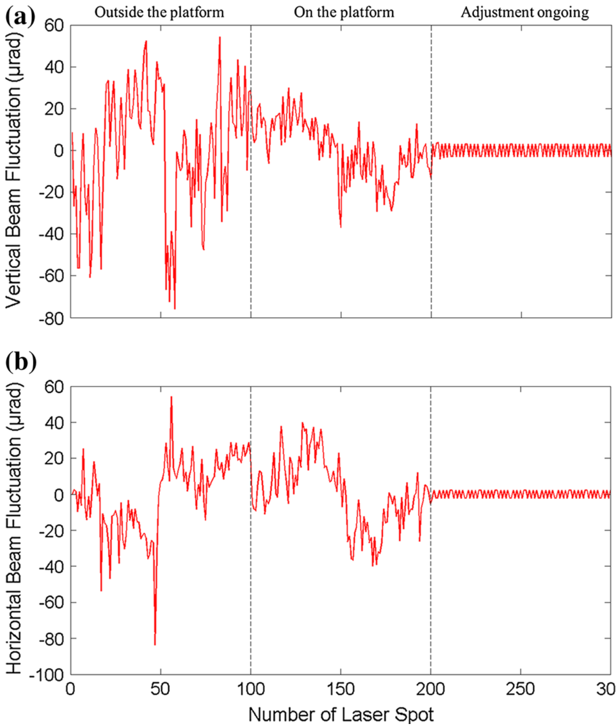

Fig. 10 Fluctuations in the beam position with and without renovations

valid as long as the cameras do not move. As a result, the misalignments can be found in time and the drifts can be corrected by adjusting the mirror mounts control program in the laboratory.

Results and Discussion

In order to assess the effects of these renovations, the images of the laser spot captured by the camera 6 are processed to record fluctuations of the beam position. Figure 10a, b present the results of vertical and horizontal directions with and without these renovations. The contrast shows that the vertical beam fluctuations are reduced by the vibration isolation platforms while the horizontal ones are not reduced so obviously. Fortunately, after using the remote supervisory and control system, both the vertical and horizontal beam fluctuations could be mitigated effectively. In fact, the laser pointing stability is reduced from about 120 to 10 μrad, which is good enough for the diagnostic system.

Conclusion

We have developed vibration isolation platforms and a remote supervisory and control system for laser alignment to improve the laser beam pointing stabilization for EAST Thomson scattering diagnostic. The contrast of the beam fluctuations in the horizontal and vertical directions with and without these renovations proves that the laser beam pointing stabilization can be improved efficiently by these renovations. The experimental data show that the laser beam position fluctuations are decreased from about 120 to 10 μrad. Thus, results of the renovated EAST Thomson scattering diagnostic system are considered to be more reliable than those of the old system.

Acknowledgments This work is funded by the National Natural Science Foundation of China with contract Nos. 11275233 and 11075187, and National Magnetic Confinement Fusion Science Program of China under Grant Nos. 2013GB112003 and 2011GB101003.

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