Automatic 4-mirrors system for alignment of high-power laser radiation

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Abstract

This paper presents the automated system for minimizing the deviation of the path of passage and the divergence of a secondary radiation source with parameters similar to ones of the main beam of a high-power Ti:Sa laser using mirrors in kinematic mounts on the motorized stages. As an alignment laser, the diode laser with a fiber output was used with radiation characteristics coinciding with the parameters of the main beam (wavelength, beam diameter). The successive approximation algorithm was used to minimize the beam deflection. The positioning accuracy and beam size matching were analyzed on the near-field camera and were equaled to 28.6 µm along the X-axis and 26.4 µm along the Y-axis. Beam size mismatch was equaled to 0.151 mm. The pointing accuracy was analyzed on the far-field sensor and equaled 15.34 µrad along the X axis and 12.03 µrad along the Y axis. The curvature of the wavefront was 0.06 µm.

Keywords: Ti:Sa laser, automatic alignment, beam position, ultrahigh-power laser radiation.

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Introduction

To date, the development of laser facilities for fundamental research of processes in the atomic nucleus, vacuum physics, modeling of interatomic interactions, laboratory astrophysics, particle acceleration, studying the mechanisms of interaction of laser radiation with matter, as well as studying the properties of high-temperature plasma, where pulsed sources of laser radiation of peta- and exawatt power are used [1, 2]. However, their use is associated with the problem of providing the passage of the beam over long distances along a strictly defined path to the interaction chamber, as well as the presence of radiation distortions under influence of local turbulence, the statistics of which differs from the traditional Kolmogorov [3].

The first problem is solved by using secondary laser sources ("pilot" lasers) with identical characteristics (wavelength, radiation intensity distribution, wavefront curvature), but with lower power, which makes it possible to reduce the risk of damage to expensive equipment by stages of adjustment of the optical scheme, as well as to increase the safety of used laser complex and eliminate the influence of the human factor on the final result of the adjustment. In this case, the direction of radiation propagation of the "pilot" laser, the beam size, as well as the wavefront aberrations should correspond to the main ("live") laser [4 – 6]. The second problem can be solved by using adaptive optics means [7 – 17]. In this paper, our attention will be focused on solving the first problem.

At present, the so-called reference approach is used in the alignment of high-power pulsed laser systems; beam convergence occurs in real time with simultaneous analysis of the beam position both in the near- and far-fields. The parameters of the "live" laser are taken as reference and after that, with the help of motorized optomechanical devices, gradual decrease in the divergence of the main and secondary beams occurs. A similar approach has been implemented in a number of projects: at the Livermore Scientific Laboratory to combine 192 beams for focusing on target [18 – 21], in the French Laser MegaJoule (LMJ) project [22], on the Russian UFL-2M facility [23], on the Chinese complex Shenguang III (SG-III) [24].

There is also known an analysis method based on data processing of the two-dimensional function of the spectral power density of the beam image in the near-field, which allows obtaining information about the position of the beam, as well as on the analysis of the spatial frequency characteristics of the beam, which provides information about the centering of the beam with the optical axis [25]. According to the authors, this method is a simple, effective and cost-effective alternative to the traditional reference method, where both near- and far-field cameras are used. However, this method has a number of disadvantages: when analyzing the power spectral density using a CCD camera, there are problems with the sampling frequency of the cameras, which can lead to the loss of part of the signal, and increase in the frequency will necessitate the processing of more information, which will reduce the speed of the system. Moreover, this method is very sensitive to background noises that inevitably arise in the process of data analysis. Increasing the threshold values in order to suppress noise can lead to an error in determining the initial beam parameters.

Both presented approaches assume the passage of "pilot" radiation through all optical elements of the laser complex, including amplifiers of optical signals. Therefore, without the use of elements of the laser system (pumping, cooling systems), the use of such low-power light beams is not effective. Especially when adjusting the optical end stage, the parabolic mirror, diffraction gratings of compressor, which are sometimes placed at considerable distances from the main amplifying laser. In this regard, in modern laser systems, it became necessary to use additional "pilot" lasers, which are already located after all active optical elements that change their properties during the operation of the main laser beam. At the same time, the requirements of modern security systems also imply 100 % automatic adjustment of such "pilot" complexes.

The purpose of this work was to create a fully automated system for combining the "pilot" laser beam, the direction of propagation and divergence of which would correspond to the characteristics of a "live" laser beam with the required accuracy.

1. Requirements of accuracy for beams coincidence and principal alignment scheme

The quality of beams alignment could be defined in 4 main parameters:

- beam size matching;
- positioning accuracy;
- pointing accuracy;
- wavefront curvature mismatch.

The positioning accuracy of the "pilot" beam and the coincidence with the "live" beam is provided on the near-field camera. The beam pointing accuracy is analyzed using a far-field camera. Wavefront curvature data as well as precise wavefront tip-tilt can be obtained using a Shack-Hartmann sensor.

When creating alignment schemes, high requirements are imposed on the accuracy of minimizing beam deflection. Thus, the mismatch in the size of the beams leads to a loss of radiation power when focusing on the target, the divergence of the centers of the beams causes the appearance of additional aberrations of the wavefront when passing through the focusing elements.

It is also necessary to ensure high accuracy of beam pointing in the far-field. For example, the divergence of beams by 20 µrad leads to a shift in the position of the beam focus on the target by about 180 µm, which is about 2 % for an average target size of 10 mm [26].

The values of the indicated parameters must comply with the requirements presented in Tab. 1.

Tab. 1. Requirements of accuracy for beams alignment

Parameter	Necessary value
Beam size matching	Not more than 1 mm
Positioning accuracy	Not more than 0.5 mm
Pointing accuracy	Not more than 20 µrad
Wavefront curvature mismatch	Not more than 0.1 µm

The development and construction of the optical scheme is based on determining the characteristics of the "live" beam and the choice of the "pilot" light source of lower power, but with identical parameters. The choice was made according to the following categories: wavelength, intensity distribution, power. As "pilot" source radiation Aerodiode 808LD-1-2-2 fiber-coupled diode laser was used. (Tab. 2).

Tab. 2. Characteristics of laser radiation for "pilot" and "live" beam sources

Characteristic	"Live" Beam	"Pilot" beam
Wavelength	808 nm	808 nm
Intensity distribution	Super Gaussian	Gaussian
Beam diameter	96 mm	96 mm

Principal scheme for realization of minimization of deviation of laser beams is shown in Fig. 1. Elements of the system were placed on the 3 optical breadboards (two 300×1200 mm and one 300×600 mm).

The scheme could be divided on three key arms:

- "pilot" beam system;
- system of active minimization and positioning of laser beams;
- system of analysis of laser beam parameters.

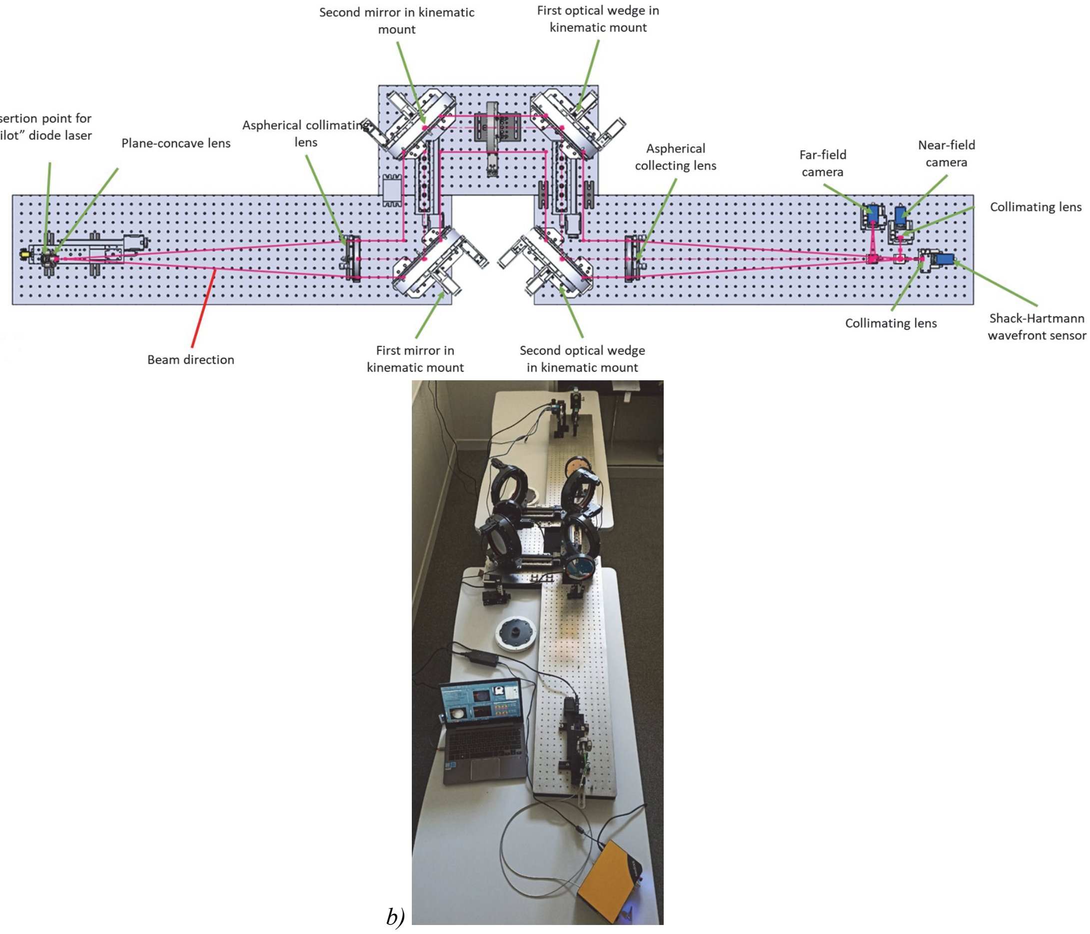
The "pilot" laser system consists of a number of optical and optomechanical elements optimized in accordance with the requirements from Tab. 1. It includes a fiber-coupled diode laser with a 3 mm collimating lens, resizing optics with a 0.5-inch lens with a focal length of 24 mm and a 5-inch aspherical lens with a focal length of 800 mm (provides a 22× magnification). Correspondingly, at a fiber diode laser divergence of 12^0, radiation with diameter of 96 mm at a level of $1/e^2$ falls on the lens. To compensate for the curvature of the wavefront, the fiber output of the laser diode was mounted on a motorized stage with the possibility of moving the platform in a horizontal position over a distance of 100 mm with a minimum step of 0.31 µm.

The active beam minimization and positioning system includes 4 two-coordinate kinematic mounts with mirrors with a light aperture of 152 mm. Since the mirrors are located at an angle of 45^0, radiation with a diameter of approximately 138 mm falls on them. Two mounts are located on motorized stages from Standa Ltd., which allow to remove the reflecting mirrors from the laser beam. In order to avoid damage to the camera sensors in the beam parameter analysis system, it is proposed to use 2 mirrors with a highly reflective coating in the IR range (> 98 %) and 2 optical wedges with a reflectance of 4 % in order to reduce the optical power (Fig. 1).

The beam parameters monitoring system consists of a lens with a focal length of 770 mm, 2 beamsplitter cubes (20 mm and 10 mm), as well as three CCD cameras with a sensor size of 0.5 inches and a pixel size of 4.8 µm for analyzing the beam characteristics: near-field camera with resizing optics (12.5 mm lens, 35 mm focal length), far-field camera and Shack–Hartmann sensor with resizing optics (12.5 mm lens, 35 mm focal length) with microlenses array of 26×26 pcs [27]. The automatic beam deviation minimization scheme was controlled using specially developed software with the possibility of simultaneous monitoring of key system parameters and remote control.

2. Algorithm of minimization of beams deviation

At the moment, there are two most used algorithms: successive approximation and based on influence functions. The first algorithm is based on the analysis of the position of the beam after the application of test perturbations; in a sense, it is an analogue of the “hill-climbing” method [28]. The use of this method takes a long time, but provides greater accuracy, and, most importantly, it is resistant to noise. The second one makes it possible to minimize the beam divergence by analyzing the displacement of the beam position when a single control voltage is applied to the stepper motor, calculating the vector of control signals and applying them to the stepper motors (it is a modification of the phase-conjugation method [29]). The application of this algorithm speeds up the process of beam deflection minimization, but, nevertheless, can lead to significant errors during alignment, appearing due to incorrect measurement of the influence functions themselves and the nonlinearity of the response of the kinematic drives.



a) b)

Fig. 1. Principal design (a) and photo (b) of automatic alignment system

The method for measuring the position of beams on the cameras of the near- and far-fields corresponds to the international standard ISO 11146, where the accuracy of finding the position of the beam on the camera is determined as follows [30]:

- the number of illuminated pixels must be at least 20 pcs (measurement error is not more than 0.5 %);
- the camera must provide a pixel depth of at least 8 bits (measurement error is no more than 0.5 %).
- the ratio between the total size of the camera sensor area and the beam size on the camera sensor must be at least 1.5:1. (measurement error is no more than 0.3 % for a beam with a super-gaussian intensity distribution).

The centroid determination accuracy is 0.5 pixels or 2.4 µm (at 22× magnification – 53 µm).

The coordinates of the center of the beam spot are calculated by the method of finding the “center of gravity” of the pixels that make up the beam, where its intensity acts as the “weight” of the point. The use of the “center of gravity” method provides a high speed of information processing, which is important in real-time systems. Spot center coordinates (x_c, y_c) are calculated using the following formulas:

$$x_c = \sum_{i=1}^{n} x_i I_i \Big/ \sum_{i=1}^{n} I_i , \quad (1)$$

$$y_c = \sum_{i=1}^{n} y_i I_i \Big/ \sum_{i=1}^{n} I_i , \quad (2)$$

where x_c, y_c are coordinates of the focal spot center,

n is the number of points in the summation area,

x_i, y_i – coordinates of the i-th pixel,

I_i is the intensity of the i-th pixel.

The summation is carried out over some region surrounding the focal spot.

To ensure the reliability of the adjustment, we chose the algorithm of successive approximations. It can be divided into 5 steps:

Step 1. Initial measurement and fixation of the "live" beam parameters by adjusting the first and second optical wedges and using the coordinates of the radiation centers in the near- and far-fields, as well as the Shack-Hartmann sensor as reference ones (Fig. 2*a*);

Step 2. Next, the second mirror is introduced into the radiation path of the "live" laser, and by tilting the first mirror in the kinematic mount, the centroids of the "pilot" beam coincide with the reference parameters on the near-field camera using stepper motors (Fig. 2*b*). After reaching the specified accuracy, or after the beam leaves the analyzed area of the camera, the algorithm proceeds to tracking the beam deflection in the far-field.

Step 3. By tilting the second mirror in the kinematic mount, the deviation of the "pilot" beam centroid relative to the reference parameters on the far-field camera is reduced using stepper motors on the kinematic mount. After the specified accuracy is reached, or the beam leaves the analyzed area of the camera, the algorithm returns to minimizing beam deflection in the near-field.

Step 4. Repeat steps 2 and 3 to achieve the required accuracy on the near- and far-field cameras simultaneously.

Step 5. Compensation for the overall curvature of the wavefront by analyzing the defocus with the Shack-Hartmann sensor and sequentially moving the laser diode on the motorized stage.

Next, the first optical wedge is removed from the radiation path of the "live" laser, and the radiation of the "pilot" laser is ready for aligning various optical elements (Fig. 2*c*).

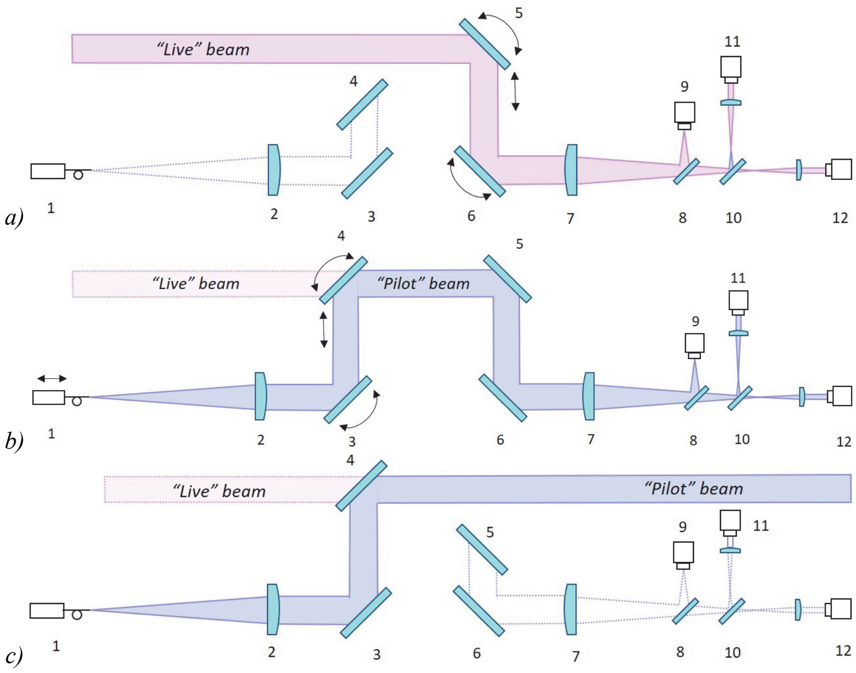


Fig. 2. Alignment procedure: a) analysis of "live" beam parameters, b) minimization of deviation of "pilot" and "live" beam parameters, c) "pilot" beam usage as "live". 1. Laser diode. 2. Collimating lens (f – 800 mm). 3. First mirror in kinematic mount. 4. Second mirror in kinematic mount. 5. First optical wedge in kinematic mount. 6. Second optical wedge in kinematic mount. 7. Collecting lens (f – 770 mm). 8. Beamsplitter cube 20×20 mm. 9. Far-field camera. 10. Beamsplitter cube 10×10 mm. 11. Near-field camera. 12. Shack-Hartmann wavefront sensor

3. Alignment of laser beam radiation in automatic regime

At the first step, manual adjustment and alignment of optical and optomechanical elements is performed.

The effectiveness of the alignment system was measured and compared directly with the "live" beam. To do this, the reference for the alignment system was initially measured (the center of the far-field, the center and diameter of the near-field, as well as the initial wavefront using a Shack-Hartmann wavefront sensor) using the "live" laser. The radiation of this laser was directed to the central region of both cameras (near- and far-fields), as well as to the center of the wavefront sensor. All measured data are shown in Fig. 3.

After that, at the command from the computer, the "live" laser was turned off and a second mirror in kinematic mount was introduced into the optical path (Fig. 2*b*) to start the system for monitoring the "pilot" beam and its automatic alignment using the method of successive approximations. Ultimately, the indicated accuracy of coincidence of the "live" and "pilot" laser beams was achieved - the results of automatic alignment are presented in Tab. 3 and in Fig. 4.

The relative mismatch of the beam center along the X axis and along the Y axis is 0.1 µm on the near-field camera. It could be explained by the fact that under the conditions of a laboratory experiment, fluctuations in the intensity of the "live" beam arise, which leads to a relative asymmetry of measurements for the reference values.

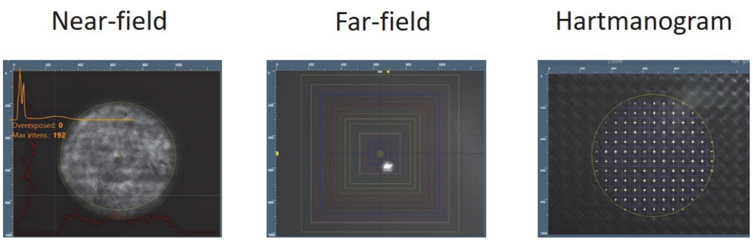


Fig. 3. “Live” beam parameters

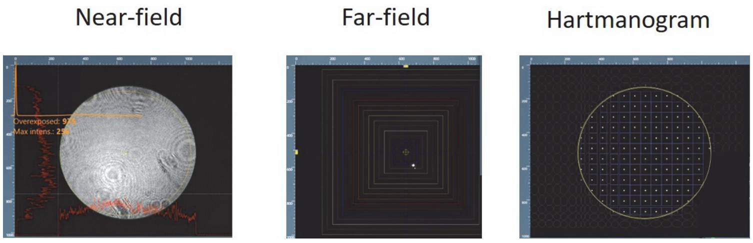


Fig. 4. Results of deviation minimization between “pilot” and “live” laser beams after automatic alignment

Conclusion

An automatic 4-mirror system for adjusting high-power laser radiation was developed and tested for using beam convergence in pulsed laser complexes of peta- and exawatt power levels. The scheme consists of a diode laser used as a secondary source of radiation, the key parameters of which (wavelength, intensity distribution, etc.) coincide with the characteristics of the main beam, 4 tip-tilt mirrors in the kinematic mounts for active convergence of beams, cameras of the near- and far-fields for analysis of the location of the focal spot, size, distribution of beam intensity. Also in the scheme, the Shack-Hartmann sensor was used to analyze the magnitude of the curvature and tip-tilts of the wavefront. The use of the method of successive approximations made it possible to ensure the coincidence of the beam sizes with an accuracy of 30 µm, the accuracy of beam guidance in the far-field was no more than 16 µrad, and the curvature mismatch of beam radiation was 0.06 µm.

Tab. 3. Results of alignment of laser beams in accordance with the requirements

Parameter	Necessary value	Obtained value for “live” beam
Beam size matching	Not more than 1 mm	Beam size deviation - 0.151 mm
Positioning accuracy	Not more than 0.5 mm	1.3 µm along X axis (22× telescope – 28.6 µm) 1.2 µm along Y axis (22× telescope – 26.4 µm)
Pointing accuracy	Not more than 20 µrad	15.34 µrad along X axis 12.03 µrad along Y axis
Wavefront curvature mismatch	Not more than 0.1 µm	0.06 µm

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