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Metrol. Meas. Syst., Vol. XXII (2015), No. 1, pp. 165–172.

METROLOGY AND MEASUREMENT SYSTEMS

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ACTIVE STABILIZATION OF THE BEAM POINTING OF A HIGH- POWER KrF LASER SYSTEM

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Abstract

An active beam-pointing stabilization system has been developed for a high-power KrF laser system to eliminate the long-term drift of the directional change of the beam in order to have a stable focusing to a high intensity. The control of the beam direction was achieved by a motor-driven mirror activated by an electric signal obtained by monitoring the position of the focus of the output beam. Instead of large sized UV-sensitive position sensitive detectors a simple arrangement with scatter plates and photodiodes are used to measure the directionality of the beam. After the beam stabilization the long-term residual deviation of the laser shots is ~14 µrad, which is comparable to the shot-to-shot variation of the beam (~12 µrad). This deviation is small enough to keep the focal spot size in a micrometer range when tightly focusing the beam using off-axis parabolic mirrors.

Keywords: diffraction-limited UV pulse, beam-pointing stabilization, long-term drift, photodiode.

1. Introduction

The stability of laser parameters is essential in the investigations of laser-plasma interactions, especially in case of tightly focused short pulse laser beams. The beam pointing stability is one of the most important requirements for high-power laser systems. Diffraction-limited laser beams of short wavelengths can be focused into a very small spot [1]. Especially in case of beam focusing with off-axis parabolic mirrors, it is crucial to avoid the astigmatism. Excimer laser amplifiers have a low saturation energy; therefore, in order to obtain an intense radiation of an excimer-amplified UV radiation, long optical path-lengths and large beam diameters have to be used. The focusability of practical UV laser systems is dependent on eventual phase distortions and the shot-to-shot fluctuation – arising from mechanical vibrations of optical components, optical tables – which can be hardly eliminated. Moreover, a mechanical vibration of the temperature-induced mechanical deformations results in a long-term drift even for our modest-size, 100GW KrF laser system [2] which can well be corrected and stabilized by an active beam-pointing stabilization system.

The present paper aims to develop a simple method for improving the directional, i.e. the spatial stability of the laser beam. It is well-known that besides the spatial drift, a long-term temporal drift is generally present in the time domain in pulsed gas lasers as well. This is because in case of the high voltage discharge pumping of the KrF laser amplifiers the switching time of thyratrons – called the anode delay – is not constant, due to the temperature modifications it has a long-term drift of a few hundred nanoseconds. Thus, in order to reduce

Article history: received on Jun. 03, 2014; accepted on Dec. 31, 2014; available online on Mar. 15, 2015; DOI: 10.1515/mms-2015-0014.

this jitter a precise time-synchronization was developed earlier to compensate this long-term drift of the anode delay [3].

Several studies were carried out on the directional stabilization of different laser systems (cw, pulsed laser). Most of the control devices are based on four-quadrant photodiodes [4] and piezo-driven mirrors. S. Grafström et al [5] reported the stabilization of the output beam of a cw free-jet ring dye laser. An automatic beam alignment system using personal computers for the optimization was developed for pulsed infrared lasers [6]. Beam stabilization systems were also introduced to improve the direction properties of Ti:sapphire lasers. T. Kanai et al [7] built a system for the beam pointing stabilization of a high-power femtosecond laser operating at the repetition rate of 1 kHz. Stabilizing-monitoring both the near- and far-field distribution was realized for the single-shot operation or for repetition rates below 2 Hz by G. Genoud at al [8]. M. Mori at al [9] developed a beam-pointing stabilizer for improving the long-term pointing stability of a 10-TW laser system.

Laser plasma experiments with high-intensity KrF lasers generally require tight focusing of the beam. The focusability of KrF excimer laser systems is generally very good, due to a short wavelength and the minimum optical distortion in the gaseous active medium [1]. The nearly diffraction-limited beam allows to generate focal spots of diameters less than 1 μm, which is - however - very sensitive to the beam pointing, especially in case of focusing by off-axis parabolic mirrors. Due to the earlier-mentioned low saturation energy density of the KrF amplifier the diameter of the laser beam is large. Most of commercially available position-sensitive detectors are produced for small-size beams of the infrared radiation of solid-state laser systems. Large-sized position-sensitive UV detectors are difficult to obtain and are very expensive. In our laboratory an active beam-pointing stabilization system was developed to compensate for directional drifts of the ultrashort excimer laser beam. Using photodiodes with a scatter plate instead of a quadrant detector is much less expensive and can easily be matched to the actual beam size. The position-sensitive detector monitors the position of the laser pulse in the focus. Basing on this information a feedback system with a motor-driven mirror aligns the laser beam to the adequate direction.

2. Description of the stabilization system

The basic component of the beam-pointing stabilization system is the position-sensitive detector consisting of 4 photodiodes (BPW21R) positioned behind a quartz scatter plate, as illustrated in Fig. 1. The photodiodes are situated 35 mm behind a 2.5 mm thick scatter plate. Two rectangular metal plates of 0.8 mm thickness separate symmetrically the four diodes to form four spatial segments (13x13 mm each). The illumination is detected by these photodiodes when the laser pulse is focused onto the centre of the scatter plate. It is shown herewith that this arrangement is a suitable position-sensitive detector even with focusing the laser beam and thus using a small-sized detection system.

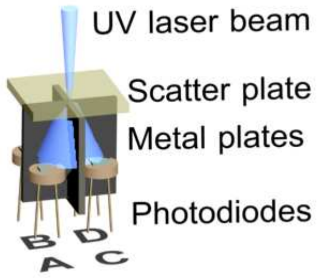

Fig. 1. The spatially-sensitive detector, four segmented diodes behind a scattering plate.

The glass windows of the photodiodes were replaced by quartz windows to ensure the UV transparency. These photodiodes give signals proportional to the intensity, therefore the ratio of the diode signals is dependent on the position of the incident laser pulse. In our experimental arrangement the laser beam was focused onto the center of the scatter plate with a 56 μm diameter of the focal spot (FWHM). The distance between the scatter plate and the photodiodes was set to optimize the signal of the photodiodes.

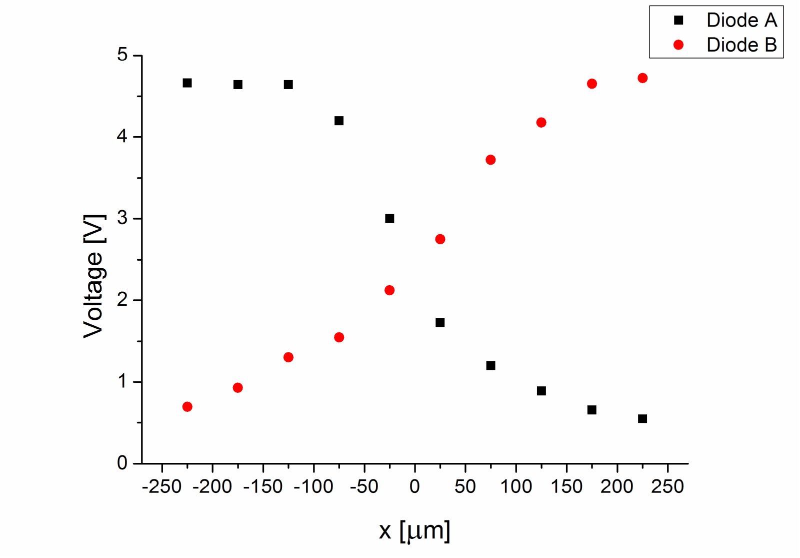

Fig. 2. The measured voltage on diode A and diode B as a function of the focal spot position on the scatter plate of the detector.

In Fig. 2. the measured voltage on two photodiodes along the x axis are shown as a function of the focal spot position on the scatter plate of the detector. The zero is set to the position of the metal plate separating the two segments. It can be seen that moving from the center position by 10 μm results in significantly different voltage levels on the separate photodiodes. This is less than the diameter of the focal spot (the full width at half maximum, FWHM was ~56 μm) on the scatter plate surface, thus the sensitivity of the arrangement is accurate enough for aligning the beam to the initial position. However, it must be noted that the metal plate thickness is larger than the focal spot size. The photodiodes can detect the scattered laser pulse when the focal spot is in the centre of the position-sensitive detector because some part of the focused laser pulse can be reflected by the edge of the rectangular metal plate and re-scattered by the scattering plate. In that way, the combination of photodiodes with a scatter plate − instead of a quadrant detector − can well be matched to the actual beam size.

The photodiode current is converted into the voltage by a TL071 amplifier. Then, a fast peak-hold circuit (OPA350) holds the voltage for further processing. Another part of the control system is a DC motor driver. It contains a slow peak hold (PKD01) catching the pulse after the fast peak-hold circuit. Then, with analog adding and substracting 4 signals of the diodes (A, B, C and D), two signals are generated ($U_x = (A+B)-(C+D), U_y = (A+C)-(B+D)$) which determine the position of the light spot on the detector in both dimensions. Fig. 3 shows a block diagram of the electronic system. The microcontroller and the slow peak hold circuit are synchronised by optical fiber-based trigger signals from the laser. Two DC motors − used for mirror alignment − are driven by pulse-width modulated square signals, where the filling factor and polarity of the signals are calculated based on the current of the photodiodes. Beyond U_x and U_y, the sum of the channels (U_s) can be used to measure the intensity of the incident beam. In case $U_s < 0.8$V and $U_s > 3.5$V an indicator LED flashes and the alignment of the mirror is suspended to avoid a noisy operation or saturation.

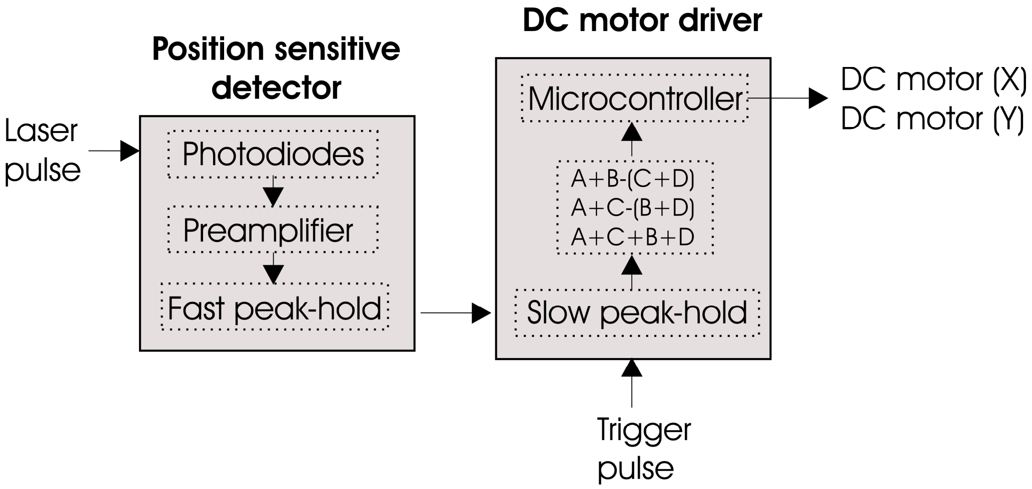

Fig. 3. A block diagram of the electronics, the position-sensitive detector and the DC motor driver.

3. Experimental results

In the laser plasma experiment a high-quality off-axis parabolic mirror (F/2 or F/3) is used to produce relativistic intensities (up to 10^{19} W/cm^2 [10]) in the ultraviolet regime. During the test of the beam-stabilization system a cares was taken to eliminate the astigmatism to obtain a stable high-intensity focus of the minimum size. The present tests were carried out using a subpicosecond hybrid, dye-excimer UV laser system which is based on a twin discharge EMG150 Lambda-Physik excimer laser [2]. The XeCl laser oscillator pumps a pulsed, femtosecond dye-laser chain operating at 497 nm, then - after the frequency conversion - the second harmonic is amplified by the KrF amplifier tube. After 2 passes of the off-axis amplification scheme the output beam has the pulse energy of 12 mJ and the 510 fs pulse duration at the 248 nm wavelength. It must be noted, that in the case of laser-plasma experiments a further amplifier is used, providing energies up to 80 mJ [2, 11], which was not used throughout these tests.

The setup of the beam-stabilization system is shown in Fig. 4. A quartz plate is used as a beam splitter to send part of the beam onto a UV-sensitive CCD camera; the rest goes onto the position-sensitive detector. The combination of a positive lens with the 300 mm focal length and a negative lens with the -140 mm focal length is used to generate a beam of a finite (small) numerical aperture over a small distance.

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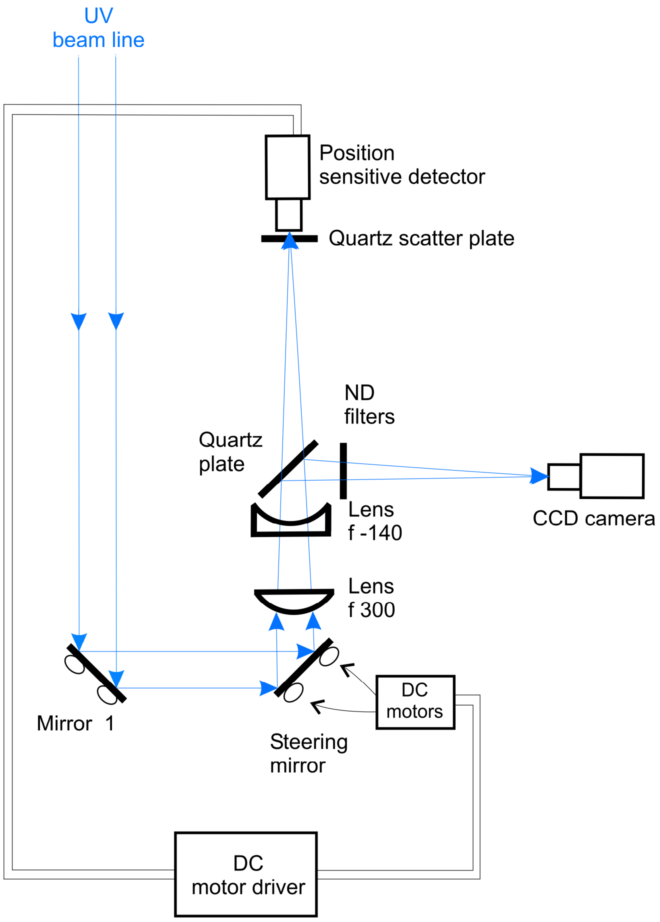


Fig. 4. The detailed setup of the beam-stabilization system.

The output beam of UV lasers suffers from the shot-to-shot fluctuation and from the long-term walk-off. The shot-to-shot variation of the laser pulse position in the focus was measured using a CCD camera. Figures 5a and 5b show the shot-to-shot fluctuation of the focal spot in the vertical and horizontal directions without using a beam-stabilization system. Here, the center of the beam is assigned and the width of the profiles obtained from 100 shots corresponding to a deviation of ~12 μrad (FWHM) with a standard error of 14% when fitting Gaussians onto the measured positions.

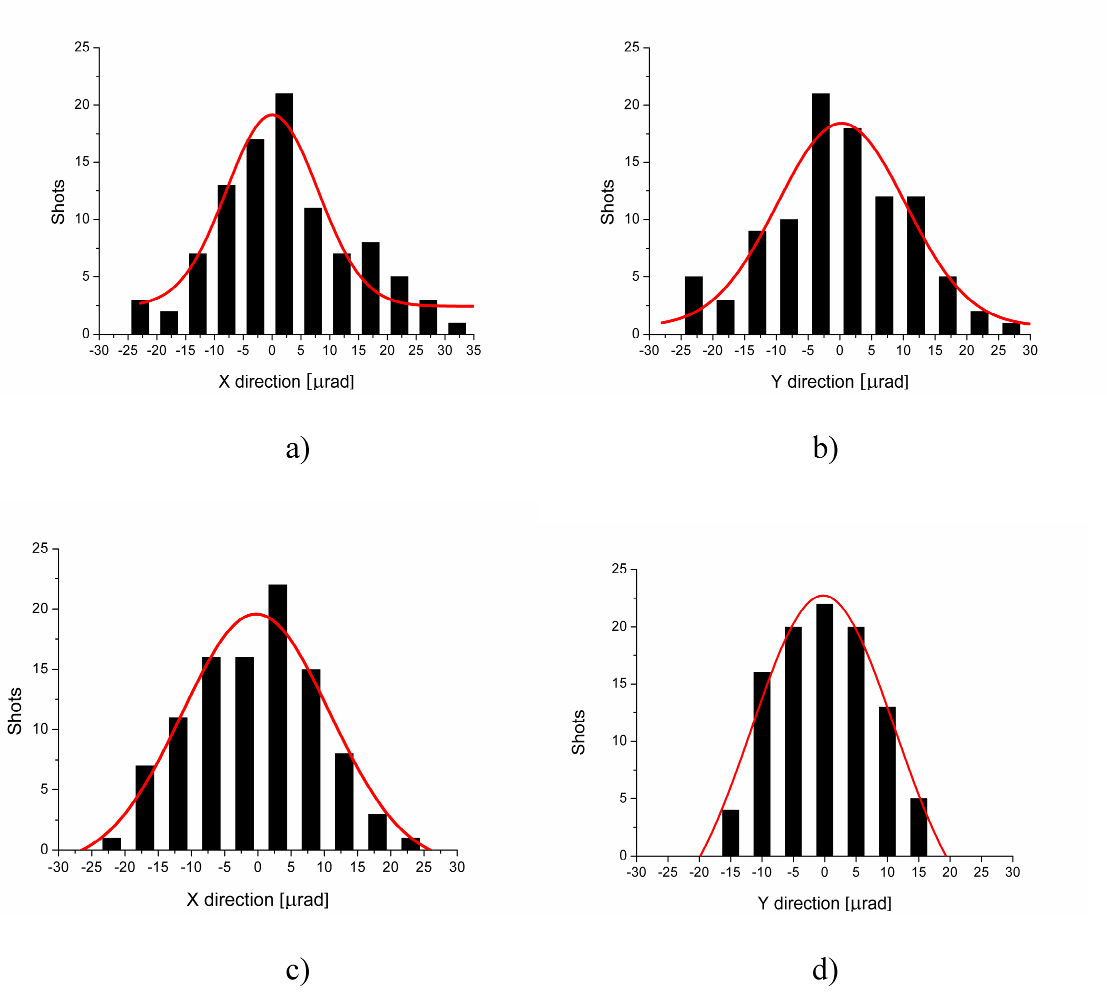
The beam stabilization system is tested against the long-term drift of the beam which was equal to 19 μrad in one day and 61 μrad in six days. The feedback stabilization system was tested by slight misaligning the beam with mirror 1, thus simulating a long-term drift. The results of the correction were detected after 1 minute of the laser operation with the 1 Hz repetition rate, and then the position of the spot on the camera was saved. Figures 5c and 5d show the results of the beam stabilization for 100 shots. It is seen that the residual deviation is ~14 μrad (FWHM) for both X and Y directions, with a standard error of 15%. It means that the beam stabilization eliminates the long-time walk-off, and the directional instability remains as low as ~14 μrad. The bandwidth of the feedback loop is 1 kHz for our stabilization system.

Next, these results are compared with the divergence of the beam and with the requirements for tight focusing using off-axis parabola mirrors. From the width of the 0th order of the focal spot, a diffraction-limited divergence of ~15 μrad ±7% is found. The long-term directional drift of the beam was 19 μrad in 24 hours. When the stabilization system was switched on, the direction of the beam was readjusted with an accuracy of ~5 μrad. After

6 days when the direction of the beam was changed with 61 μrad without a stabilization, the system corrected this deviation with the same precision. When focusing by a parabolic mirror with a small F-number, the tolerance of the misalignment of the parabolic mirror is given by [12], as

$$\Delta\phi = \pm \frac{\pi w^2{}_0}{\lambda f_0 tg\phi} \cdot \sqrt{\left(\frac{w_A}{w_0}\right)^2 - 1}\,, \tag{1}$$

where w_0 is the radius of the focal spot of the laser beam for the optimal adjustment, w_A is the radius of the focal spot of the laser beam for a nonoptimal adjustment, λ is the wavelength of the laser pulse (in our case 248 nm), ϕ is the angle of incidence of the laser beam, f_0 is the effective focal length of the parabolic mirror. For our Janostech off-axis parabola, $\phi=30°$, $f_0=100.45$ *mm,* the input beam diameter is 35 mm. Allowing a 25% increase of the focal spot size the tolerance of the misalignment of the parabola is ±123 μrad. It is seen that the directional stability provided by the beam-stabilization system is nearly an order of magnitude better than the one required for optimum focusing by an F/3 parabolic mirror. In our previous experiments [13] this requirement for the tight focusing is confirmed even without using the stabilization system.



a) b)

c) d)

Fig. 5. The directional distribution of the focal spot without (a, b) and with (c, d) the beam-stabilization system for the X (a, c) and Y (b, d) directions.

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4. Conclusion

An active beam-pointing stabilization system has been built for a high-power KrF laser system. The control of the spatial position of the ultrashort laser beam was achieved by a feedback loop consisting of a special position sensitive detector, a DC motor driver, and a motor-driven mirror. With this beam stabilization a long-term stability of ~14 µrad for the directional distribution is obtained, which approximately corresponds to the shot-to-shot (not predictable) directional fluctuation of the pulse. To our knowledge this device is the first beam stabilizing system for high-power KrF laser systems. The most important advantages of our instrument are its low cost and easy insertion into the laser setup. Using photodiodes with a scatter plate instead of a quadrant detector can easily be matched to the actual beam size. These results show that similar setups can well be used at large facilities with high-energy, high-power laser systems when the beam diameters are significantly larger.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commision. It was also supported by the COST MP1208 and MP1203 activities. The project was partially financed by "TÁMOP-4.2.2.A-11/1/KONV-2012-0060" - "Pulsed lasers for use in materials science and biophotonic", supported by the European Union and co-financed by the European Social Fund.

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