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Characterisation of the stability and long-term evolution of the properties of a 45TW laser operating at 10Hz

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Abstract. Industrial quality applications of high-power lasers working at high repetition rates, including laser-driven particle acceleration, will require laser systems capable of operating in a stable and prolonged manner. Several factors can affect this stability, including the environment conditions, such as temperature or humidity, and the progressive heating of the optical components involved. Here we report on the evolution of the main laser parameters for a 45 TW system operating at 10 Hz, showing that a significant change in the wavefront and direction of propagation, even when the laser energy remains sufficiently constant. These results highlight the importance for future laser systems to integrate closed-loop beam tracking diagnostics that can correct the temporal evolution.

1 Introduction

The progress in laser technologies over the past couple of decades has led to an increasing interest in laser-driven particle acceleration. These accelerators benefit from the huge acceleration gradients that can be sustained by the plasma, more than three orders of magnitude greater than the fields achieved in conventional accelerators. Impressive results recently reported include the acceleration of protons to energies up to 100 MeV from solid targets [1], or the acceleration of electron beams to energies up to 7.8 GeV from a single stage a few centimetres long [2].

Beyond the ongoing efforts to further improve the acceleration mechanisms, laser-plasma accelerators are reaching a level of maturity that enables their widespread use as an alternative to conventional accelerators. An example in this direction is the EuPRAXIA project [3], an European-funded development aiming to build a plasma-based electron accelerator of industrial quality capable of producing narrow-band and high-current electron beams with energies up to 5 GeV, in a stable and consistent manner. Additionally, such stable operation and consistent acceleration must be maintained while operating continuously at high repetition rates for extended periods of time. Significant work is being carried out to optimise the acceleration process, as well as on the production of targets compatible with repetitive operation at such rates, including studies up to the kHz range [4]. Beyond the production of improved target systems, a stable laser-based accelerator will also require the laser system to remain stable for extended periods of time.

There are several elements that can affect the evolution of a laser system, including changes in humidity or temperature of the room, or the long-term evolution of the laser pumps, which have a direct impact on the energy and direction of propagation of the laser beam. In addition to these, the effects of the heating of optical elements along the beamline in the case of systems operating at high repetition rates has recently attracted significant attention. In particular, given the high intensities reached on the compressor of systems based on chirped pulsed amplification (CPA), the effects of heating of the gratings responsible of the final pulse compression producing the ultra-short pulses on the beam properties are being actively analysed, including studies on the spatial and temporal evolution of systems operating at 5 Hz [5]. These effects are expected to become more relevant as the repetition rate is further increased.

Here we analyse the long-term evolution of a high-power (45 TW), commercial laser system operating at 10 Hz through a 6-hour period, particularly the evolution of the energy, pointing, and wavefront of the laser beam.

2 Experimental Setup

The experiment was carried out at the Laser Laboratory for Acceleration and other Applications facility (L2A2, Universidade de Santiago de Compostela), by employing the high-energy beamline of the STELA (Santiago TErawatt LAser) system, a Ti:Sapphire laser providing ultra-short (τ = 30 fs, Full-Width-at-Half-Maximum) pulses with an energy per pulse of $\sim$ 1.2 J and a peak power of 45 TW, central wavelength $\lambda = 800$ nm, high contrast ratio (>10^{10} at 5 ps), and operating at a repetition rate of up to 10 Hz.

In order to fully characterise the stability and long-term evolution of the different laser parameters, a number of diagnostics is distributed throughout the system, including the laser chain, compressor, and target area.

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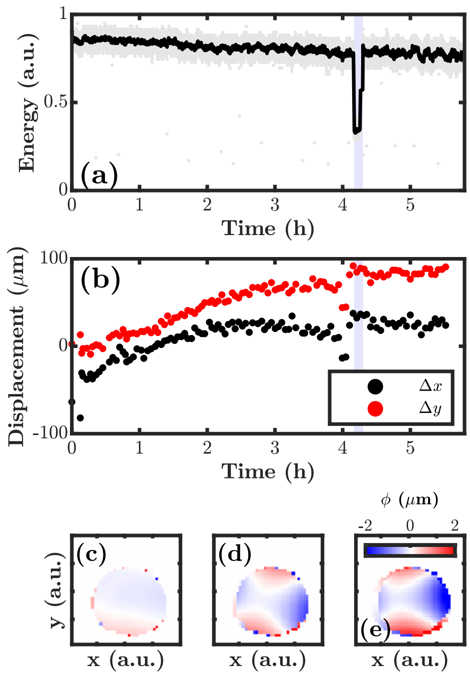

Figure 1. Evolution of the laser parameters. **(a)** Evolution of the laser energy. **(b)** Drift of the far field. **(c-e)** Wavefront of the laser beam after operating the laser for a period of (c) 45 min, (d) 1.5 h, and (e) 5.5 h.

The compressed beam is characterised using the leak through one of the mirrors inside the compressor vacuum chamber. The leaked beam is then propagated passing through a *BK7* window, and de-magnified ($M \sim 1/5$) using a pair of metallic spherical mirrors ($f_1' \simeq -200$ mm, $f_2' \simeq 800$ mm). The resized beam is then subsequently divided using a range of beam-splitters and propagated to a full suite of diagnostics, namely a calorimeter for energy characterisation, SPIDER system for temporal characterisation, a HASO Shack-Hartmann camera to characterise the beam wavefront, a spectrometer for spectral characterisation, and a far-field and near-field diagnostics to characterise the pointing and spatial profile of the laser beam.

Following compression, the high-energy beam is propagated into target area through an 8 m vacuum pipe. The beam is attenuated by a factor of $\sim 10^{-4}$ using a pair of uncoated dielectric wedges, and subsequently focussed using an $f/3$ off-axis parabolic mirror. The focal spot is characterised using a long working-distance microscope objective, imaging the focal plane onto a CMOS camera with a magnification of $M \simeq 220$. Additionally, the beam pointing and energy reaching the target area are measured using the leak passing through the one of the attenuating wedges.

3 Results

3.1 Energy

The evolution of the laser energy is shown in Fig. 1(a). Overall, the energy was found to remain stable throughout the 6-hour measurement, albeit exhibiting a slowly-decaying trend. In this case, the total energy drop was ~ 20 mJ, equivalent to an energy degradation rate of 0.33% of the total laser energy per hour of irradiation. It should be noted that the the brief drop in energy observable in Fig. 1(a) for a time ~ 4.15 h corresponds to a failure and recovery of one of the laser pumps.

In addition to the steady loss, the energy is found to exhibit an oscillatory behaviour with a characteristic periodicity of 9 minutes. Such temporal evolution is speculated to correspond to temperature oscillations in the laser area.

3.2 Pointing

The pointing of the laser beam was characterised at different stages throughout the laser system. The evolution of the pointing in the case of the compressor leak is shown in Fig. 1(b). A significant drift in the direction of the beam is observed, particularly along the vertical direction. It should be noted that this drift is not observed when the pump energy in the amplifiers is reduced, lowering the total energy contained in the high-power pulse, which indicates that such a drift would be associated with the heating of optics along the beamline, particularly the heating amplifier crystal or the compressor gratings.

3.3 Wavefront

The phase shifts of the beam wavefront at different times of the run are shown in Fig. 1(c-e). Such shifts are observed to be continuously increasing, with a tendency to introduce a phase that closely matches the phase for a vertical astigmatism. The phase shift is only observed to appear when the laser operates at full power, which indicates that it would be associated to the heating of optical elements, as previously reported.

4 Conclusions

The long-term evolution of a high-power laser system operating at 10 Hz through a 6-hour period has been studied, particularly the evolution of the energy, pointing, and wavefront of the beam. The energy is found to remain sufficiently stable throughout the run. The beam pointing evolves significantly, potentially associated to the heating of the compressor gratings. Also related to the compressor heating, the wavefront is found to evolve significantly, showing the appearance of a phase related to vertical astigmatism. These measurements highlight the need for closed-loop correction systems to ensure the stability of high-power laser systems, particularly in the context of demanding applications such as laser-plasma accelerators.

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