6th Asia-Pacific Conference on Plasma Physics, 9-14 Oct, 2022, Remote e-conference

Towards high-quality LWFA operation with a Petawatt laser

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After having operated stable laser-wakefield accelerators at the initially 100-TW class ATLAS laser system for the last two decades[1-4], including several major system upgrades, we were confident that our recent upgrade to several PW peak power would hold no surprises for the LWFA stability and performance. However, after the commissioning of the PW laser system we experienced dramatic instabilities in the LWFA performance, whose origin was not clear from the beginning. Despite seemingly very good laser performance (shot-to-shot energy fluctuations <1%, Strehl ratio >0.93, compressed pulse duration <1.05 x transform limit, ASE contrast >1010), and a fully enclosed laser table and stable temperature, the LWFA energy stability never fell below 10% rms.
With a 9-cm beam diameter and an optical path length of >100m in the last two amplifiers alone, the susceptibility of a PW laser system to air turbulence is much higher than standard 100 TW systems with amplifier beam sizes of 2-3 cm and 10-m path length. Such fluctuations lead to minute shot-to-shot wavefront aberrations that, while leading only to few-percent intensity variations in focus, causes >20-percent intensity variations approx. one Rayleigh range before focus. Here, the intensity is already high enough to trigger self-focusing in the entrance gradient of typical plasma targets such as gas jets. A shot-to-shot varying morphology of the intensity pattern in this intermediate field thus causes strong variations in beam propagation and self-focusing behaviour.
We take a many-pronged approach to mitigate such effects. On the side of the laser, great care is taken to remove or actively cool all potentially heat-emitting devices on the laser table, such as cameras, power supplies etc.. Secondly, the amplifier enclosure is split up into many separate compartments in order to break down large convection cells. All these measures were not necessary in our previous 100-TW system.
Moving from an f/25 focusing system as in our 100TW system to f/50 helps to overcome the problem of seeding the self-focusing behaviour from the intermediate field, at the expense of a much less compact setup and more pointing jitter. Using a sub-aperture beam of 20 cm after compression instead of the full 30 cm seems to avoid some of the edge aberrations of the gratings that cannot be corrected by our 3-mirror adaptive optics system. While this comes at the cost of reduced energy, this is less of a problem if the system used below its maximum power.
On the target side, strategies for a stable, jitter-free injection are employed to reduce the influence of varying self-focusing performance due to the laser-induced instability. This involves the use of an optically field ionized planar shock wave with a negligible position jitter, as opposed to the hydrodynamic supersonic shock used previously[2]. New gas jet designs are currently being studied with a focus on short entrance gradients and minimized gradient in flow direction, which would refract the laser away from a straight propagation.
One of the largest remaining obstacles is the residual beam pointing, mainly caused by vibrations of the building infrastructure (air conditioning, pumps). Here we are currently working on strategies to actively stabilize the beam pointing at the 10-cm beam size level towards >100 Hz by active load balancing in a piezo-controlled mirror as well as predictive position estimation.
Finally, we are developing single-shot methods for measuring the wavefront and spatio-temporal couplings of the beam in order to learn more about minute fluctuations of the laser field. Their precise knowledge is a prerequisite for developing viable strategies for full beam stabilization.

References
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