Journal of Physics: Conference Series

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To cite this article: L.A. Gizzi *et al* 2019 *J. Phys.: Conf. Ser.* **1350** 012157

10th International Particle Accelerator Conference IOP Publishing
Journal of Physics: Conference Series **1350** (2019) 012157 doi:10.1088/1742-6596/1350/1/012157

Lasers for Novel Accelerators

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Abstract. Novel accelerator schemes are rapidly emerging in the wake of laser-plasma acceleration research and involve advanced high-power laser drivers for their operation. Significant progress has been made in laser performance during the past decade, including repetition rate, average and peak power, and footprint, making these systems attractive for many applications, including novel accelerators. Here we discuss laser driver requirements for the proposed novel accelerator schemes, examine emerging technologies and introduce a viable laser driver concept for a first generation of plasma accelerators.

1. Introduction

After two decades of dramatic developments in laser-plasma acceleration [1,2,3,4,5] following the original idea of Tajima and Dowson[6], enabled by the invention of CPA lasers [7] and the diffusion of high ultrashort pulse lasers worldwide [8], record electron energy in the lab is now approaching the 10 GeV [9]. As a consequence, concepts for a new generation of industrial, high gradient accelerators based on highly advanced laser-plasma acceleration schemes are emerging rapidly.

Among these, the European H2020 project named EuPRAXIA[10] aims at the realization of a European Plasma Research Accelerator with eXcellence In Applications and is delivering a conceptual design of a plasma based electron beam accelerator to final energies between 1 and 5 GeV, with bunch duration of a few fs, transverse emittance of about 1 mm-mrad and relative energy spread reaching from a few % down to a few 10^{-3} total and few 10^{-4} in a 1 micro-meter slice of the beam. The EuPRAXIA specifications [11] approach the regime of modern X-ray free-electron lasers (FELs) and fulfil basic requirements for a 5 GeV plasma accelerator stage of a linear collider.

The EuPRAXIA concept, like other similar programmes world-wide, builds upon ultrashort pulse laser drivers [12] with kW average power and up to petawatt-scale peak power, with a repetition rate ideally up to 1 kHz and beyond. Such laser systems are not currently available, but the scenario for enabling technologies is evolving rapidly. Indeed, new architectures are emerging with the promise of addressing medium and long-term objectives of laser-plasma acceleration and future plasma-based particle colliders. Scaling the technology of existing high peak power lasers to higher average power, while maintaining key technological performance requirements, is challenging and required high average power pump laser sources. Pulsed high energy solid state lasers have demonstrated continuous operation at 100J scale energy per pulse and repetition rates up to 10 Hz, like the DIPOLE laser [13] and the industrial P60 [14]. Solid-state lasers with peak power in the petawatt class and pulse energies exceeding 10 J have reached an average power of tens of watts, like the BELLA system [15], with HAPLS aiming at 300 W[16]. It is therefore clear that a one order of magnitude or higher improvement in the average power of ultrafast lasers is needed to meet laser requirements for novel plasma accelerators.

2. Technology paths

Motivated by endeavours like the kBELLA project (LBNL, US)[17] and also by EuPRAXIA [10], new concepts are emerging which are now entering the design and prototyping demonstration phase for intermediate average power levels and may offer solution for kHz and higher rep-rate systems. Depending on the required laser parameters, the time to construction and the expected performance, several approaches can be identified starting from laser technologies currently available and evaluating their scalability to the required specifications. In the following, a brief description of the leading technologies is given, sorted according to their efficiency, outlining pros and cons in the perspective of designing a driver for a laser-plasma accelerator.

2.1. Titanium Sapphire

Currently used in almost all the laser-plasma acceleration laboratories and facilities, Ti:Sapphire based technology is certainly the most advanced and mature. Featuring a broad gain bandwidth, Titanium doped Al_2O_3 (Ti:Sa), allows for the amplification of a few tens of fs pulses. It is therefore perfectly suited for the laser pulse duration targeted by current LWFA driver parameters, at a wavelength of about 800 nm. On the other hand Ti:Sapphire must be pumped in the visible, typically between 500 and 550 nm, commonly obtained by frequency doubled Q-switched Nd:YAG lasers. The wall-plug efficiency of the whole system is usually quite low, in particular when flash lamp pumped Nd:YAG lasers are used. Moreover, the high (~ 34%) quantum defect between the pump and the fluorescence photon energy imposes a high thermal load on the gain medium. These elements make the operation at high average power quite challenging. Replacement of flash lamp, with diode-pumped solid state (DPSSL) lasers provides a significant improvement in wall-plug efficiency, with major European industrial endeavour in place. In very recent years, demonstration of innovative concepts and the construction of DPSSL prototypes are leading to kW average power pump lasers, possibly scalable to multi-kW [13,14].

The lack of diode pumps capable of pumping directly the Ti:Sa, forces us to use diode-pumped Nd lasers. This double-step impacts on the overall efficiency of the system, eventually limiting further scalability. Also, high-energy laser systems will require large aperture gain elements and, since Ti:Sa can only be produced as a single crystal, the size of the gain element is another limitation.

2.2. Direct Pumping Chirped Pulse Amplification

Other technologies are developing which aim at more efficient configurations removing the double-step in the pumping architecture, with direct pumping of the ultrafast amplifier with diodes. This is a mandatory step to deliver higher repetition rate and higher average power levels. Direct Chirped Pulse Amplification using lasing media that can be pumped directly with diodes offer an ideal alternative solution for higher efficiency and higher rep-rate. Direct CPA concepts under consideration have been explored in detail and some issues have been identified, including the minimum achievable pulse duration and the scaling of listed architectures.

Examples of Direct CPA are Yb based systems like Yb:YAG and Yb:CaF_2: with respect to the Ti:Sapphire, Yb based gain media have many advantages in terms of pumping efficiency:, they allow direct pumping by semiconductor lasers at 930-970 nm, without further wavelength conversion stages. Moreover, the quantum defect between the pump photon energy and the laser photon energy is rather low (around 10%) because the emission wavelength (usually 1030-1050 nm, depending on the host) is close to the pumping wavelength. This reduces the thermal load on the gain medium and thus the power dissipation requirements. Both these elements are advantageous for a high average power operation regime.

The main drawback of the Yb-based gain media is the reduced gain bandwidth, that makes it difficult to achieve pulse duration of 100 fs or less for high-energy pulses, whereas operation in the range 100-200 fs is more easily achieved. Another potential drawback is that in Yb doped media the saturation fluence of the laser transition often largely exceeds the damage threshold of the host so that amplification stages cannot operate in saturation. Finally, several hosts allow doping with Yb, and this provides some flexibility in the choice of the gain media parameters (e.g. emission spectrum, but also thermal conductivity and thermo-optical parameters). Besides, several hosts can be fabricated with ceramics technologies, which can more easily allow large gain elements.

Another promising concept of direct CPA, with enhanced potential performance at very high rep rate is based on the Tm:YLF gain media which offers significant lifetime advantage over the well-established Yb doped materials traditionally used for diode pumped fiber and bulk systems. When operated in the multi-pulse extraction, it is as efficient at >70% at rep-rates > 1 kHz, while at 100 Hz is still capable of ≈ 20% efficiency. Among the host materials, YLF offers several attractive properties, including a negative dn/dT, low linear and nonlinear refractive index, and natural birefringence. The Tm dopant in YLF emits laser radiation at ~1.9 μm, and has a long upper-state lifetime (15 ms). It can be pumped with commercially-available, technologically-mature, high-brightness CW laser diodes at 800 nm. Also, Tm:YLF is commercially available in boule sizes consistent with 300 kW average power operation of a 30J compressed at 10 kHz or up to 160J at lower repetition rates [17].

Another robust and well established architecture is based on Nd:glass. Some high energy systems adopt Nd:glass as gain medium for the final power amplification stages. Nd-doped glasses provide a gain bandwidth suitable for the generation and amplification of pulses in the 100 fs time range. Large gain elements can be produced with glasses more easily than with crystal growth technologies. Moreover, Nd:glasses can be directly pumped with diode lasers, which is advantageous for the overall efficiency and power dissipation requirements of the pump system. On the other hand, even though the thermally dissipated pump power fraction is moderate (around 20%), the operation at high average power levels of Nd:glass bulk amplifiers is limited by the poor thermal conductivity of the glass host.

An additional alternative method for the amplification of high peak power pulses is based on parametric light amplification in nonlinear optical crystals, namely Optical Parametric Chirped Pulse Amplification (OPCPA) [18,19]. Instead of using ordinary laser media based on the excitation/de-excitation of an atomic transition, the amplification is based on optical difference frequency generation in nonlinear crystals. With respect to standard amplification, OPCPA has several specific features that can be potentially advantageous: first, it can reach a very high amplification factor of chirped pulses: up to 3-4 orders of magnitude per pass in terms of energy. Moreover, the parametric gain exists only when the pump pulse is present, so that the amplification process inherently acts as a temporal contrast gate, enabling high temporal contrast pulses. Finally, the process is non dissipative, because the energy difference between the pump (highest energy) photon and the amplified signal (lower energy photon) is emitted as a third photon (the so called idler) and it is not dissipated into the crystal, as it happens in stimulated emission process. Therefore, the parametric amplification process imposes a much lower thermal load on the amplified medium with respect to the amplification based on the emission from atomic transitions. The amplification of high energy pulses requires large aperture crystals: this limits the choice of the possible nonlinear materials, mainly to KDP, DKDP and LBO.

2.3. *Other concepts*

Finally, a very promising approach that has attracted a major attention for its potential compactness and the strong link with the industrial world of telecommunications is based on Fiber laser technology, which is currently offering the best wall-plug efficiency for a laser, now exceeding 50% in CW mode. For high peak power architectures, solutions based on the coherent combination [20] of a very large number of fiber amplifiers is being developed and prototype developments are in progress. Studies show that this technology is really optimized for repetition rate of 10 kHz and above and will be particularly suited and cost-competitive if laser driver parameters are going to evolve towards small energy (J level) per pulse and higher repetition rate (>1kHz).

3. Industrial driver

In the perspective of a short term approach, a driver for a plasma accelerator capable of outstanding parameters, like those required by the EuPRAXIA laser, should be based on components with a high Technology Readiness Level, ideally sourcing from a lab environment where specific technology have been explored in depth. Ti:Sa technology is certainly an excellent platform that leads to the required specifications by scaling existing systems. As anticipated, scaling still requires innovative solutions for high repetition rate, DPSSL pump lasers and thermal management in both the amplifier and the whole transport chain from the compressor to the target plasma.

As anticipated, kW scale lasers suitable for pumping Ti:Sa in the 10-20 Hz range repetition rate are just emerging with industrial systems like the P60 [14] or prototypes like the DIPOLE [13], and can be integrated in advanced Ti:Sa amplifiers design, provided a geometry with efficient cooling ensures heat removal from the amplifier head. This is an important conceptual aspect of laser design that has impact on both the complexity and the compactness of the final system. As shown in Fig.1, transmission and reflection geometries of the amplifier head are considered in this context.

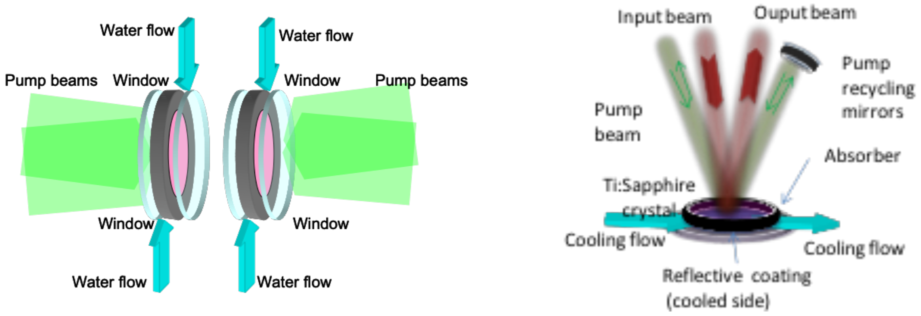

Figure 1: Possible conceptual configurations of an amplifier head, the core of a laser driver where efficient heat exchange between the gain material and the heat sink is crucial to enable high average power operation.

Indeed, in currently explored designs, heat exchange sets the limit of accessible average power to ≈1kW, leaving options for a 10 Hz system at 100 J per pulse. Higher repetition rate, namely 100 Hz at 10 J or possibly 1kHz at 1J pulse energy, are also possible, provided higher repetition rate, high power diode laser operation can be achieved. Also, a modest increase (2X) of the average power performance is accessible using multiple pump units simultaneously. This approach, while inevitably increasing the complexity of the pumping geometry, has the advantage of increasing the robustness of the driver operation against failure of individual components.

Higher rep-rate will require developments to increase the repetition rate of currently available high power diode lasers and to enhance thermal management in the amplifier head [21]. Yb:YAG and Yb:CaF_2 are both candidates as gain media, however major numerical modelling and experimental data is needed to demonstrate the path to commercial availability of diode pump sources needed for a reliable kHz driver.

4. Transport and stability

The general layout of the driver delivery to target plasma includes a number of components that ensure control and stability of the wakefield generation. Indeed, experimental studies are currently focusing attention of the role of driver beam quality, namely focal spot intensity distribution, energy and pointing stability, that are key factors behind the stability of the accelerated electron bunch.

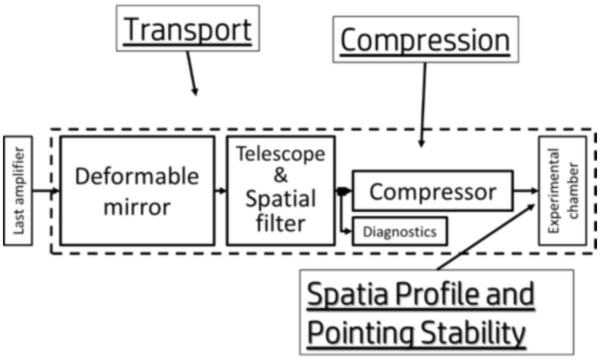

Figure 2: Schematic layout of the post-amplification section required to deliver the driver beam to the target plasma and to maintain control of the beam quality.

The block diagram of Fig.2 shows the main components required to gain angular, spatial and temporal control of the driver. Scaling these components to the beam size and average power currently required is a very challenging task that calls for a significant development. Spatial beam diagnostics in the focal plane are necessary in order to measure and improve the beam spatial quality, in a closed loop with the deformable mirror, and in order to estimate the beam intensity achieved during the acceleration experiment. Requirements on beam pointing stability are highly demanding, with pointing accuracy well below the μrad to ensure no impact on the pointing instability of the accelerated electron bunch, typically set by the acceleration process. Here a combination of pointing detector and active pointing control is envisaged in the full-scale implementation of the driver.

5. Conclusions

The first generation of high quality laser-plasma accelerator design is progressing rapidly and needs a new generation of ultrashort pulse laser drivers, with high average power and high stability. A range of candidate technology paths is being considered and will develop according to timescale for implementation and required driver performance. Evolution of widely explored Ti:Sa based system may provide viable short term solution for kW scale drivers with rep-rate up to the kHz, while higher rep-rate, high average power solutions will build on newer, more efficient technology and high efficient direct DPSS CPA laser technology.

6. Acknowledgements

This work was supported by the European Union‘s Horizon 2020 research and innovation programme under grant agreement No. 653782. LAG, LL, and PK also acknowledge financial support from the CNR funded Italian Research Network ELI-Italy.

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