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ABSTRACT

The activity of Task 6.2 Lasers for Plasma Acceleration (LASPLA) was dedicated to the study of recent developments in the field of laser technology relevant for the development of laser drivers for plasma accelerators. This is a very active field of research with several companies and research institutes and groups delivering new results at a fast pace. This scenario emerged clearly during the IFAST **Workshop on *Laser Drivers for Plasma Accelerators*** held on 20-23 of April 2022 at the Ecole Polytechnique (Palaiseau, France) and more recently at the ***LASPLA Laser Technology* Workshop** held on 19-22 of September 2023 in the framework of the 6th EAAC 2023 at Elba, Italy. In these workshops organized by LASPLA, several leading groups presented updates of their recent work with major progress towards solutions of the main technological bottlenecks identified so far for high average power ultrashort pulse lasers. Based on these developments, effort is ongoing for the technical development of even more efficient and scalable novel laser architectures including efficient high repetition rate laser drivers tackling, among the others, 100 Hz Ti:Sa architectures, pump lasers, amplifier modules, and optical compressor technologies as well as novel approaches to efficient kHz technology including post-compression of industrial, kHz ps pulses at 1μm and amplification of 2μm pulses with Thulium-doped gain media. These activities will strengthen the knowledge base of laser technology setting strategic pathways for future laser-drivers for plasma acceleration.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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1 Introduction

The use of lasers as power drivers for plasma accelerators has been emerging dramatically in the past decades, not only for the well-known effectiveness in exciting and driving plasma waves, but also for the fast-developing technologies that lead to the continuous improvement of lasers in terms of performance and specifications. Beyond that, entirely new technologies are also maturing, with specifications significantly more advanced than those of the lasers originally used in the context of pioneering laser-driven acceleration experiments, opening up the perspective for the delivery of viable drivers for industrial grade plasma accelerators.

Laser-plasma accelerator systems are currently based on PW-scale peak power lasers, with ultra-short pulse duration, down to 30 fs or less, and an energy per pulse up to 100 J, at a repetition rate for user applications up to 100 Hz and above. Such laser specifications in terms of repetition rate and average power, are beyond current industrial capabilities, limited to a few tens of Watts, with the most advanced scientific systems now in the 100 W range. Baseline laser systems relies on Ti:Sa technology, ideally with pump lasers featuring diode pumping. The demanding specifications of pump lasers for Ti:Sa amplifiers, requiring nanosecond pulse duration and relatively short wavelength, are a challenge for the scalability of this technology. The possibility of scaling plasma acceleration further to meet particle physics needs requires higher efficiency, beyond the capabilities of Ti:Sa established technologies, thus calling for new solutions. Several different approaches, based on entirely new concepts, materials and architectures, need to ne developed to overcome fundamental limitations of present laser systems in terms of wall-plug efficiency, compactness and, ultimately, average power. Here we recall recent strategic advances in both high average power Ti:Sa technology and other platforms that are being developed for longer term, higher efficiency solutions.

Currently available on-the-shelf technology is mainly based on flashlamp pumping and is limited to a few tens of Watts average power and Hz-level repetition rate. Remarkably, new approaches based on robust solid-state diode laser pumping technologies are already emerging as powerful alternative solutions to overcome such limitations. Planned laser-based plasma accelerator infrastructures, like the laser-driven pillar of the EuPRAXIA infrastructure, rely on multi-kW average power, petawatt peak power, ultra-short pulse laser systems with ultra-short pulse duration, down to 30 fs or less, combined with an energy per pulse up to 100 J at a repetition rate for user applications up to 100 Hz and beyond. Scaling existing systems to kW average power still requires innovative solutions, including the transition from a flashlamp pumping to the efficient, fully diode pumping, and sustainable thermal management in both the amplifier and the whole transport chain, from the compressor to the target plasma.

LPA platforms currently rely on Ti:Sapphire-based (Ti:Sa), the most advanced, commercially available solid-state, high peak power, high intensity laser amplification technology. Ti:Sa is developing fast towards high-average-power amplification and holds the promise to deliver revolutionary performances. Ti:Sa technology is currently extensively used in the HAPLS system at ELI-Beamlines and in the EPAC system at UKRI, two of the four candidates to host for the EuPRAXIA laser-driven site. HAPLS delivers today’s highest available average power of 100 W and aiming at 300 W. At the same time, Optical Parametric Chirped Pulse Amplification (OPCPA) also promises to deliver high average power, high efficiency systems that are close to demonstration at pulse energies relevant for GeV scale electron laser-plasma acceleration.

In both Ti:Sa and OPCPA, the availability of high quality, high average power, efficient pump lasers is a crucial requirement. Existing architectures, feature multi-slab with gas cooling that cannot be easily scaled to the required heat removal capacity for multi-kW-scale systems. Possible solutions include the use liquid cooling in place of gas cooling, requiring a major effort in counteracting the depletion of beam quality stemming from propagation through a non-uniform, refractive material, or implementing alternative cooling concepts to avoid propagation through the cooling liquid, like the “active mirror” concept. Both pumping schemes and cooling architectures are key aspects of the laser design that have an impact on both the complexity and the compactness of the final system. The industrial delivery of these technologies requires significant increase of the TRL, especially for amplifier modules, high brightness diode pumping systems and main transport sections, from the compressor down to the interaction point.
On the path to higher efficiency and higher repetition rate, new directions are emerging that exploit either existing industrial thin disk picosecond Ytterbium (Yb) based systems or new Thulium (Tm) doped gain materials capable of broadband amplification and suitable for direct diode laser pumping. Industrial Yb:YAG thin disk picosecond systems are a potential breakthrough as kHz drivers in combination with either plasma modulation techniques or non-linear broadening and post compression to reach tens of femtosecond and multi-TW regime. Among Tm doped materials, crystalline (YLF) or polycrystalline/ceramic (sesquioxides) media offer unique potential for efficient, scalable, very high repetition rate and average power.
In view of these required developments, a shared strategic approach is needed putting together major laboratories with a leading role in these areas of development, together with industrial partners.

2 Pillars of strategy

2.1 LASPLA APPROACH

Current laser technology has advanced significantly on peak power and this is enabling frontier science. At the same time it is lagging behind significantly in terms of average power and wall plug efficiency, limiting industrial and practical uses. Laser-plasma acceleration in the current definition has been scientifically demonstrated 20 years ago. In spite of that, at the moment, there is not yet established industrial or clinical application, mainly because of the lack of maturity of laser technology at high average power. On the other hand, a number of startups and spinoff initiatives looking into these applications are emerging, looking for industrial laser-driver solutions capable of kilohertz operation with multi-joule energy per pulse, compactness and wall plug efficiency able to cope with power drivers of conventional accelerator technologies, while providing higher electron energy for example, high flux x-ray sources using either betatron or Thomson scattering. In parallel, medium and large scale user facilities based on laser-plasma acceleration are implementation and rely on even higher quality and efficiency. As shown schematically in Figure 1, LASPLA approach is to consider two pathways, possibly to be developed in parallel, one aiming at exploiting existing industrial technology to fulfill the short-term goal of establishing laser-plasma accelerators technologies for applications and the other to set the conditions for future goals high repetition rate and efficiency.
Industrial Ti:Sa technology is currently the preferred platform for laser-plasma accelerator development, that can lead to the specifications to support applications and establish the first

generation of user facilities based on laser-plasma accelerator systems (e.g. EuPRAXIA). Advanced schemes, alternative to Ti:Sa, include OPCPA, direct diode pumping of new gain materials like Tm doped crystals and ceramics and coherently combined fiber lasers. These longer term developments are required to address the higher specifications, primarily in terms of repetition rate and energy efficiency, of future, high performance accelerator systems.

The activity of the LASPLA Task, including the LASPLA *Laser Technology* Workshop held on 19th, 20th and 22nd of September 2023 in the framework of the 6th EAAC 2023 at Elba gave the opportunity of an update on several of these topics directly from leading labs and companies in the framework of user facilities developments, like EuPRAXIA (EU), EPAC (UK), ILIL (Italy), CLPU (Spain) and ELI-ERIC (Prague) and other national initiatives like the Kaldera (Germany) or kBella (USA). Here we focus on some of these technologies, primarily solid state lasers, and we identify the main strategic development pillars.

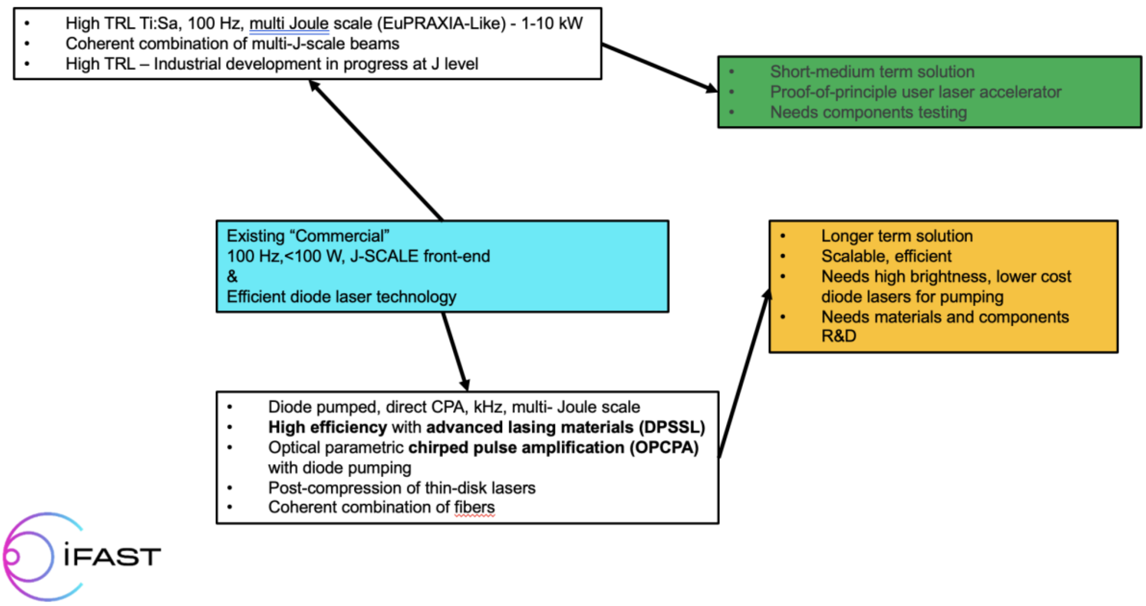

Figure 1. Schematic view of the LASPLA strategy for development of laser drivers for plasma accelerators identifying two possible development paths.

2.2 Recent progress in Key Technologies

One of the challenges in the construction of higher repetition rate, multi Joule, Ti:Sapphire amplifiers is the development of effective cooling methods to manage the high thermal loads in amplifier heads. Another key challenge is to field pump sources ensuring high (multi kW) average power, 24/7 operation reliability, compactness and high wall plug efficiency. Yet another challenge is to control and compensate for heat load and stability on the entire laser driver chain, from seed oscillator to plasma target. These are the most critical blocks of the entire architecture of laser drivers for plasma acceleration based on ultrashort Chirped Pulse Amplification. Here we describe status and limitations following a path of development established over the past years in the framework of infrastructures and lab developments with common goals and complementary approaches.

2.2.1 Cooling architectures

Indeed, liquid cooling of multidisks is the key enabling technology for high rep rate PW lasers being developed also by laser companies (e.g. Amplitude Technologies and Thales Las) to address 100 Hz repetition rate for both pump lasers and Ti:Sa heads. At the same time, pump laser units developments aim at 3-10 J pulse energy, 100 Hz @532nm (upgradable 200-500Hz). Pump lasers use multidisk Nd:YAG diode-pumped heads with longitudinal liquid cooling in a modular architecture. These units are also compatible with OPCPA pumping. The current status includes laser head validation with consistent gain & gain homogeneity, cooling efficiency and low wavefront distortion. These developments also include implementation of passive wavefront compensation using SBS mirror which has demonstrated 95% reflection measured up to 120 J input energy. Future developments include >10J laser assembly and commissioning, with operation planned for 2026. Similarly to pump lasers, Ti:Sa heads also exploit liquid cooling of multidisks. Water cooling is used with longitudinal heat extraction. The development includes modular architecture with 4 to 40 J energy and 100 Hz PW compressor technology relying on MLD gratings technology already mastered kW Yb lasers. Crucial for these developments is the extensive use of active stabilization of critical stages based on diagnostics and metrology fully integrated in the control system.

2.2.2 Pump lasers

Progress in pump laser development is also emerging from ongoing developments (e.g. DIPOLE programme at STFC). The DIPOLE is used as pump laser for the EPAC system. Dipole is a multi-slab cryogenic gas-cooled Yb:YAG amplifier technology, at 1030 nm wavelength, with 1 or 10 Hz operation, 75 mm square beam, 15 ns pulse duration, pulse shaping capability. Phase 1 foresees 120 J output (Wojtusiak *et al*, Proc. SPIE 12577-07, Photonics West (2024)), while Phase 2 is aiming at 200+ J output. Currently, Yb:YAG slabs are pumped by 350J, 1ms (350kW) @ 940nm at 10Hz, using Coherent diode lasers units. DIPOLE 100 Hz repetition rate is also being pursued after the successful operation at 10 Hz and 100 J per pulse. In fact, DiPOLE-100Hz is a nanosecond, diode-pumped Yb:YAG was originally designed (M. De Vido *et al*., "Design of a 10 J, 100 Hz diode-pumped solid state laser," Advanced Solid State Lasers, JTu3A. 14 (2019) for future 100 Hz laser drivers for plasma accelerators. Stable operation of 100 Hz operation was indeed demonstrated recently (M. De Vido *et al*., "Demonstration of stable, long-term operation of a kW-class nanosecond pulsed DPSSL operating at 10 J, 100 Hz," Optics Express 32(7), 11907-11915 (2024)), showing 25.4% optical-to-optical efficiency for ~300,000 shots @ 10 J and ~1.5M shots @ 7J, showing 1% rms energy stability. Joule-class diode-pumped Nd :YAG lasers operating at repetition rate from 100 Hz to 500 Hz (THEIA product) have been developed by Thales (N Bruel & al - Europhoton conference 2024 - https://doi.org/10.1051/epjconf/202430704050). The frequency-doubled version can deliver an output energy of 750 mJ per pulse at 532 nm. Their development dedicated to industrial applications with 24/7 operation and high availability requirements make them particularly suitable for the laser-driven plasma accelerators concepts.

2.2.3 High Quality Front-end

Development of high quality front-end systems for Ti:Sa is another important part of a laser-driver systems. A reference front-end system has been designed for the EuPRAXIA infrastructure and is currently under implementation for the ILIL system at CNR-INO based on the most established industrial-grade technology, incorporating high contrast, ultra-short pulse duration <20 fs operation at 100 Hz. Further advances in high performance front-end are being pursued in the framework of similar projects like the Kaldera project at Desy, where an OPA seeded (T. Eichner et al., Opt. Express 31, 36915 (2023), T. Hülsenbusch et al., Opt. Express 32, 23416 (2024)) system has been demonstrated with auto-tuning capabilities for reproducible working points using machine learning (T. Eichner et al., Opt. Express 31, 36915 (2023)). Additional important development at Kaldera includes the implementation of multi-layer gratings in an out-of-plane geometry, with verified concept at low energies. These studies show that this compressor configuration has a sufficient bandwidth to support 25 fs pulses (C. Werle et al., Opt. Express 31, 37437 (2023)), with LIDT tests showing promising performance. In addition of the XPW/OPCPA front end developed some years ago for multi-PetaWatt lasers (ELI-NP), Thales has more recently developed a new OPCPA-based front end where the pump laser is built from the initial 800 nm beam stretched to picosecond duration, then amplified and frequency-doubled to 400 nm to pump OPCPA stage. Output of such OPCPA frond end rises up to several hundreds of microJoules and has been used to seed a 100 Hz TiSa CPA delivering 300 mJ amplified pulses. Such pulses have been compressed at reduced energy and temporal contrast measurements show values better than 10^{-8} at 10 ps, 10^{-10} at 30 ps and 10^{-11} at 100 ps before the main pulse (paper in preparation).

2.2.4 100 Hz Ti:Sa Technology

Ti:Sa technology is rapidly evolving towards 100 Hz repetition rate, with increasing average power and increasingly exploiting diode pumping. Besides the milestone HAPLS system at ELI, featuring PW peak power and 3.3 Hz repetition rate with 10 Hz target value, fully diode-pumped industrial products are entering stadily in the 100 Hz repetition rate with J-scale performance. Several such systems are being commissioned at labs with LPA programmes, especially for the delivery of repetitive operation of 100 MeV scale electron accelerators for radiotherapy applications (e.g. ILIL (Italy), LAPLACE (France)). Development of these systems is providing the enabling laser-driver technology for the first generation of user-oriented laser-plasma accelerators. An alternative path to 100 Hz operation is based on the use of few-cycle (<10 fs) systems where repetitive operation with mJ pulse energy is established, including target and diagnostics management. An example is the few-cycle beamline of the 100 Hz system at University of Szeged that is being developed in line with operation for a secondary source facility (P. Gaal et al., Appl.Sci. (2024)). These are crucial steps towards the establishment of all the required blocks that will then need to be up-scaled for EuPRAXIA operation or other similar user infrastructures. In this context Thales has developed a new technology of backside-cooled TiSa active mirror amplifiers. Thanks to this geometry, thermal lensing within TiSa crystals can stay at moderate values even at room temperature under high average power pumping such as 150 W green (focal length staying above 5 meters). 300 mJ amplifiers have been successfully built and successful laboratory demonstration of 850 mJ amplified output from a single disk (250 mJ input) is the prequel of an ongoing development which aims to lead in 2025 to the amplification up to 1.5 J at 100 Hz in order to deliver compressed pulses of 1 Joule. In order to ensure proper operation of the compression, techniques of active cooling of gold-coated gratings have been successfully tested demonstrating limited temperature rise under substantially high thermal loading while keeping an adequate wavefront quality.

2.2.5 Diode laser technology

The development of efficient pump lasers for Ti:Sa requires high efficiency diode lasers. Indeed a key diode laser pump challenge is now the delivery of affordable 100 Hz diode laser technology. Existing industrial solutions are capable of delivering diodes with coolers efficiency limiting to 10 Hz repetition rate. At this level of performance, current large scale, economic industrial solution relies of products available from key producers and vendors including Trumpf, Leonardo, Coherent. Other vendors from UK include Jenoptik, Lumibird, Monocrom while competitive vendors from Asia include Hamamatsu, Focuslight, Everbright. Existing milestone projects include DIPOLE, with 940 nm pump diodes from TRUMPF for Yb:YAG, and HAPLS with 870 nm pump diodes from Leonardo for Nd:YAG. For higher repetition rate, say 100 Hz, other solutions solutions exist from research, as those delivered by FBH, but these are currently very expensive. Industrial solution are similarly very expensive and are limited to 2 kW at 100 Hz (De Vido M. et al., Proc SPIE PC12399, PC123990C (2023)). Developments of less expensive solutions are being investigated also in response to the increased interest for laser-driven fusion that would require a massive use of diode lasers. TRUMPF is funding internally research in this field (T. Barnowski *et al.* Proc SPIE 12867 1286713 (2024)). Similarly, studies concerning progress at λ = 940 nm to scale power, duty cycle and frequency (M. Elattar *et al.*IEEE J. Sel. Top. Qu. Electr. 31(2), 1500407 (2025), FBH Annual report 2023 / 2024) and progress at λ = 780...800 nm for compact kW-CW industrial modules H. Alder *et al.* Proc. 42nd International Congress on Applications of Lasers & Electro-Optics, Chicago, USA, Oct. 16-19 (2023) are being carried out at FBH. These studies will be boosted by the PACRI project that forsees activities focused on the development of 100 Hz and kHz diode lasers, for Yb:YAG and Tm doped materials, as well as direct diode pumping option for Ti:Sa.

2.2.6 Thulium doped gain media

Schemes based on Thulium doped materials lasing at 2 µm wavelength have been proposed as a promising ultrashort pulse laser platform, with high average power, high repetition rate for their potential high-energy storage capability (I. Tamer et al., Opt. Lett. **46**, 5096 (2021)) mainly because of the long fluorescence time, of the order of milliseconds, and the convenient pumping wavelength, just below 800 nm. These features enable diode pumping with industrial-grade systems and also operation in the so-called multi-pulse extraction regime (T.C. Galvin volume 11033, page 1103303,442 International Society for Optics and Photonics, SPIE,443 (2019)) at very high repetition rate. Recently, short pulse operation of Tm:YLF was also demonstrated (I. Tamer et al.,Opt. Lett. **49**, 1583 (2024)) with TW level peak power, confirming the potential of this platform. Thulium doped polycrystalline ceramic materials are also being considered as gain media due to their high thermal conductivity, scalability, cost-effectiveness and doping flexibility (V. Rastogi and S. Chaurasia, Photonics 11 (2024)). Among those materials, ceramic Tm:Lu2O3 along with other Thulium doped sesquioxides are being explored for their exceptional thermal conductivity, higher than that of any other laser material, suitable for relatively thick disk architectures (D. Palla et al., 156, 108524 (2022), G. Cellamare et al., Proc.SPIE, volume 11777, (2021). In spite of the large quantum defect set by the 2 µm lasing wavelength, Thulium doped materials can exhibit efficient cross-relaxation (CR), a mechanism in which the energy of excitation, initially taken by one ion, is partially transferred to a neighboring ion originally in the electronic ground state, leaving both ions in the upper laser level. While cross-relaxation has been observed in Thulium doped materials, the extent to which this mechanism can be exploited remains an open issue, raising the need for a more extensive experimental investigation. Recent studies of polycrystalline ceramic Tm:Lu2O3 with 4 at.% doping at ILIL (Italy) show that cross-relaxation is very efficient, with the cross-relaxation coefficient approaching 1.9 and leading to a slope efficiency well exceeding 70% (A. Fregosi et al., 2024). These recent results indeed confirm that Tm-based gain media can provide needed properties for a scalable laser-driver technology for plasma accelerators.

2.2.7 Exploitation of industrial kHz systems

Industrial Yb:YAG thin disk picosecond systems are a potential breakthrough as kHz drivers in combination with either plasma modulation techniques (J.J. van de Wetering, Phys. Rev. E 109, 025206 (2024)) or non-linear broadening and post compression (see for example Jaismeen Kaur *et al* 2024 *J. Phys. Photonics* **6** 015001) to reach tens of femtosecond and multi-TW regime, also with high contrast. This is a rapidly evolving field with multi-pass cell technology improving steadily. In this context it is worth mentioning that industrial products based on robust, kW average power Yb:YAG picosecond thin-disk technology is now being integrated with non-linear pulse compression technology to deliver femtosecond pulse duration at high repetition rate and high average power. Industrial lasers based on this technology is now being delivered by TRUMPF, based on gas-filled multipass cells and chirped-mirrors-based temporal re-compression, the TRUMPF Herz series is a nonlinear compression scheme to shorten the pulse duration of the Yb:YAG Dira picosecond kHz lasers to sub-40 fs and sub-J pulse energy. While scalability of this system is limited and higher average power would require significant effort, the available kHz performance, combined with the potential kW average power, is a unique working point for advanced LPA operation.

3 Planned strategic developments

3.1 Laser Development Pillars

The above outlined achievements clearly indicate important strategic directions of development for further advancing the performance of laser drivers for plasma acceleration. In view of this, LASPLA Task 6.2 contributed to conceive a coherent set of activities to contribute to both short term and medium-long term development paths outlind in Fig.1. These activities were successfully proposed for funding within several initiatives, including the recently proposed Plasma Accelerator systems for Compact Research Infrastructures “PACRI” EU Infratech project, that is gathering competences available at many of the major laboratories mentioned above, having a leading role in these areas of development, together with industrial partners, all with a consolidated track record of collaboration. Priority was given to tackle a number of open issues that hinder the further scaling of existing industrial Ti:Sa technology as outlined in Fig.2. To properly address these issues and also support longer term solutions, a number of key areas are hereby identified that represent strategic development pillars.

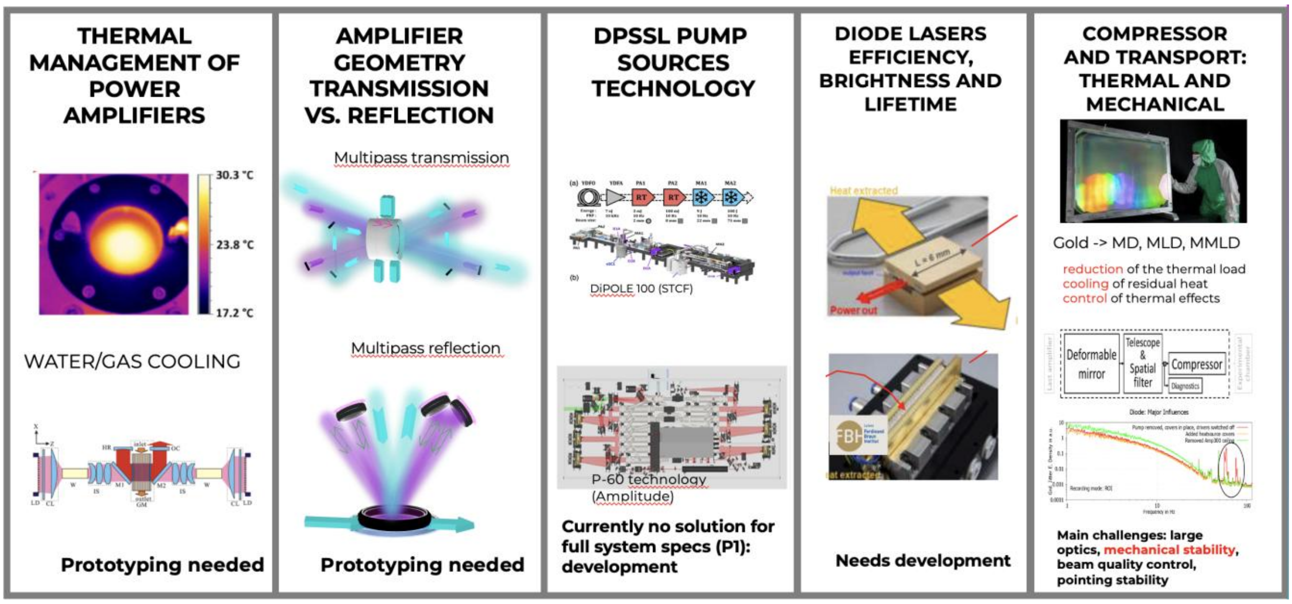

Figure 2. Pillars of the LASPLA development strategy for the development of laser drivers for plasma accelerators.

The accomplishment of these developments will provide technical solutions for the forthcoming laser-based infrastructures (e.g., EuPRAXIA) and will strengthen international competitiveness of user access to existing laser infrastructures (ELI) over the coming years.

3.1.1 Ti:Sa amplifier module development

The amplification of the pulses generated by the front end is based on chirped pulse amplification (CPA) in Ti:Sapphire pumped by frequency-doubled, solid-state Nd- or Yb-based lasers with an emission in the range of 515–532 nm. The basic amplifier configuration is like many of the systems operating worldwide, with the significant difference of the very high repetition rate of 20–100 Hz compared to the typical Hz or sub-Hz repetition rate of current petawatt systems. This results in high average pump power requirements, thus placing a severe thermal load on the amplification stages. Thermal load management is therefore the main driver in the design and construction of the amplification stages, in particular for the cooling strategy.

We foresee the use of established cooling schemes to extract excess heat from the end surfaces of the amplification crystals shaped as disks, with a relatively large diameter- to-thickness ratio, to provide an adequately large surface for heat exchange. High pressure gas or liquid cooling fluid are used following an approach that was recently proposed in the framework of the ELI-ALPS developments. To address this, development of a multi-slab architecture is employed, where face cooling by a high velocity flow of helium gas is used to manage the thermal load in Ti:Sa slabs. In parallel liquid (water) based coolant solution with a high heat transfer coefficient is also considered, investigating the impact of thermally-induced inhomogeneities in the coolant flow on transmitted laser beam characteristics.

The outcome of these studies will ideally require a demonstrator and a prototype that will inform the technical design for future high pulse rate laser drivers.
High repetition rate Ti:Sa amplifier module for laser-plasma acceleration, with the goal to develop a scalable testbed for a Ti:Sapphire (Ti:Sa) amplifier operating at 20 to 100 Hz, pumped by fully diode-pumped laser systems, and assess its operational performance at kW average power level. The main challenges include managing the thermal load in the amplifier and the beam transport, making sure fluence levels stay below the damage threshold at these high repetition rates. To be able to drive a stable plasma accelerator, the laser needs to have wavefront correction along with pointing/energy stability required for driving LPA. Another important requirement is the development of an efficient diode-pumped solid-state (DPSS) pump laser, operating in the visible (green) waveband between 500 and 550 nm, which can deliver tens of J at 100 Hz repetition rate. A strategic priority is the deliver a full design for a liquid cooling amplifier head and a prototype validated for thermal load in an operational environment demonstrating advancement compared gas cooling approach.

3.1.2 Efficient kHz laser drivers

A number of promising technologies are currently under development to enable the next leap to the kHz regime of laser-plasma accelerators, aiming at Joule scale pulse energy and kW average power, while still retaining short and ultrashort pulse duration and very high peak power. One objective here is to demonstrate the use of industrial, kW-ready thin-disk picosecond laser technology as driver of LWFA, in combination with plasma modulator (P-MoPA) and non-linear spectral broadening and post compression. Commercially available Thin Disk Lasers delivering hundreds of mJ laser pulses with 1-ps duration at kHz rate, can be used to drive wakefield acceleration up to the 100 MeV-GeV level and thus drive a kHz Thomson source. Existing platforms exist (e.g. CALA) that can be upgraded to full kHz operation to provide a test bed for the high rep rate plasma modules. Such an upgrade will demonstrate scaling up of the existing laser pulse compression unit (based on a gas-filled multipass cell), to properly handle higher power pulses.
Another objective is to prove broadband Chirped Pulse Amplification in novel gain materials for kHz operation, specifically Thulium doped ceramic materials (sesquioxides) that can be pumped directly with high efficiency laser diodes allowing to greatly increase the efficiency in comparison with Ti:Sapphire amplification which requires pumping from frequency doubled DPSSLs. Tm-based CPA broadband amplification stage require diode lasers operating at ∼ 800 nm, could provide an alternate route to kHz laser plasma excitation, capable of higher rep rate and efficiency than the CPA in Ti:Sapphire. In this contest, laser diode pump units currently under development (FBH) will be integrated with the Tm:Lu2O3 broadband amplifier currently under development (CNR), exploring the potential of this technology for high average power, high rep rate CPA at 2 μm.
This pillar includes development of components for kHz ultrashort pulse laser drivers for plasma accelerators including the advancement of diode laser pulsed pump capability towards higher duty cycle (100 Hz industrial delivery, 1000 Hz research prototype). These objectives aim at achieving a major advancement in energy efficiency exploiting full diode pumping technology.

3.1.3 High Rep-rate pump sources

The most crucial components of potential high repetition rate laser drivers for plasma acceleration are stable and reliable pump laser for the short pulse amplifier, with innovation at every stage from diodes to beam delivery. Whether using Ti:Sapphire technology or OPCPA amplifying near 800 nm – 900 nm, the DPSSL pump laser must be able to handle high average powers and pulse energies while maintaining excellent beam quality and wavefront for efficient second harmonic generation. The requirements for OPCPA pumping and Ti:Sapphire pumping are not identical. OPCPA typically requires shorter pulse durations (on the order of 3 ns as opposed to 10-20 ns) and finer control of the temporal profile. Additionally, in OPCPA amplification the profile of the pump laser imprints itself on the amplified seed and amplification is wavefront and polarisation dependent, so the wavefront and spatial profile of the output beam are very important. Despite these differences in requirements, pump lasers for both amplifier types face similar challenges and can benefit from similar improvements.

It is key to develop technologies for high average power DPSSL pump lasers suitable for Ti:Sapphire and OPCPA systems. With this goal in mind, all the activities foreseen in this pillar are directly related to the goal of producing high energy pulses (>10J) in the 3 – 20 ns regime with excellent wavefront, profile, and SHG efficiency at high average powers suitable for pumping high repetition rate OPCPA or Ti:Sapphire, with a focus on Yb:YAG as a pump laser gain medium. Practical goals consist in minimising depolarization and thermal aberrations using an existing Yb:YAG pump laser at ELI ERIC. Much of the focus of this will be on reducing the gain required from the main amplifier head and, therefore, thermal effects on the beam. This is primarily achieved by developing a higher energy front end and improving round-trip net gain by investigating the suitability of low loss coatings which tend to be less durable in the nanosecond, high average power regime. Additional effort will be needed to correct residual wavefront distortions on the output of the amplifier to ensure high efficiency SHG and high quality wavefront suitable for OPCPA. In parallel with these practical efforts at a lower, 20 Hz, repetition rate, groundwork for 100 Hz pumping is foreseen through numerical simulation and design work. One such task focuses for example on exploring the suitability of the cryo cooled Yb:YAG multi-slab DPSSL architecture as a pump laser for OPCPA in the 100 Hz regime, through numerical modelling (UKRI). Current commercial diode pumps are constructed with economic cooling assemblies that are nearing their performance limits, with high repetition rate (100 Hz) only possible at increased costs in €/W or lower performance. Efforts to bypass these limits are underway in current industrial-academic collaborative research studies, both publicly-funded and proprietary, based on progress in diodes, assembly technology and heat extraction techniques. Combining the latest results of these studies is a key path to deliver the needed diode sources for large scale (many 100 kW) pumping of Yb:YAG (FBH) with improved energy efficiency, higher duty cycle, and lower cost in €/W than is currently commercially possible.

3.1.4 High average power compressors

This is a critical component for ultrashort pulse lasers with compressor gratings being the limiting factor due to the lower damage threshold and the sensitivity to heat load. The current technology for high energy, broadband compressors is based on gold gratings. This technology is clearly limited in terms of average power because of a non-negligible absorption of the coating and is not suitable for kW beamlines. On the other side, dielectric gratings have already demonstrated the capacity to compress kW average power beamline for other types of laser systems with limited impact on wavefront distortion. There is a compelling need for advancing the technology for high repetition rate, high average power optical compression for CPA lasers using novel grating technology and implementing control of heat load effects on compressor gratings to ensure beam quality at the laser focus. It is crucial to approach these issues with a combination of modelling and experimental characterization to address impact on beam quality.

Specifically, modelling is needed of the impact of thermal load on grating under vacuum to be validates with existing systems to develop a robust modelling tool for compressor design under vacuum. This modelling tool is needed to estimate substrate deformation, substrate temperature increases due to thermal load and then deduce the impact on phase distortion for laser pulse and impact on beam intensity. Design of dielectric grating suitable for <50 fs laser pulses @ 800 nm will then follow, with the support of grating suppliers, to address needs in terms of bandwidth, reflectivity, damage threshold, and stretching factor. Experimental characterization of dielectric grating samples with power density compatible with a kW beamline is also needed to enable the measurement of the diffraction efficiency on large bandwidth, grating distortion and temperature increase under vacuum with density power compatible with kW beamline and LIDT in ps and fs regime for dielectric grating designed for 800 nm system. Final goal of this pillar is the development of a full compressor design based on dielectric grating technology for a kW beamline using dielectric gratings, suitable to compress kW power.

3.1.5 System Architectures

Another key strategic pillar consists in providing a full path to the delivery of an overall architecture of a laser driver that incorporates all the advanced components to deliver a high-quality laser pulse to the focal point (plasma) with the specifications and quality required to drive a laser-plasma accelerator. Among the multiple key objectives shared within the community, it is key to ensure focal spot pointing stability better than 0.1 µrad and focal spot profile stability representing a stability of the Strehl ratio better than 3%. This is a major step compared to existing large laser facilities showing at the best 1.5 µrad pointing stability and where the stability of the Strehl ratio is not well known and in any known case is at best around 15% peak to valley. Studies will need to investigate the combination of active loops working together on the same laser beam and unfold their impact on the other laser specs. More generally, objectives concern the identification and solution to improve reproducibility and stability to the level needed for user operation of laser-driven accelerators and secondary sources.

Specifically, the subsystems necessary to operate an intense laser to stabilise the focal spot position on target, including the alignment approach and the required online metrology need to be integrated. This integration activity will require interfaces between the subsystems to ensure that the global performances will be achieved, and the approach will build on shared knowledge and consensus. A de-risking strategy is needed to select the systems to be studied. The goal will be the definition of a risk mitigation strategy on operation, sustainability and maintainability. Such an approach will allow industrial partners in the future to commit to the delivery of a laser dedicated to plasma-based particle accelerators. Demonstrators or prototypes would need to be tested on existing laser facilities (e.g. Apollon, Palaiseau, France; BELLA, Berkeley, US; L3, ELI-Beamlines, Prague,

Czech Republic; ILIL, Pisa, Italy, PALLAS at ICJLAB, France etc.,). A survey on pointing stability on such existing facilities will enable a comparison of the different strategies used to stabilise the position of the focal spot, including active system, passive system, way to measure the position, before shots, in between shots, with quasi-CW laser as reference, with high repetition rate reference pulse trains, at location of the leakage, and classify them considering the targeted application, including repetition rate, average power, focusing system and focal spot size.
Finally, it is foreseen to define a new way to measure beam pointing stability in commissioning and in operation phases and manage the integration conflict with the target and the particle diagnostics in the experimental areas. Experimental approaches to be explored include beam samplers with optimised coating and weight reduction of large optics for large bandwidth pointing jitter frequency stabilisation covering the acoustic range. The laser beam stabilisation demonstrator system need to be qualified with its critical subparts and featuring relay imaging between the optics where the active system works and the focal spot. Test of active systems will be needed to improve beam pointing stability at intermediate repetition rate of 10 Hz and higher repetition rate of 100 Hz and 1 kHz.

4 Future plans / Conclusion / relation to other IFAST work

The summary of recent technical results in the field of lasers presented here tackles important achievements mostly related to the ongoing development of laser-plasma accelerators. It shows that a wealth of new results is emerging at a very fast pace and quickly being transformed into industrial products. These engaging circumstances are motivated by the perspectives in scientific and industrial applications of lasers and laser-driven plasma secondary sources, even beyond the needs of user infrastructure developments.

While this content is not meant to provide an exhaustive overview of the field, it highlights future directions and strategic development pillars. LASPLA continues to serve as an open discussion platform where needed work is being identified and prioritized and where funding for critical technical developments is successfully motivated and achieved, as presented in Section 3. These activities benefit from collaboration between different research and industrial partners, each with a well-known scientific role and capability, further strengthening the full scope of the LASPLA Task in fostering Lasers for Plasma Accelerators and for the entire WP6 Novel Particle Accelerators Concepts and Technologies.