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Diode pumps for future laser plasma accelerators: perspectives from research and industry

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ABSTRACT

Diode laser pumps are a critical technology for advanced accelerators based on laser plasma accelerators, and essential system components when higher repetition rate operation is needed. They are also a significant cost element in larger systems. An overview of progress in research and industry is presented, summarizing status of the technology, focusing on efforts to economically scale peak and average power and to enable new options in plasma acceleration, for example the use of thulium-doped gain media with its pumping wavelength at 780 nm. Development needs to support the accelerator community will be collected, covering topics such as efforts to lower cost in €/W by raising the diode laser output power, to increase repetition rates to 100 Hz and even up to 1 kHz, to scale TRL of emerging diode laser technologies, and to ensure low-failure-rate operation of large systems.

Keywords: laser plasma accelerators, laser wakefield acceleration, secondary-source generation, diode laser pump, high duty cycle, quasi-continuous wave, power scaling, cost reduction

1. INTRODUCTION

A new class of laser-based applications is emerging world-wide, that make use of extremely high intensity laser pulses to produce many different types of high energy radiation, in a process commonly termed secondary-source generation, itself making use of techniques in laser-driven plasma acceleration, reviewed in [1]. The high energy beams generated in secondary-source trials have the potential to enable the development of a series of entirely new applications that were previously only accessible at a very small number of dedicated large radiation facilities, such as DESY[1] in Germany, amongst others. Essentially, lessons and techniques from high intensity laser research are moving step by step toward real industrial application, in a similar manner to the way that skills in the basic science of quantum optics are enabling step-by-step an entirely new industry of quantum photonics.

Specific examples of the use of secondary-sources include the generation of highly intense X-rays for diagnostic studies in life and material sciences [2-4], the generation of neutron or positron beams for volumetric non-destructive inspection and material studies [5,6], the development of new forms of radiation therapy for cancer patients [6], and their use in basic studies in accelerator science, photon science, laser science and high energy physics. A recent overview is provided in [1,7-9].

The social and economic importance of studies into secondary-source generation is underlined by the establishment of national excellence centers, such as the Extreme Photonics Application Center (EPAC) in the UK[2], the development of multinational research centers, for example the EuPRAXIA facility[3] and the establishment of start-up companies

[1] https://www.desy.de/, last accessed 28.01.2024
[2] https://www.clf.stfc.ac.uk/Pages/EPAC.aspx, last accessed 28.01.2024
[3] https://www.eupraxia-facility.org/, see also [8]

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specializing in the field, such as TAU-systems[4]. Rapid research progress is also reported in the field at large laser facilities world-wide, for example at members of the Helmholtz Association in Germany[5].

High power diode lasers are a critical component in these large secondary-source systems, providing the original photons used, being deployed as pumps for the high-energy pulsed lasers. The diode lasers are a key limit to the achievable performance and are a large contributor to the total purchase and operating cost of the systems. We therefore provide here an overview of the current status and emerging requirements for diode laser pumps for secondary-source systems based on techniques in laser plasma acceleration. The article is structured as follows. First, we provide a brief overview of the anticipated design and construction of a laser plasma accelerator, for both large facilities and smaller units suitable for industrial application. Then we review the expected requirements for diode pumps, discuss status of provision from industry and summarize progress in diode laser research, before concluding. We note here for convenience that many of the techniques and technologies needed in secondary-source systems are of equal importance to emerging applications in power generation via laser-induced fusion, where a massive use of diode lasers is also foreseen, although these concepts are reviewed in detail elsewhere [10-12].

2. DESIGN OF LASER PLASMA ACCELERATORS

We next briefly note some details of how a plasma accelerator can be constructed, with special focus on the relevance to diode laser pumps. The construction is illustrated using information from the planned European research infrastructure, the EuPRAXIA facility[3], that is currently in the preparatory phase and whose concept is described in some detail in [8]. The basic power source for driving particle acceleration in a plasma consists of an ultrashort pulse based on Chirped Pulse Amplification (CPA) [13], consisting of a series of stages, using an optical arrangement as shown schematically in Fig. 1. The CPA technique, for which D. Strickland and G. Mourou were awarded the Nobel Prize in 2018, enables very high peak powers to be achieved without triggering either severe non-linearities that degrade the pulse or physical damage to the amplifiers.

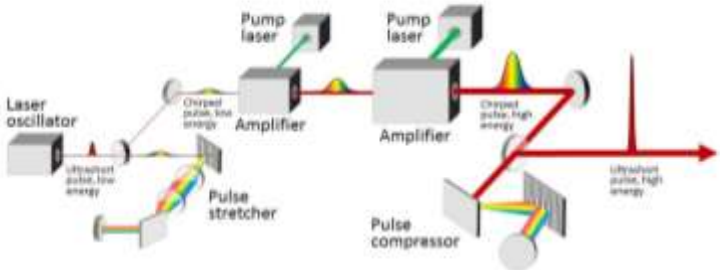

Figure 1. Basic schematic layout of a Chirped-Pulse Amplification (CPA) laser (Used with permission, courtesy of Richardo Torres, University of Liverpool and the EuPRAXIA facility).

A laser oscillator produces a seed pulse that typically has a central wavelength of λ = 800 nm and a bandwidth of tens of nanometers, a pulse energy E_p in the nJ range and a pulse width τ_p in the femtosecond range. This pulse is stretched in time using a dispersive device, e.g. a grating, that spreads the spectral content of the pulse in time, so that the peak power of the pulse is much reduced. The wavelength-chirped pulse is then delivered to a set of amplifiers, typically titanium-sapphire based, which boost the pulse energy E_p up to the many joule class. After amplification the pulse is compressed again using a further grating-based optical compressor, to reduce pulse width τ_p into the femtosecond range, leading to optical pulses with peak power in the TW to the multi PW range. For example, in the highest power configuration planned [14] for the EuPRAXIA facility (LASER3), final light pulses with $E_p \sim 100$ J and $\tau_p \sim 50$ fs are targeted. These extremely high peak power and high energy pulses are subsequently delivered and focused into a gas target, a jet or a plasma cell, illustrated in Figure 2. As the highly intense laser pulse propagates through the plasma cell, a large amplitude electron plasma wave is excited by the wake-field behind the laser pulse, whose longitudinal (parallel to the laser propagation direction) electric field can be orders of magnitude larger than those possible in a conventional radiofrequency (RF) accelerator. Therefore,

[4] https://www.tausystems.com/, last accessed 28.01.2024
[5] https://www.helmholtz.de/en/, last accessed 28.01.2024

particle acceleration at relativistic energies can be achieved in a very short distance, in a very compact configuration, using laser-plasma acceleration. Exploitation of these high fields and resulting acceleration enables the production of many different kinds of radiation, via secondary-source generation processes, for example the generation of intense collimated X-ray beams via Thomson scattering or via the Betatron emission mechanism. Such plasma accelerators are over 10-fold smaller than current accelerators based on RF techniques, so that their future exploitation for applications in mid-size facilities such as factories and hospitals is anticipated.

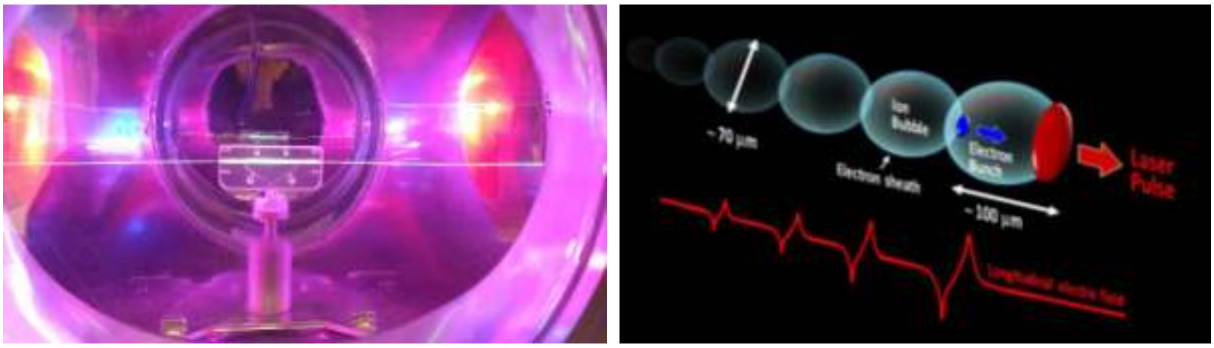

Figure 2. (Left) An exemplary plasma cell, suitable for use in studies of laser wake-field acceleration. (Right) An illustration of the Laser Wakefield Acceleration process. (Used with permission, images courtesy of Richardo Torres, University of Liverpool and the EuPRAXIA facility).

The anticipated size of the EuPRAXIA facility, that is based on the delivery of a very high-quality electron beam up to 5 GeV, is illustrated in Fig. 3, with the accelerator needed to generate τ_p ~ 50 fs pulses with E_p = 100 J occupying a space with a length of around 60 m, strongly reduced compared to conventional RF accelerators of the same electron energy. A smaller-scale commercial plasma accelerator in development at TAU-Systems[4] based on light pulses with around 10-fold smaller pulse energies that is suitable for direct deployment in factories, hospitals and engineering and test facilities, is also depicted schematically in Fig. 3, for orientation.

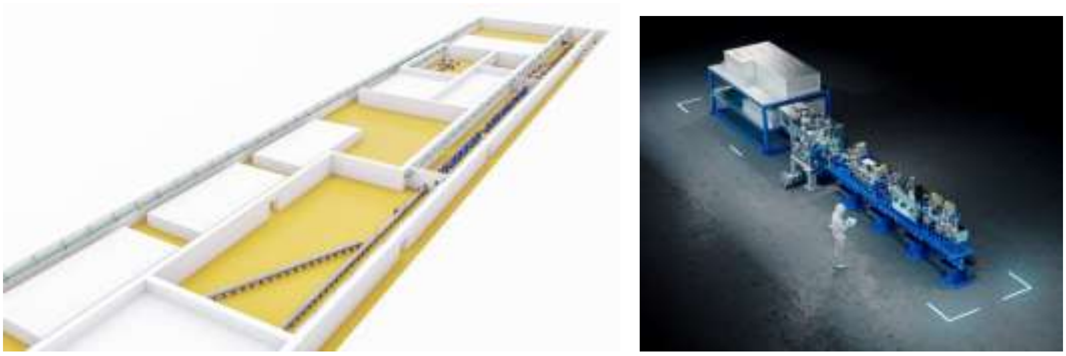

Figure 3. (Left) 3D depiction of the anticipated layout of the E_p = 100 J laser plasma accelerator (LASER3) planned within the EuPRAXIA facility [8] (used with permission, image courtesy of the EuPRAXIA facility). (Right) Anticipated layout of an industrial-grade laser plasma accelerator (laser wakefield accelerator, LWFA) suitable for use as a source of intense collimated X-rays on the production line floor (used with permission, image courtesy TAU-Systems Inc.).

In both the case of the large-scale public research facilities and industrial exploitation of plasma acceleration, laser pulses are needed with high repetition rates, so that images can be quickly collected, for example in detailed 3D scans of complex shapes using intense, collimated X-ray or neutron beams or for rapid industrial processing. Specifically, repetition rates of at least f = 20…100 Hz are sought, which can only be achieved using diode laser pumping in place of the commonly used flash-lamp pumping. In fact, current industrial Ti:Sa lasers mostly used for development of laser-plasma accelerators require laser pumping which is currently provided by flashlamp pumped neodymium or ytterbium lasers. Given the large heat load imposed by flashlamps on the Nd- or Yb-doped gain medium, the average power obtainable from such systems is severely limited, typically to a few tens of W, which for 100 J pulse energy would lead to a 0.1 Hz repetition rate or less.

This limitation can be overcome replacing flashlamp pumping with diode pumping, thus dramatically reducing the heat load and enabling a 10-fold increase in average power. This technology is now rapidly developing, with industrial systems becoming available at an average power of 100 W, and research systems aiming at 300 W average power. Crucial in this average power escalation are the performance and the cost in €/W of diode lasers. Therefore, in the next section, we review in more detail the diode laser requirements.

3. DIODE LASER REQUIREMENTS

The Titanium-sapphire (Ti:Sa) amplifiers used in the amplifier chain shown in Fig. 1 are pulse-pumped with a high-quality beam at wavelength around λ = 515…530 nm, generated by frequency conversion of the output of a pulsed solid-state YAG laser. The diode lasers serve as pump sources for the solid-state lasers, and the overall configuration is illustrated schematically in Fig. 4. In the example shown, diode laser arrays provide a pulsed pump beam at around λ = 940 nm, that is used to drive a large-area multi-slab solid-state amplifier, that itself scales power from an appropriate input supplied by a seed laser. The generated beam is frequency converted using techniques in second harmonic generation, and delivered to the Ti:Sa, to serve as a pump.

There are two main reported configurations that have been used in large-scale systems to deliver a suitable green pump beam to the Ti:Sa crystal. First, the amplifier can be constructed based on Nd-doped YAG material, itself pumped using diode lasers around λ ~ 808 or 870 nm, where the amplifier is cooled using flowing helium gas. Such an approach is used at a large scale in the HAPLS system, developed at Lawrence Livermore National Labs in the USA [15], and installed and in current use at the ELI Beamlines facility in the Czech Republic [7-9].

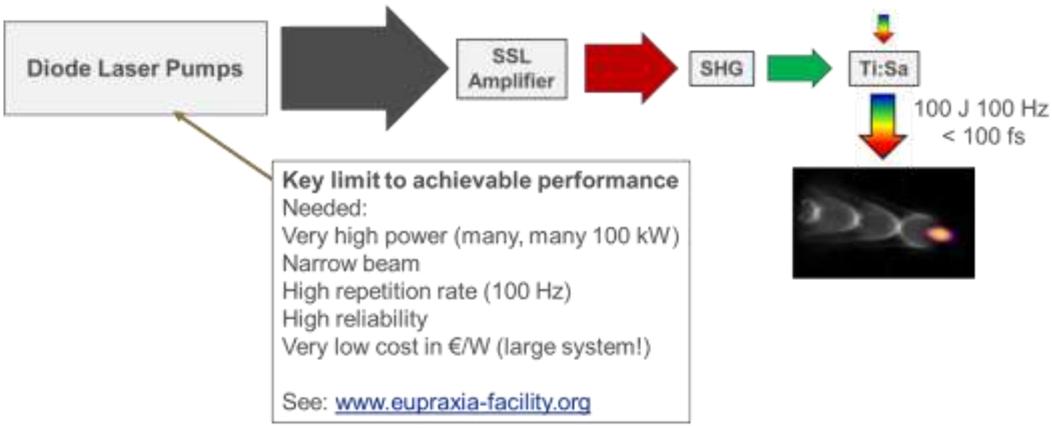

Figure 4. Schematic configuration of the diode-laser driven pump source for a high energy Ti:Sa-amplifier, as used in a laser plasma acceleration. Schematic adapted from [15]. Bottom right: Simulation of laser-driven plasma wakefield acceleration (Used with permission, courtesy of Alberto Martínez de la Ossa, DESY, and the EuPRAXIA facility).

In a second approach, as implemented in the DIPOLE system, the amplifier can be constructed using Yb:YAG slabs, pumped using diode lasers around λ ~ 940 nm, where the amplifier is cooled using cryogenic (liquid) helium, as developed at the Central Laser Facility, Rutherford Appleton Labs, in the UK, and installed and in current use at the HILASE facility in the Czech Republic, for example [16-17]. A technical drawing of a recent configuration of the DIPOLE system is shown in Fig. 5, where a pre- and post-amplifier enable pump-pulses with τ_p in the nanoseconds and E_p = 100 J to be delivered at f = 10 Hz repetition rate to the frequency-doubler crystal.

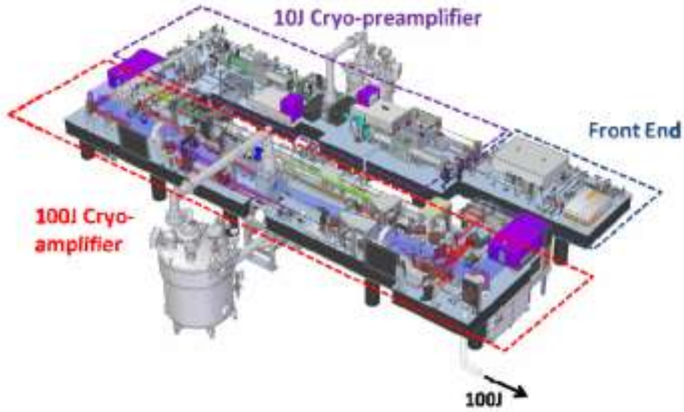

Figure 5. Technical drawing of the layout of the DIPOLE Yb:YAG-based high-energy-class diode-pumped solid-state laser, suitable for use in pump Ti:Sa in a laser plasma accelerator, image reproduced from [17] for convenience.

Diode laser pumps for these sophisticated large-scale systems must fulfill demanding specifications, as recently summarized in [18], illustrated using the anticipated requirements of the EuPRAXIA facility. Specifically, a diode laser pump beam for a system that generates E_p = 100 J from the Ti:Sa amplifier is required that is pumped with green light pulses of energy around E_p = 200…300 J. Allowing for losses in the system, this leads to a total optical pump power being needed of around P_{opt} = 300…1200 kW, depending on the exact conditions, with a brightness of B = 0.8…1.0 MW·cm^{-2}·sr^{-1} (following definition in [18]). The diode pump beam must have a homogenous flat-top intensity profile, adapted to match the solid-state crystal used, typically many cm^2 in size (e.g. 100 mm × 100 mm square in DIPOLE [17]). The repetition rate should be in the f = 20…100 Hz range (ideally larger), and the pulse width of the diode pump beam adapted to appropriately match the upper state lifetime of the amplifier used, with τ_p ~ 100…400 µs for Nd:YAG and τ_p ~ 500…2000 µs for Yb:YAG. Overall diode laser design and beam parameters must be carefully selected based on knowledge of the cooling capabilities and damage thresholds of the solid-state amplifiers used. Further, in these large systems, long operational lifetimes, high conversion efficiency and low purchase costs in €/W are strongly demanded. Although very highly optimized pump units are available commercially from several leading suppliers, no current diode laser pump can fulfill all these requirements. We next provide a brief overview of the status of industrial supply, before summarizing efforts in research to address performance gaps and enable alternative approaches.

4. STATUS OF INDUSTRIAL DIODES

Several industrial suppliers have publicly reported multi-100 kW diode laser pump modules for high-energy-class laser systems, and a brief summary of current status was recently presented at the 6th European Advanced Accelerator Concepts (EAAC) workshop [19], collecting input from TRUMPF, due to their role as providers of pumps for DIPOLE [17,20], Leonardo, due their role as providers of pumps for HAPLS [21] and Coherent and Jenoptik, due to their publication record on supply of pumps for high-energy-class systems [22,23]. Other suppliers are also active (e.g. Hamamatsu [24]), and this is not an exhaustive list. We summarize key conclusions from the EAAC workshop here, for convenience.

4.1 Examples of current state of technology

Large-scale diode pump arrays are based on stacked arrays of 1-cm diode laser bars, mounted either as a series of close-spaced bars on a single water cooler located on the rear edge of the stack (forming a quasi-continuous-wave, QCW-stack), or as a stacked array of microchannel coolers, as shown in Fig 6. Microchannel coolers (one water cooler per bar) provide the highest overall performance, with around P_{opt} = 400…500 W continuous wave (CW) power per bar for use in high-specification industrial laser processing tools [25]. Such configurations have high purchase costs, so are not preferred for very large systems, not least as microchannel coolers require very specialized handling to ensure long lifetime, although they do find use in specialist high-value applications such as pumping of alkali-lasers [26]. In contrast, although the bars in water-cooled QCW stacked arrays can operate with P_{opt} = 400…600 W, the cooling configuration (one water cooler for many 10's of bars) is typically only suitable for use in low-duty cycle operation of around 1%, limiting the achievable repetition rate of the coolers to f = 20 Hz or less. Higher duty cycle operation rates up to 6% are achievable by a properly adapted design, that increases the spacing of the bars (fewer bars and hence less peak power per cooler) [22]. 2D-arrays of rear-edge cooled QCW stacks with emission power in the many 100's of kilowatts are available from several suppliers for build of large systems, with an example shown in Fig. 6 [21].

Figure 6. Photograph of exemplary diode laser packaging, for 1-cm bars. (Left) Rear-edge cooled QCW stacked array, of many 10's of bars on a single cooler, and (center left, without-, and center right, with protective enclosure) its integration in a P_{opt} ~ 1000 kW QCW 2D array (images courtesy of Leonardo Electronics USA Inc. and reproduced from [20]). (Right) Single bar mounted on a microchannel cooler [23].

4.2 Industrial efforts to enable lower cost in €/W and increase duty cycle

As reviewed in [25,27] and discussed in briefly in [18], cost reduction in QCW stacked arrays can be achieved by using advanced automation, by scaling fabrication to larger area wafers, integrating and simplifying micro-optics and by efforts in defect minimization, amongst other measures. Cost reduction can also be achieved by scaling power per bar, with P_{opt} = 500…600 W now available, via use of advanced diode laser designs with higher peak power (lower temperature sensitivity), and advances in device technology such as the implementation of high-quality, high throughput facet passivation. Powers of prototype industrial bars into the P_{opt} = 1000 W range are also reported, showing a path to further cost reduction [21]. In further recent efforts, rear-edge water-cooled QCW stacked arrays have been used to successfully construct 100 Hz pump modules for demonstration efforts towards a 100 Hz Yb:YAG-based DIPOLE, but this leads to significant reduction in power per module and hence increase in cost, due to the limited cooling [20]. Further, the operating lifetime of QCW stacked arrays is normally rated in numbers of pulses. Increased repetition rates will also therefore reduce the operating lifetime, both due to more rapid pulsing and due to higher overall heat loads, which is a known cause of accelerated degradation, and leads to observed earlier failure in fielded units [8].

5. PROGRESS IN DIODE RESEARCH THAT SUPPORTS PLASMA ACCELERATORS

From the sections above, there are clear performance gaps, where development efforts in diode laser pumps are urgently needed. We summarize here recent efforts to address these gaps, illustrated using results from studies at the FBH. We start with an overview of research towards improved pumps for established Ti:Sa-based petawatt lasers. We then follow this looking at how innovations in diode lasers can also support the development of alternatives to Ti:Sa, before collecting briefly other research topics in diode lasers that are a general enabler for large laser systems.

5.1 Research toward performance-scaling of diodes for pumping YAG amplifiers within Ti:Sa-based systems

Yb:YAG amplifier crystals can be efficiently diode pumped at around λ = 940 nm, where the Yb:YAG absorption spectrum is broad, or at the zero-phonon line (ZPL, for reduced heating in the Yb:YAG crystal) around λ ~ 970 nm, where the Yb:YAG absorption spectrum is narrow, so that wavelength stabilization is needed. Research to demonstrate further scaling of QCW P_{opt} above the commercial level of 500…600 W (product level) and 1000 W (prototype level) offers a path to more economic pumping, by reducing cost in €/W, with some recent research highlights shown in Fig. 7. For example, in recent work, the peak demonstrated power per bar at 25°C in low duty cycle QCW mode has been increased at λ = 940 nm to P_{opt} = 1.9 kW at currents of 2000 A [28]. Diode laser bars around λ = 970 nm with monolithically integrated gratings for wavelength stabilization have also been recently demonstrated with P_{opt} = 800 W of low duty cycle QCW output power within a 1 nm spectral width, suitable for ZPL pumping [28], and should enable ZPL pumping to be used in large systems, without the (likely prohibitive in very large systems) additional cost of external wavelength stabilization using volume Bragg gratings.

A path to further power scaling is offered by parallel developments of bars for use in short-pulse LIDAR applications at λ = 905 nm. Here, several active lasers have been stacked on top of each other on a single wafer substrate using tunnel-junction-technology, whilst simultaneously implementing wavelength stabilization, enabling powers per bar of P_{opt} = 2200 W at lower currents of around 1000 A to be demonstrated within a narrow spectral line [30]. Power scaling of bars for pumping Nd:YAG at λ = 808 nm or for ZPL pumping around λ = 870…885 nm remains more challenging, due to the properties of the available semiconductor materials, but low duty cycle QCW P_{opt} of over 1000 W has also been demonstrated here [31].

Overall, based on these developments, there is potential for wavelength-stabilized diode pump bars to become mid-term commercially available with significantly reduced cost in €/W, due to operation at the multi-kilowatt-level.

Increased power itself is however insufficient: for further reduction in operating costs, diode lasers with increased power conversion efficiency η_E are also strongly demanded, to reduce the needed electrical input power and cost of cooling. Scaling of peak η_E remains highly challenging, and this remains close to η_E = 70%. Instead, in parallel to research studies to understand and bypass the efficiency limits, most recent technological and design efforts have focused on scaling operating η_E at high power, so that this moves ever-closer to the peak achievable values, with η_E > 60% now achieved at P_{opt} = 1000 W [28].

In the example of the DIPOLE system, the solid-state crystals are cryogenic cooled, and this offers a further opportunity for performance scaling. Specifically, if this cooling to sub-zero could be extended to the diode lasers, further increases in η_E and P_{opt} are possible due to increased gain (less temperature broadening) and improvements in material properties (higher mobility). In initial demonstration efforts using custom low-temperature-optimized designs, peak η_E and P_{opt} per 1-cm bar were shown to increase to 77% and 2200 W respectively at 200 K operating temperatures, and efficiency at P_{opt} = 1000 W was also increased to 70% [28,32].

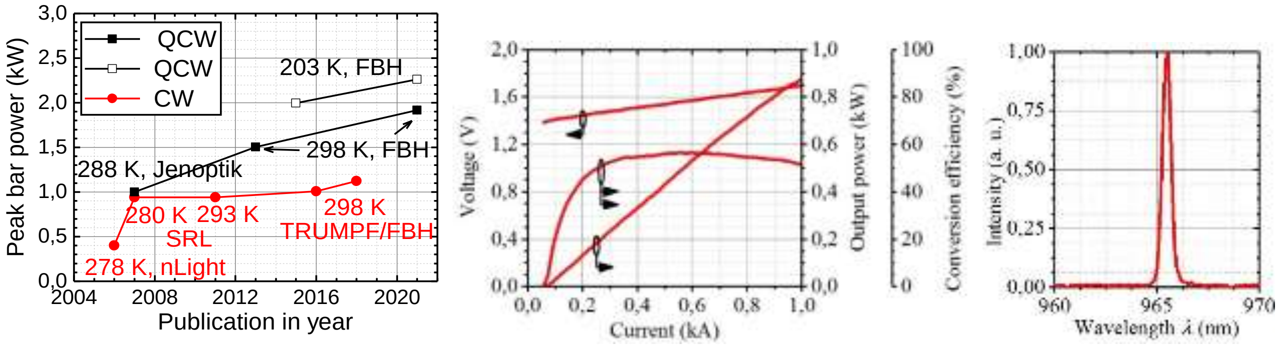

Figure 7. Recent research highlights in efforts to scale per-bar power. (Left) Summary of developments in peak power per 1-cm bar at wavelength around 940 nm [28]. QCW performance of a single laser bar for ZPL pumping around λ_p = 970 nm, that includes monolithic wavelength stabilization via a surface etched DBR-grating [29]: (Center) low duty cycle QCW output power, voltage and power conversion efficiency as a function of drive current and (right) spatially integrated intensity as a function of wavelength at low duty cycle QCW P_{opt} = 800 W.

5.2 Research toward high duty-cycle modules for pumping YAG amplifiers within Ti:Sa-based systems

As noted in section 4, the requirements of the high energy laser and plasma acceleration community are exceeding the capability of commercial QCW stacked arrays that are based on established economic cooling techniques, due to ever-increasing demands on scaling of duty cycle, without compromise in power, efficiency, beam properties or operating lifetime. Alternative concepts are urgently needed, to address the emerging needs. Research prototypes of stacked arrays are available that meet all performance requirements for pumping of YAG amplifiers in large-scale plasma acceleration systems [18], based on many years of applied research at the FBH, with an example shown in Fig. 8. In these stacked arrays, two water coolers are used (rather than one), the spacing between diode lasers is increased to around 3 mm, and the coolers are located at the sides of the stack, rather than at the rear edge, for reduced thermal path between heat source and cooler for more effective overall heat extraction. Using these techniques, QCW operation of $\lambda = 940$ nm stacks at duty cycles up to 50% is possible (e.g. 500 µs pulses at $f = 1000$ Hz), with low (< 10%) degradation in power, efficiency and far field [18], at costs lower than microchannel-cooler based designs. However, the arrangement currently limits the maximum width of the diode lasers and hence the reliable operating power per stack into the few kilowatts range. Overall, these prototype stacks currently represent a proof-of-principle approach, suitable for small-series demonstrations into the many 10's of kilowatts rather than being a solution for large-scale commercial systems requiring many 100's of kilowatts of pump power, where complex optical combination techniques would be needed to realize the needed flat-top beam profile. To address this ongoing performance gap, in recently started research project HOTSTACK, alternative approaches are sought based on lessons from these earlier developments, that enable higher per-stack powers whilst maintaining very high duty cycle operation without compromising performance elsewhere [33].

Figure 8. Edge-cooled QCW stacked arrays from the FBH, based on an innovative side-cooling approach and suitable for pulsed-pump applications up to 50% duty cycle [18] (image © FBH/schurian.com).

5.3 Diode research to enable alternatives to DPSSL pumped-Ti:Sa (Thulium-based systems)

As noted above, petawatt pulsed laser systems worldwide are produced using Ti:Sa amplifiers, typically following the scheme shown in Figs. 1 and 4. Although these systems deliver extremely high peak power and high pulse energies, they are limited by the characteristics of the Ti:Sa material itself, namely (adapted from [34]): a large quantum defect (~34%, leading to high heat generation in the crystal), a short radiative lifetime (3.2 µs, limiting possible energy storage and hence requiring very high pump fluence), and lack of absorption at wavelengths currently (easily) accessible by high power semiconductor lasers (being pumped at $\lambda \sim 515 \ldots 530$ nm), therefore requiring the use of the sophisticated pumping scheme, as discussed in section 3. Direct diode pumping of Ti:Sa has been demonstrated by several groups, remains highly challenging, although strong progress is reported as visible diode laser performance steadily improves [35,36].

An alternative is emerging, namely the use of thulium-doped gain materials, where the radiative time is long (> 10 ms), and pumping can be achieved at either a broad absorption peak around $\lambda = 780$ ..793 nm (which is available from high power diode industry with high quality) or in ZPL mode around $\lambda = 1600 \ldots 1700$ nm (where is only very limited diode availability), which can lead to strong improvement in performance, due to the reduced heat load in the material [36]. Thulium-doped amplifiers provide light around $\lambda = 2$ µm, which is predicted as being applicable in plasma acceleration [1]. In most recent demonstrations using CW direct diode pumping of Tm:YLF at $\lambda \sim 790$ nm, $E_p = 100$ J pulses have been generated for the first time [38], promising for the eventual efficient realization of petawatt laser pulses at high repetition rate of kHz and beyond. Ceramic-based Tm-doped materials also look very promising for high efficiency lasing with scalable size gain media geometry. For example, sesquioxides like Lu_2O_3 are being investigated at CNR where a platform for kHz repetition rate amplification of ultrashort pulses is also being investigated [39] as a driver of future laser-plasma accelerators.

To support these developments, diode laser research at the FBH has focused on making high duty cycle pumps available at $\lambda_p = 780$ nm, with τ_p matched to the radiative lifetime of Tm:YAG. After initial demonstrations of low duty cycle QCW $P_{opt} = 1000$ W at $\lambda = 780$ nm from 1-cm diode laser bars [31], the diode technology was adapted for use in high duty cycle stacks, as shown in Fig. 8, supported by design efforts to scale η_E and P_{opt} [40]. These studies allowed stacks to be realized that delivered $P_{opt} = 1.4$ kW per stack at 10% duty cycle ($\tau_p = 10$ ms, $f = 10$ Hz), and operate to 50% duty cycle ($\tau_p = 10$ ms,

f = 50 Hz) with only small reduction (~10%) in output power to P_{opt} = 1.25 kW, as shown in Fig. 9. These efforts support the development of pulse-pumped Tm:YAG lasers with reduced heat load suitable for multi-joule pulse generation.

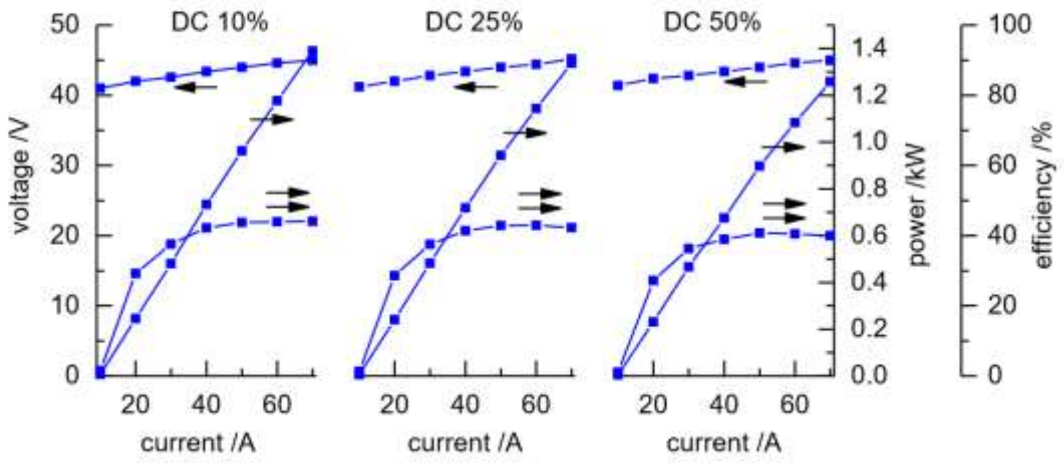

Figure 9. Voltage, in-pulse optical power and conversion efficiency for a λ = 780 nm high duty cycle edge-cooled stack from the FBH (see Fig. 8) as a function of bias current in QCW mode with 10 ms pulse width and duty cycle of 10%, 25% and 50% (pulse repetition frequencies: 10 Hz, 25 Hz and 50 Hz), reproduced from [40] for convenience.

5.4 Further diode research as an enabler of emerging large-scale laser systems

Here for completeness we note some parallel studies in diode laser research, that support large laser systems. Diode laser cost reduction can be enabled by maximizing fabrication yield, for example by use of innovative III-V technology enabling the use of extremely thick p-side epitaxy for simplified and higher-yield assembly, without performance penalty [41]. In addition, the ongoing implementation of artificial-intelligence-based automated defect screening is anticipated to enable higher quality diode lasers to be realized at lower cost, even in early-stage research [42]. Lower cost and TRL scaling is also enabled by using the same technology platform to serve parallel industrial markets, for example by exploiting λ = 780 nm stacks originally developed for pumping Tm:YAG for the efficient direct material processing of aluminum [43]. Efforts to increase diode reliability include ongoing studies in facet passivation technology to suppress sudden failures [43] and investigations of contributing material factors to gradual degradation such as the presence of background oxygen contamination [45].

6. CONCLUSIONS

The production and exploitation of high energy secondary radiation sources based on laser plasma acceleration is a rapidly emerging field, that is transitioning from research towards industrial uses, and is expected to enable applications in imaging, spectroscopy and medicine to be developed at a compact and affordable scale that is impossible or very challenging with any other technique. Diode laser pumps are a critical enabling technology, and essential components as the repetition rate scales towards 100 Hz and above, as they are the only light source that can deliver the needed many 100's of kilowatts of pump power in a narrow beam at high repetition rate with high reliability. Diode laser research and technology development at the FBH and others seeks to address the requirements of this community, by filling gaps, scaling performance and cost and by enabling trials of new approaches.

First, research efforts continue to address a critical gap in industrial supply: although pulsed pump arrays with P_{opt} up to 1000 kW are commercially available, these are limited to a duty cycle of around 1% by the use of economical cooling, and even the most advanced units achieve a maximum of around 6% duty cycle, at increased cost in €/W and reduced overall output power per stack. Research prototypes from the FBH have been specifically developed to fill this gap, making use of innovative edge-cooled mounting technology to realize kilowatt-class QCW stacks that operate with duty cycle of 10…20…50% with < 10% variation in output power. These stacks are currently in intensive further development [33].

Second, performance scaling of diode lasers continues, with peak power in low duty cycle QCW testing of $\lambda = 940$ nm material increased to around 2000 W per bar, and with monolithic gratings successfully implemented in $\lambda = 970$ nm bars. Combined, these measures offer a potential path to the eventual commercial supply of spectrally stabilized multi-kilowatt bars, as a cost reduction measure. Efforts to scale efficiency at these very high powers also continue, with conversion efficiency at 1000 W / bar now > 60%.

Third, developments in diode laser can enable new approaches in pumping, with recent success in developing high duty cycle pulsed-pumps at $\lambda = 780$ nm supporting efforts to implement high energy lasers for use in plasma acceleration based on direct diode pumping of thulium-doped amplifiers, as a more efficient alternative to established Ti:Sa technology.

Overall, joint efforts continue to use advances in diode laser technology to support the exciting developments in the plasma acceleration field, in a close cooperation between research and industry.

REFERENCES AND ACKNOWLEDGEMENTS

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