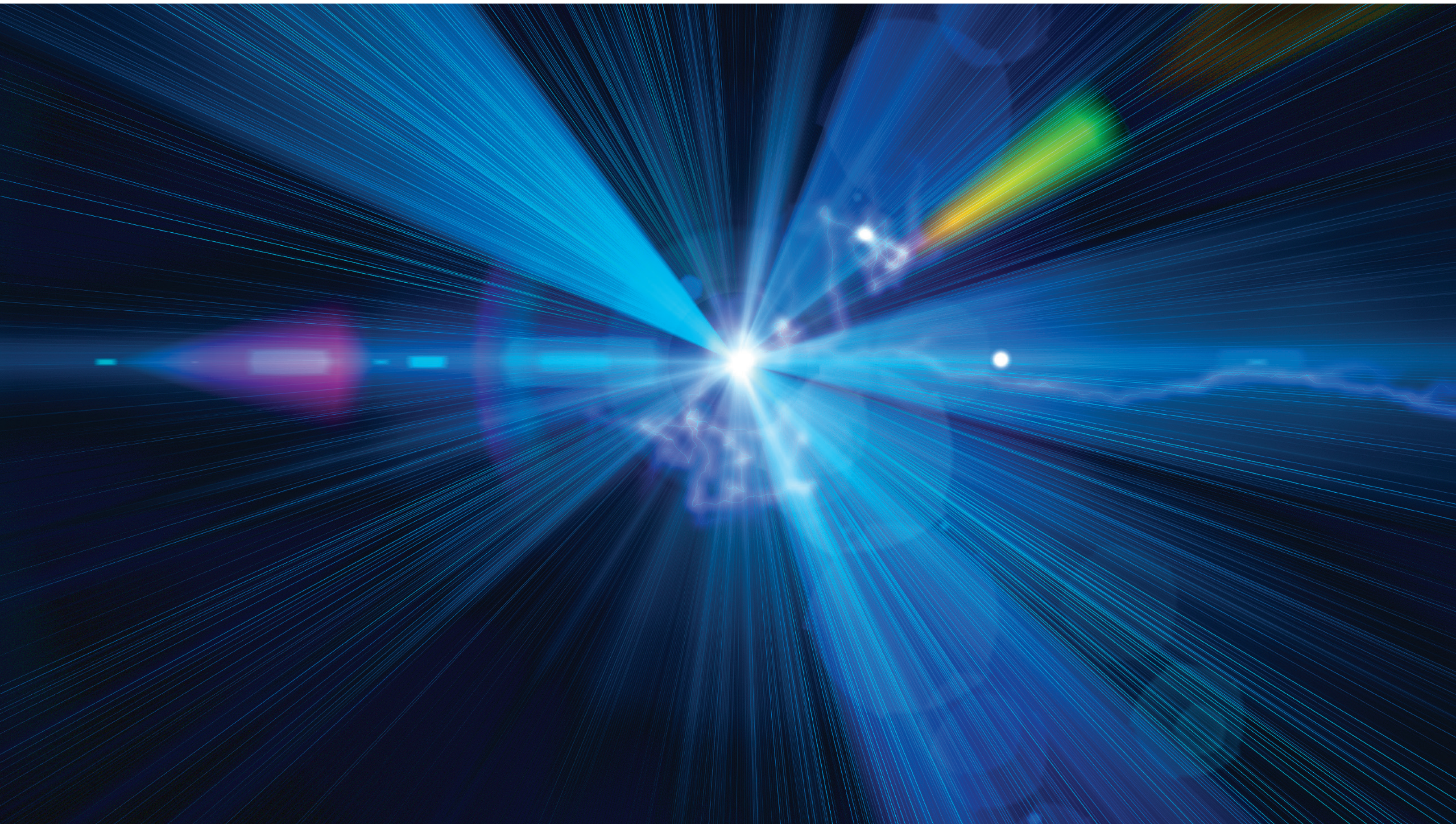
REPORT OF WORKSHOP ON

Laser Technology for k-BELLA and Beyond



MAY 9–11, 2017

WORKSHOP HELD AT

LAWRENCE BERKELEY NATIONAL LABORATORY

17-AF-4192

Table of Contents

PREFACE

These are exciting times in both laser-plasma accelerators and one of their key enabling technologies: ultrafast lasers of higher energy, power, and efficiency. Substantial incremental improvements beyond today's state of the art will be needed for our next step, called "k-BELLA" for its kilohertz/kilowatt performance, and even greater improvements will be crucial along the road to our ultimate goal of an LPA-based collider. Improvements in laser technology also promise many spinoffs throughout the accelerator community and beyond.

With several competing technologies for the near- and long-term needs, and optics R&D required as well, we convened representatives from throughout the laser community for a "Workshop on Laser Technology for k-BELLA and Beyond" May 9-11, 2017. The 34 participants (Appendix B) represented three US Department of Energy national laboratories, two European laboratories, five university faculties or research centers, and six private-sector companies. Three days of presentations about our goals, the resulting performance needs, and the state of the art and development paths of the candidate technologies, as well as lively discussion, gave way to the two months of writing and reviewing that resulted in this report.

This report's goal is to represent a community consensus and therefore it is the work of many hands. Major contributors included Michael Campbell and Jon Zuegel (University of Rochester Laboratory for Laser Energetics); Enam Chowdhury of Ohio State University; Vladimir Chvykov of the Extreme Light Infrastructure-Attosecond Light Pulse Source (Szeged, Hungary); Jay Dawson and Constantin Haefner of Lawrence Livermore National Laboratory; Tso Yee Fan and Peter Moulton of the Massachusetts Institute of Technology Lincoln Laboratory; Almantas Galvanauskas of the University of Michigan; Cameron Geddes, Carl Schroeder, and Csaba Tóth of LBNL's BELLA Center; Manoj Kanskar of nLIGHT, Inc.; Jens Limpert of Friedrich Schiller University (Jena, Germany); Jorge Rocca of Colorado State University; and Russell Wilcox of LBNL's Berkeley Accelerator Controls and Instrumentation Program.

The support of the operations team under Asmita Patel here in LBNL's Accelerator Technology and Applied Physics Division was invaluable throughout these efforts. Martha Condon, Lucky Cortez, and Giselle Jiles organized not only the hospitality and logistics, but also the Indico website, for the workshop, and Joe Chew edited the report.

I would like to take this opportunity to thank everyone who contributed to this roadmap effort. We all look forward to exploring and realizing the potential of these laser and optical technologies and the LPAs and other applications made possible by them.

Wim Leemans
Chairperson, Workshop on Laser Technology for k-BELLA and Beyond
Lawrence Berkeley National Laboratory

1. EXECUTIVE SUMMARY

A workshop was held at Lawrence Berkeley National Laboratory on May 9-11, 2017, gathering 34 world-leading laser scientists, laser users and industry representatives to discuss technological solutions towards ultrafast lasers that could operate in the multi-kW to even hundred-kW average power range.

For near-future applications (in the next 5 years), a nominal 3 J, 1 kHz laser operating at 30 fs pulse duration, referred to as k-BELLA, would enable high-average-power demonstration experiments of the rapidly advancing laser plasma accelerator (LPA) technology. These developments would yield, in the near term, applications in radiation sources and ultrafast science, as well as laser-based machining, and, in the long term, a next stepping stone towards an LPA based collider. Alternatively, a laser that provides 30 mJ at a repetition rate of 100 kHz would enable chemical, condensed matter or biological experiments at the new generation of high-repetition-rate free-electron lasers and synchrotrons. For future collider applications (>10-20 years), as well as applications that require high throughput (>7-15 years), lasers in the tens to hundreds of kW are needed.

The workshop was guided by key questions that assess the current laser needs for applications, the technical readiness of today's technologies, which technologies are or will be available to dramatically increase the average power of ultrafast lasers, what the challenges are, and the resources needed to address these challenges.

Following talks reviewing the current state of the art, six technical approaches were presented that had different levels of technical maturity. Three of the six approaches rely on the use of titanium-doped sapphire (Ti:Sa) as the gain medium with different methods of pumping, gain medium design, and thermal management . Currently Ti:Sa, operating around 0.8 um wavelength, is the workhorse laser of choice in high field science and laser plasma acceleration due to its ability to support ultrafast laser pulses down to the 20 fs range with high energy per pulse and the required pulse contrast. One of the key challenges towards higher average power operation is the construction of suitable pump lasers that can provide energetic pump pulses at a wavelength of ~530 nm and at average power adequate to the application. The approaches that were presented based on Ti:Sa indicate straightforward scaling from the current few tens of watts to the multi-kW range and possible scaling to the 10 kW range.

The fourth approach relies on technologies developed for fusion-energy-laser architectures and the use of Tm:YLF as a gain medium with an operating wavelength of 2 μm, and offers the potential of reaching tens to hundreds of kW with pulse durations of 40-100 fs. On the one hand, pulsed lasers relying on Tm:YLF have been built for applications requiring only tens to hundreds of mJ; on the other hand, continuous wave operation of Tm:YLF slab lasers above 200W average power have been demonstrated, and this gain material holds the promise of operating at high wall plug efficiency through direct diode pumping, which is an essential condition for future colliders. Its anticipated performance parameters are consistent with most applications. For laser wakefield accelerators, longer lasing wavelengths require more accelerator stages but less peak power, and an integrated system study would be needed to assess its full potential.

The fifth and sixth approaches rely on coherent beam combining using multi-core fibers and coherent temporal, spatial, and spectral stacking, respectively, of pulses produced by diode-pumped fiber lasers. Such lasers have potentially the highest wall-plug efficiency and could offer compact, very high power systems with tens to hundreds of kW average power in the mid to longer term. The key challenges are scaling the number of apertures, control system complexity, pulse contrast, and ensuring high efficiency when combining the beams.

A consensus among all attendees is that 1-5 kW class systems producing the required performance characteristics to advance the state of the art in laser-driven science can now be built. R&D and industrial capacity development is needed to mature all of the concepts, including demonstrating scaling to and beyond the kW level; demonstration of the feasibility of pumping high energy Ti:Sa amplifiers with multiple fibers at the 10-J level; demonstration of feasibility of operating high energy Ti:Sa amplifiers pumped by frequency doubled disk amplifiers at multi- kW average power; demonstration of thulium-doped yttrium lithium fluoride (Tm:YLF) as a suitable gain medium for high energy lasers; coherent combining of fiber laser arrays; spectral combining to increase the spectral bandwidth of Yb-doped fiber lasers; and efficient methods for pulse contrast in some fiber-based technical approaches.

R&D areas that would benefit all approaches include: mode profile control; high repetition rate laser control systems; and grating and mirror, and anti-reflection coatings that can handle high peak and high average power operations. In addition, investments in material science are need in order to explore new gain media that have low quantum defect and appropriate saturation fluence, and can operate at high average power levels with high wall-plug efficiency. These advances would expand the options and applications for high peak and average power lasers.

2. OVERVIEW AND MOTIVATION

2.A. Laser technology to drive the accelerators of the future

PW-class, short-pulse lasers are required to drive high field science, including plasma based particle accelerators with the potential to enable future particle colliders and radiation sources, and to enable new experiments at high repetition rate light sources.

Presently, PW-class, short-pulse laser systems such as the BELLA PW laser at LBNL, the HAPLS[1] laser at LLNL, operate currently at an average power of about 50 W and the laser system built at Colorado State University operates at up to 83 W average power. Current performance parameters of a few representative high energy lasers are shown in Table I.

Table I: Performance levels of high energy per pulse laser systems based on various architectures for amplifying pulses in Ti:Sapphire. Note that the BELLA operating values are current operational levels delivered on target. The HAPLS laser has been designed to operate at 10 Hz and petawatt peak power (30 J/30 fs) – design parameters are in parentheses. It will be commissioned and ramped further in performance at the ELI-Beamlines facility beginning circa the end of 2017.

	Ti:Sa, BELLA[2]	**Ti:Sa, HAPLS[3]**	**Ti:Sa CSU[4]**
Pump-laser concept	Multi-aperture Nd:YAG	Single-aperture, gas-cooled Nd:Glass	Single-aperture, edge-cooled slab-ND:Glass pump
Wavelength [um]	0.8	0.8	0.8
Energy/pulse [J]	49	>16 (>30)	25
Pulse duration [fs]	30	28	30
Average power [W]	49	53 (>300)	83
Repetition rate [Hz]	1	3.33 (10)	3.33

[1] The HAPLS laser system is the first fully diode pumped short pulse laser system and is designed to deliver petawatt pulses with an average power of 300 W. Still in the commissioning phase, it has already demonstrated ~50 W of 16-J, 28-fs pulses at a 3.3 Hz rep rate.

[2] K. Nakamura et al., "Diagnostics, Control and Performance Parameters for the BELLA High Repetition Rate Petawatt Class Laser," IEEE Journal of Quantum Electronics **53**, 4 (25 May 2017), 1200121.

[3] C. L. Haefner et al., "High average power, diode pumped petawatt laser systems: a new generation of lasers enabling precision science and commercial applications", Proc. SPIE 10241, Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers III, 1024102 (June 26, 2017); doi:10.1117/12.2281050. The values in parentheses are design values that are expected to be reached in future operations.

[4] Y. Wang et al., "0.85 PW laser operation at 3.3 Hz and high contrast ultra-high intensity λ=400 nm second harmonic beamline," accepted by Optics Letters (prepress version online 1 September 2017).

The vast majority of applications relevant to the DOE and other agencies require average powers and rep rates higher than the present state of the art by, in some cases, more than a factor of 1000. Some of these applications and laser requirements are discussed in previous workshop reports,[5] and a brief summary of applications and requirements for colliders and light sources is given in Section 3.

At the workshop we discussed possible laser technology paths to reach three goals:

1. Near term (5 years): 3 kW average power – relevant to radiation sources and assessment of collider control and average heat loading and to light source experiments.
   a. 3 J at 1 kHz, 30 fsec which we refer to as the k-BELLA laser to drive a 1 GeV LPA;
   b. 30 J at 100 Hz, 30-100 fs (e.g., laser driven ion acceleration at high repetition rate) with high temporal contrast; and
   c. 30 mJ at 100 kHz, <30 fs (e.g., pump-probe experiments at light sources).
2. Medium term (5-15 years): 30 kW average power – relevant to radiation source and prototype collider module.
   a. 3 J at 10 kHz, 30-100 fs, 30 J at 1 kHz, 30 mJ at 1 MHz
3. Long term (10-20 years): 300 kW average power collider module drivers and high flux radiation sources
   a. 100 fs pulses of 3 J at 100 kHz, 6 J/30 J at 50/10 kHz.

Across the near, medium, and long terms, we also discussed the path towards optical components that are compatible with operating at both high average and peak power levels.

Particular emphasis was given to the near-term goal of developing a demonstrator and flexible research facility for a 1-GeV, 1-kHz LPA (driven by a k-BELLA-class laser: 3 kW, 3 J, 1 kHz, 30 fs). The purpose of this demonstrator facility is threefold: (1) develop and demonstrate the laser technology needed to drive a 1-GeV, 1-kHz LPA; (2) develop know-how in handling high average power ultrafast lasers and LPA technology, including power handling systems, feedback controls and high repetition rate operations/data acquisition; and (3) develop, optimize and utilize a 1 GeV, 1 kHz LPA facility for a wide variety of experiments on science and applications relevant to DOE and other agencies. Laser techniques to meet this near term need are detailed in Section 4.A.

Because this near-term 1-kHz facility is needed as an end product in its own right, serving as a facility for a wide variety of science experiments, it was generally agreed by the workshop attendees that the laser technologies used to deliver this near-term facility do not necessarily have to scale to higher rep rates and higher average powers, although it is clear that reduction to practice of systems and technologies such as thermal management, optical components, validation of laser modeling, beam control, and wall-plug efficiency that could scale to a future facility would be beneficial. For some of the proposed technical approaches, extension of the near-term kHz-facility is possible by adding an additional stage to enable experiments at higher

[5] E.g., U.S. Department of Energy, *Summary Report of the Workshop on Laser Technology for Accelerators* (Jan. 23-25, 2013).

energy and high average power. This could provide an attractive route to a future 300 kW LPA test facility by retiring associated technical risks in a staged approach.

A second topic of particular emphasis was the identification and development of laser technologies that *would* scale to meet the most demanding long-term goal of providing a driver for a 5 GeV collider module (~10 J, 100 fs, tens of kHz, hundreds of kW). The high-level parameters that drive a near-term 3 kW and long-term 300 kW laser facility for LPA studies are outlined below. A more in-depth discussion of the required laser parameters for colliders and light sources, and the parameters that drive other applications outside of LPA based devices, is given in Section 3. Laser techniques to meet these long-term needs are detailed in Section 4.B.

2.B. Laser technology for a near-term 1 GeV, 1 kHz demonstrator facility

Several laser technologies were discussed towards providing a driver for a 1 GeV, 1 kHz LPA facility that would enable LPA based radiation sources and beam diagnostics as well as testing of LPA average power and control issues relevant to future particle colliders. Laser requirements were discussed in detail, starting from basic laser parameters, i.e., 3 J, 1 kHz, 30 fs, 0.8 μm; or 6 J, 1 kHz, 60 fs, 1.9 μm (as determined by LPA physics studies).[6] Furthermore, LPA operation benefits greatly from a pure Gaussian transverse mode but does not have very stringent requirements on the laser intensity contrast, as is required, for instance, for ion acceleration from solid-density targets. Requirements on using plasma mirrors for coupling laser beams into plasma channels lie in between those used in laser plasma accelerator experiments and those used for ion acceleration. Typical intensity on such plasma mirrors is of the order of 10^{17} W/cm^2 and hence would require a temporal laser pulse contrast of 10^6 or better.[7, 8] Laser efficiency is not an essential aspect of this demonstrator facility, though it is for medium and long-term applications. The parameters for a 1 GeV, 1-kHz LPA demonstrator facility are summarized in Table II.

Table II: Nominal laser parameters for a near-term 1-GeV, 1-kHz LPA demonstrator facility.

	~1 micron laser wavelength	**2 micron laser wavelength**	**laser wavelength (λ) scaling**
Energy [J]	3	6	λ
I [10^{18} W/cm^2]	10-20	2-5	λ^{-2}
Duration, FWHM [fs]	30	60	λ
Peak power [TW]	90	90	*None*
Rep. rate [kHz]	1	1	*Application dependent*
Average power [kW]	3	6	λ
Efficiency [%]	n/a	n/a	-
Contrast	10^6	10^5	λ^{-2}

[6] C.B. Schroeder, C. Benedetti, E. Esarey, and W.P. Leemans, "Laser-plasma-based linear collider using hollow plasma channels", Nuclear Instruments and Methods A **829**, p. 113-116 (2016).

[7] B.H. Shaw, S. Steinke, J. van Tilborg, and W.P. Leemans, "Reflectance characterization of tape-based plasma mirrors", Physics of Plasmas **23**, 6 (2016), 063118.

[8] S. Steinke et al., "Multistage coupling of independent laser-plasma accelerators", Nature **530**, 7589 (11 February 2016), pp. 190-193.

The ability of the laser technologies discussed at this workshop to provide in the near term (within the next 5 years) a driver for a 1 GeV, 1 kHz demonstrator facility is briefly summarized below. The first three approaches all require modest R&D; however, subsystem technologies or architectures are considered sufficiently mature to support scaling to the kHz demonstrator facility. More details are presented in the section on technical approaches. The performance parameters of this laser (pulse duration, pulse energy, repetition rate including shot-on-demand) should be as flexible as possible to enable a range of experiments. Operational aspects (mode quality, pointing stability, contrast, turn-on time, day-to-day stability, etc…) must be optimized to maximize the utility of such a laser.

Ti:Sa with incoherently combined fiber pump lasers and an OPA "front end." This approach was presented by MIT-LL and University of Rochester and could deliver in the near term a 1 GeV, 1 kHz LPA demonstrator facility. It relies on pumping a single, cryo-cooled Ti:Sapphire crystal by multiple, frequency-doubled commercial high-power fiber lasers. Scaling to very high average power (10 kW and beyond) is very challenging and will not have the wall plug efficiency needed for future colliders.

Ti:Sa with diode pumped lasers (thin or thick disc). This approach was presented by Colorado State University and the ELI ALPS project and could deliver in the near term a 1 GeV, 1 kHz LPA demonstrator facility. It relies on a cryo-cooled active mirror Ti:Sa amplifier pumped by diode by dual-beam line cryo-cooled Yb:YAG thick-disk amplifier. Scaling to very high average power (10 kW and beyond) is very challenging and will not have the wall plug efficiency needed for future colliders.

Tm:YLF with direct CPA and operating at a wavelength of 2 μm. This approach was presented by LLNL and could deliver in the near term a 1 GeV, 1 kHz LPA demonstrator facility. It relies on a single-aperture, directly diode pumped, gas-cooled Tm:YLF crystal. It does operate at a longer wavelength than Ti:Sapphire; therefore, there is limited experimental expertise in LWFA at this wavelength. It could potentially scale to very high average power with high wall plug efficiency.

Fiber-based lasers with coherent combining. An approach relying on pulse stacking in time, and spectral and spatial beam combining, was presented by a team from the University of Michigan, LLNL, and LBNL. A second approach relying on spatial combining of beams from multi-core fibers was presented by the Fraunhofer Institute Jena, Germany. One near term goal—30 mJ, 30 fs, 100 kHz, 3 kW—is indeed in reach with today's technology without significantly more R&D. Promising advancements in energy scaling have been made to date, and these approaches hold the promise of scaling to very high average power with high wall plug efficiency, but,overall they require more R&D and are not ready to deliver in the near term on a 1 GeV, 1 kHz LPA demonstrator facility, which requires a 3 J, 30 fs, 1 kHz, 3 kW laser.

2.C. Laser technology for a long-term 10 GeV, 100 kHz LPA collider module

Several laser technologies were discussed for providing a driver for a 10 GeV, 10-100 kHz LPA collider module. Besides the requirements on the basic laser parameters, i.e., of order 10 J, 10-100 kHz, 100 fs (as determined by studies based on LPA physics as we understand it today), other laser requirements were discussed in some detail. As was the case for the 1 GeV, 1 kHz demonstrator facility, LPA operation benefits greatly from a pure Gaussian transverse mode, and the use of plasma mirrors for in-coupling requires a contrast of 10^6 or better. Note that plasma mirror technology compatible with high repetition rate systems will require development. A more detailed discussion of the required laser parameters for colliders and light sources is given in Section 3. High efficiency (tens of percent) is essential for high-energy collider applications.

The ability for the laser technologies discussed at this workshop to provide the driver for a 10 GeV, 100 kHz LPA collider module in the long term is summarized briefly below. More details are presented in the section on technical approaches.

Ti:Sa with incoherently combined fiber pump lasers. This hybrid OPCPA-Ti:Sa approach was presented by MIT-LL and U. Rochester. Owing to technical limitations on achieving high efficiencies (though efficiency is independent of rep rate), this approach is unlikely to be useful in the long term for powering many 10 GeV, 100 kHz LPA collider modules. It could be applied for the injector stage of an LPA collider where wall-plug efficiency is not so critical, or as a driver for a stand-alone single-stage LPA powering future light sources (FELs, gamma ray sources, etc.).

Ti:Sa with diode pumped lasers (thin or thick disc). Two approaches were presented by Colorado State University and the ELI ALPS project. Owing to technical limitations on achieving high efficiencies (though efficiency is independent of rep rate), this approach is unlikely to be useful in the long-term for powering many 10 GeV, 100 kHz LPA collider modules. It could be applied for the injector stage of an LPA collider where wall-plug efficiency is not so critical or as a driver for a stand alone single stage LPA powering future light sources (FELs, gamma ray sources, etc.).

Tm:YLF with direct CPA. This approach was presented by LLNL and Fraunhofer ILT in Aachen. This approach is promising and could be capable of delivering, with high wall-plug efficiency, 2-μm-wavelength laser pulses with high average power (tens to hundreds of kW). Large-aperture, joule-class pulsed Tm:YLF lasers have not been operated to date; demonstration of scaling Tm:YLF to operating at the multi-joule level is required in order to assess the true potential of this approach.

Fiber-based lasers with coherent combining. This approach was presented by University of Michigan, LLNL, LBNL, and Fraunhofer Institute at Jena, Germany. This approach is promising and could be capable of delivering an efficient driver for a 10 GeV, 100 kHz LPA collider module. Considerable R&D is required.

Table III summarizes the various approaches that are further detailed in Sections 3 and 4.

Table III: Summary of various approaches for LPA drivers. Architectures are typically reflected in the following building blocks: Electrical energy conversion to optical (typically semiconductor laser diodes), intermediary optical energy storage (“pump laser”), and short pulse laser that converts the narrowband pump energy into broadband, short pulses.

	Approach	Elec. → Opt.	Pump Laser						Short Pulse Laser					
		Laser Diode Delivery	**Gain Material**	**Architecture**	**# of apertures**	**Quantum Efficiency**	**Heat Removal**	**λ (µm)**	**Gain Material**	**Architecture**	**# of apertures**	**Quantum Efficiency**	**Heat Removal**	**λ (µm)**
1	**Fiber-pumped Ti:Sa**	Fiber-coupled laser diodes	Yb:Fiber	Incoherent Combination	~3000	0.91	Multi-aperture fibers	0.515	Ti:Sa	CPA Power Amp w/ NOPA Front End	1	0.64	Cryo edge cooling	0.8
2	**Ti:Sa Active Disk Laser**	Laser diode arrays	Yb:YAG	Cryo. Thin-disk	2	0.91	Cryogenic thin-disk	0.515	Ti:Sa	Active Mirror Multi-Pass Amplifiers	1	0.64	Cryo Disk Cooling	0.8
3	**Thin Disk Ti:Sa**	Same as approach 1 or 2	-	-	-	-	-	-	Ti:Sa	Thin-disk Multi-Pass Amplifier	1	0.67	Cryo thin-disk	0.8
4	**Big-Aperture Thulium**	Laser diode arrays	not applicable						Tm:YLF	Direct CPA	1	0.87	IFE Gas Cooling	1.9
5	**Ultrafast Fiber Lasers**	Fiber-coupled laser diodes	not applicable						Yb:Fiber	Coherent Combining Multi-core fiber	~500	0.91	Multi-aperture edge cooled	1.03
6	**Ultrafast Fiber Lasers**	Fiber-coupled laser diodes	not applicable						Yb:Fiber	Spectral, Spatial Combining and Temporal Pulse Stacking	~300	0.91	Low challenge-distributed	1.03

3. APPLICATIONS AND LASER SPECIFICATIONS

We next discuss in detail the applications that were explored at the workshop, and what requirements and constraints they impose on the design and operation of the laser systems. These include LPA electron accelerators for particle colliders and radiation sources, plasma based x-ray lasers, accelerator beam manipulation, and ion acceleration, as well as light source relevant applications including pump-probe experiments with ~10 mJ pulses at very high repetition rates (>100 kHz).

3.A. Laser driven particle accelerators: towards a collider and near term applications

Laser-plasma accelerators (LPAs) are capable of generating accelerating gradients that are several orders of magnitude greater than conventional RF accelerators, making the LPA an attractive technology for a future lepton collider.[9] A recent DOE HEP report, the *Advanced Accelerator Concepts Research Roadmap Workshop Report*,[10] has set a ten-year roadmap for R&D in the US toward this long-term goal. The laser parameters required to accelerate electron and positron beams to TeV-scale energy, with the luminosity and efficiency needed, are extremely challenging, and laser technology development is required in parallel with accelerator development. The laser system must be capable of delivering both high peak power (of order 10 J in 100 fs) and high average power (tens of kHz repetition rate) with high efficiency (wall-to-target efficiency of tens of percent).

The required laser parameters, for both 1- and 2-µm laser wavelengths for a 1-TeV center-of-mass linear collider design[11] based on laser-driven hollow-plasma channels operating at a plasma density of 10^{17} cm^{-3}, are shown in Table IV. These parameters may be scaled to different operating densities or laser wavelengths;[12] the density and wavelength scalings are also shown in Table II. The overall active acceleration length (linac length) and required power (operation costs) are independent of laser wavelength; hence there is freedom to select this parameter. It should be noted that the number of LPA stages required to reach the desired energy grows with the density and laser wavelength as $\sim n\,\lambda^2$, such that operating at twice the laser wavelength requires a fourfold increase in the number of LPA stages, while the required peak power per stage scales with $n^{-1}\,\lambda^{-2}$.

[9] W. Leemans and E. Esarey, "Laser-driven plasma-wave electron accelerators," Physics Today **62**, 3 (2009), p. 44.
[10] Advanced Accelerator *Development Strategy* Report, US Department of Energy Office of High Energy Physics (2016).
[11] C. Schroeder et al., "Laser-plasma-based linear collider using hollow plasma channels," in Proc. 2nd European Advanced Accelerator Concepts Workshop, Nucl. Instrum. Meth. A **829** (2016), pp. 113-116.
[12] C.B. Schroeder et al., "Physics considerations for laser-plasma linear colliders," Phys. Rev. Special Topics: Accel. Beams **13**, 10 (2010), 101301.

Table IV: Laser parameters for an LPA-based 1-TeV linear collider operating at $n=10^{17}$ cm^{-3}.

	~1 micron laser wavelength	2 micron laser wavelength	Plasma density (*n*) & laser wavelength (λ) scalings
Energy [J]	6.5	1.6	$n^{-3/2}\,\lambda^{-2}$
I [10^{18} W/cm^2]	2	0.5	λ^{-2}
Duration, FWHM [fs]	130	130	$n^{-1/2}$
Peak power [TW]	50	12	$n^{-1}\,\lambda^{-2}$
Rep. rate [kHz]	47	47	n
Average power [kW]	310	75	$n^{-1/2}\,\lambda^{-2}$
LPA stages / linac	100	400	$n\,\lambda^{2}$
Efficiency [%]	>30	>30	-
Contrast	10^6	10^5	λ^{-2}

3.B. Laser driven particle accelerators: radiation sources and pump-probe experiments

The high gradients enabled by laser-plasma accelerators (LPAs) could enable compact photon sources with broad application, if repetition rates can be increased. Compact near-monoenergetic photon sources at 1-10 MeV energies, based on Thomson scattering, offer improved sensitivity at greatly reduced dose for detection and characterization of nuclear materials, and for related x-ray applications in security, industry and medical imaging.[13] Additionally, brilliant and coherent soft x-ray photon sources could be created using LPA-driven free electron lasers (FELs), which would have broad importance.[14]

The laser requirements for the LPA are similar for Thomson sources and for soft x-ray FELs, since both require a GeV-class electron beam at repetition rates from 1 kHz for initial capabilities up to 100 kHz. The laser system must therefore be capable of delivering both high peak power (of order a few J in 30-100 fs depending on wavelength) and high average power (many kHz repetition rate) with high efficiency (wall-plug-to-target efficiency at or above 10%, a requirement that becomes more stringent at higher repetition rates). In addition to the LPA drive laser, Thomson scattering sources also require a second laser with similar energy but with ps pulse length.

The requirements make photon sources a stepping stone to future systems relevant to high energy physics colliders. The required laser parameters using either 1- or 2-µm laser wavelength are shown in Table V. These parameters may be scaled to different operating densities or laser wavelengths,[15] and the density and wavelength scaling are also shown in Table V. It should be noted that the scaling of laser parameters differs qualitatively from that for the collider case, since for photon sources a single stage is used to achieve the required energy.

---

[13] C.G.R. Geddes et al., "Impact of Monoenergetic Photon Sources on Nonproliferation Applications," final project report, DOE NNSA Defense Nuclear Nonproliferation R&D (in press, 2017).

[14] Z. Huang et al., "Compact X-ray Free-Electron Laser from a Laser-Plasma Accelerator Using a Transverse-Gradient Undulator," Phys. Rev. Lett. **109** (2012), 204801.

[15] E. Esarey, C.B. Schroeder, W.P. Leemans, "Physics of laser-driven plasma-based electron accelerators," Rev. Mod. Phys. **81**, 1229 (2009).

Recent experiments have confirmed the importance of tuning the spot quality to be nearly diffraction limited over the full focal depth of the laser for photon source[16] and collider relevant[17] LPAs. This improves LPA performance compared to optimizing the spot at the focal plane only. It enables, for example, one- to three-J, 40-fs pulsed lasers to drive an accelerator in the 0.2-0.5 GeV energy class, in agreement with the predictions of simulations. Non-Gaussian lasers require higher energy.

Table V: Laser parameters for an LPA-based Thomson source or soft x ray FEL operating near 1 GeV electron energy,

	1 micron laser wavelength	**2 micron laser wavelength**	**laser wavelength (λ) scaling**
Energy [J]	3	6	λ
I [10^{18} W/cm^2]	10-20	2-5	λ^{-2}
Duration, FWHM [fs]	30	60	λ
Peak power [TW]	90	90	*none*
Rep. rate [kHz]	1-100	1-100	*application dependent*
Average power [kW]	3-300	6-600	λ
Efficiency [%]	>10	>10	-
Contrast	10^6	10^5	λ^{-2}

Other photon sources would also benefit from kHz-class laser development. Hard x-ray FELs would be enabled at multi-keV energies using electron beam energies of ~10 GeV. This requires lasers with tens of J and 130 fs for 1 µm wavelength, with the scaling to other wavelengths following Table V. High harmonic generation sources prioritize very short pulse duration, at the 10 fs scale for 1 µm wavelength. To scale high harmonics to hard-x-ray wavelengths using laser-solid interactions for high-harmonic generation, ten-joule-class energy, and contrast of 10^{10} are needed.

3.C. Plasma-based soft x-ray lasers

There is a need for compact soft x-ray laser (SXRL) sources that can be installed in individual research laboratories and industrial sites. Plasma-based SXRLs are unique in that they can produce bright ultrafast pulses of soft x-ray coherent radiation with both narrow bandwidth and high pulse energy on a table top. These compact lasers are currently enabling applications that include nanoscale resolution static and dynamic imaging; dense plasma diagnostics; single-photon ionization mass spectrometry of nanoclusters and molecules; the development of analytic nanoprobes; defect-free patterning of nanostructures; and nanomachining. However, many applications are limited by the SXRL average power available. Numerous nanometrology techniques would flourish if these tabletop lasers reached the average power of FELs.

---

[16] C.G.R. Geddes et al., "Laser technology for Thomson MeV photon sources based on laser-plasma accelerators," Proc. 2014 Advanced Accel. Conf. 2014, AIP Conference Proceedings **1777** (2016), 110002.

[17] W.P. Leemans et al., "Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime," Phys. Rev. Lett. **113** (2014) 245002.

Until recently, thermal effects within flashlamp-pumped solid-state driver lasers have limited the repetition rate of plasma-based SXRLs to 10 Hz or less, resulting in maximum average powers up to tens of µW. Recently, the development of diode-pumped ultrashort pulse solid-state laser drivers enabled the scaling of the repetition rate to 100 Hz, resulting in the demonstration of 0.1 mW average power at λ = 13.9 nm and 0.2 mW at 18.9 nm,[18] and lasers at multiple wavelengths down to 10.9 nm. The technology of efficient high energy ultrashort pulse laser drivers operating at kHz repetition rates of the type needed for k-BELLA, in combination with new plasma forming techniques, could increase the average power of plasma-based SXRLs to tens of mW and beyond. Laser parameters needed are joule(s) per pulse at kHz repetition rate. Sub-50 fs pulse duration will allow for efficient injection seeding for full spatial and temporal coherence. Such lasers would make high average power beams of coherent, narrow-bandwidth soft x-rays available to numerous applications at the locations where they are needed.

3.D. Lasers for beam manipulation and control

For applications where a laser-driven accelerator will be driving an FEL, or where optical lasers are used in conjunction with FELs driven by conventional accelerators, lasers operating at the same repetition rate as the FEL will be required in order to obtain optimal FEL performance.

FEL self-seeding has been demonstrated, and while it does work, it is not always optimal, because the seed is produced by filtering noise, and in many cases there is not enough power in the required spectral region to seed the FEL process. Because of this, self- seeding (as has been demonstrated to date) is a trade-off between spectral brightness and shot-to-shot pulse energy. At photon energies below several hundred eV, this pushes the technology towards external laser seeding.

External laser seeding in the VUV and soft x-ray spectral region requires some sort of photon energy multiplication from the optical wavelength to the required seeding wavelength. There are multiple techniques for achieving this, the most notable being cascaded High Gain Harmonic Generation (HGHG) or Echo Enabled Harmonic Generation (EEHG). Each of these techniques has its own specific laser requirements, but both typically require a few stages of frequency conversion from the fundamental to the required wavelength, sometimes in an optical parametric amplifier (OPA). This introduces an efficiency term that typically requires power from the fundamental laser in the range of several to many tens of mJ. At 1 kHz, this is within the current state of the art, but as repetition rates scale to tens of kHz or higher, the laser power required reaches the kW level.

There are also many beam manipulation techniques aimed at generating much shorter (attosecond scale) pulses than can be directly produced in an FEL. One notable example that will be tested in the next year is Enhanced Self-Amplified Spontaneous Emission (E-SASE). This technique manipulates the electron beam phase space in a way that results in a very short, high-peak-current spike in the electron bunch, which lases, producing very short pulses. Since E-SASE has yet to be demonstrated, the exact needs are not well defined, but very short mJ scale pulses in the mid-IR, possibly carrier-envelope phase (CEP) stabilized, is expected. Once again,

[18] B.A. Reagan, M. Berrill, K.A. Wernsing, C. Baumgarten, M. Woolston, J.J. Rocca, "High-average-power, 100-Hz-repetition-rate, tabletop soft-x-ray lasers at sub-15-nm wavelengths," Phys. Rev. A **89** (2014), 053820.

at 1 kHz rates, this is right at the edge of current state of the art, but as repetition rates increase, this will push these lasers well beyond what is currently possible.

It should be pointed out that as e-beam powers increase, beam manipulation and control with slits and wires becomes impossible because of the heat load on the material. As a result, significant effort is being put toward replacing some of these manipulation or measuring devices with lasers. As repetition rates scale beyond 1 kHz, these lasers will also scale beyond the current state of the art.

E. Laser driven high energy density science – ion acceleration

High peak and average power laser systems will enable novel industrial, medical and scientific applications of intense, short proton and heavy ion pulses. Lasers producing a few tens to hundreds of J in relatively short pulses (100 fs - 1 ps) would have to operate at tens of Hz to 100 Hz, and have pulses with a temporal contrast that exceeds 10^{12} at the nanosecond timescale. High repetition rate pulses of protons and heavy ions at a few MeV/u are very useful for materials analysis (e.g., by proton induced x-ray emission, PIXE, for analysis of historic artifacts, archeology, etc.)[19] and for materials processing applications such as deep ion implantation for semiconductors.[20] The short, intense ion pulses from laser-plasma acceleration further enable novel pump-probe type experiments where the ion beam is the pump pulse and where the ensuing materials dynamics can be tracked with a synchronized structural probe pulse (e.g., x-rays or electrons).[21] Further, novel materials processing regimes of "extreme chemistry" become accessible with intense ion pulses that can excite materials uniformly of a depth of tens to hundreds of microns.[22]

While these processing regimes are subject of basic research and proof-of-concept demonstrations now, they can advance to industrial application environments when high-rep-rate systems become available. For proton/ion cancer therapy[23,24] tunable narrow band high flux protons of at least 250 MeV, and carbon ions of multi-GeV energy (400 MeV/u) with dose rate of Gy/sec are required to deliver the required local doses to tumors deep inside patients' bodies. For high repetition rate proton/ion acceleration to be a routine tool, significant research and development challenges such as high-repetition-rate ultra-thin solid density targets and reliable beam transport also have to be addressed together with high-average-power laser development. Schreiber et al. recently reviewed challenges and opportunities for applications of laser accelerated ions.[25]

---

[19] M. Barberio et al., "Laser-accelerated proton beams as diagnostics for cultural heritage", Scientific Reports **7**, 40415 (2017).

[20] I.P. Jain and G. Agarwal, "Ion beam induced surface and interface engineering," Surface Science Reports **66**, 3-4 (March 2011), pp. 77–172.

[21] T. Schenkel et al., "Towards pump-probe experiments of defect dynamics beam pulses", Nucl. Instrum. Meth. B **315** (15 Nov. 2013), p. 350-.

[22] J.J. Barnard and T. Schenkel, "Materials processing with intense pulsed ion beams and masked targets," submitted for publication (26 May 2017).

[23] S. Bulanov and V. Khoroshkov, "Feasibility of using laser ion accelerators in proton therapy," Plasma Phys. Reports **28**, 5 (May 2002), p. 453.

[24] L. Yin et al., "Monoenergetic and GeV ion acceleration from the laser breakout afterburner using ultrathin targets," *Physics of Plasmas* **14**, 5 (April 2007), pp. 1–8.

[25] J. Schreiber, P. R. Bolton, and K. Parodi, "Hands-on laser driven ion acceleration: A primer for laser-driven ion source development and potential applications," invited review article, Rev. Sci. Instrum. **87**, 9 (July 2016), p. 071101.

4. TECHNICAL APPROACHES

Six technical approaches were considered that could provide the required operational specifications for near- and long-term laser facilities. A preliminary assessment of risks and mitigation strategies as well as resources needed to address the risks was developed.

Three approaches rely on using Ti:Sa as the gain medium, lasing at 0.8 um wavelength and differ in the pump laser architecture and the Ti:SA gain medium geometry (see Table I). The k-BELLA requirement for 3-J, 30-fs pulses is well within the state of the art of Ti:Sa lasers. On a single-shot basis, Ti:Sa final amplifiers have been scaled to 202 J (129 J compressed) pulses at 24-fs pulse width.[26] In terms of average power, the BELLA laser at LBNL routinely delivers nearly 50 W average power (49 J at 1 Hz in <35 fs) to experiments, and the HAPLS laser at LLNL is designed to eventually generate 430 W of power before compression at a 10-Hz repetition rate. HAPLS is presently operating with 16 J of energy at a 3.3-Hz rate before compression yielding nearly 53 W of average power with laser crystals cooled by room-temperature helium gas.[27] A 0.8 PW Ti:Sa laser at Colorado State University pumped by Nd:glass slab amplifiers designed to operate at 5 Hz repetition rate is presently delivering 35 J pulses at 3.3 Hz rate before compression [4] Commercial pulsed Ti:Sa lasers with cryogenic cooling of the final-amplifier laser crystals are also available with 10-mJ-class energies and average powers in the 20-50-W range.[28,29] Realizing average powers of 3 kW after compression for the proposed k-BELLA system will require a major advance in the state-of-the-art in average power for Ti:Sa and associated pump laser technology, and high-peak-power lasers in general.

One approach relies on the well-established helium-gas-cooling technique developed at LLNL for Inertial Fusion Energy (IFE) lasers[30] and uses cw-pumped thulium doped YLF (Tm:YLF) as a gain medium, lasing at 1.9 μm wavelength, with direct diode pumping. Tm:YLF has been utilized mainly in cw- and short pulse fiber lasers, but has been increasingly used in bulk form in cw (record: 200 W demonstrated)[31] and pulsed lasers.[32] Tm:YLF is naturally birefringent, and considering the weaker thermal lensing effect and better mechanical properties compared with other rare earth-doped materials, for a laser crystal with absorption band at around 800 nm and emission band at 1850–2000 nm it is an attractive material for efficient, simple and cost-effective diode-pumped solid-state lasers. This approach is novel and builds on the integration and scaling of demonstrated thermal management and high average power diode

[26] Zebiao Gan et al., "200 J high efficiency Ti:sapphire chirped pulse amplifier pumped by temporal dual-pulse," Optics Express **25**, 5 (2017), pp. 5169-78.

[27] Constantin Haefner, Craig Siders, and Dieter Hoffmann, "kW short pulse laser driver technology (TA3)," presented at Laser Technology for k-BELLA & Beyond Workshop (LBNL Berkeley, CA, 2017).

[28] Coherent Legend Elite Cyro PA, specified to produce > 20 mJ pulses at 1 kHz (>20-W average), with < 30 fs pulse widths.

[29] KM Labs RedWyvern, specified with options for 30 mJ pulses at 1 kHz (30-W average) and 5 mJ pulses at 10 kHz (50-W average) with < 25-fs pulses.

[30] Emmet, J.L., Krupke, W.F., Sooy, W.R., "The Potential of High-Average-Power Solid State Lasers", UCRL-53571, Sept.1984, https://www.osti.gov/scitech/servlets/purl/6294772

[31] Meissner, A., et al. "200-W Tm:YLF INNOSLAB Laser," SPIE Proc. **8599** (2013), 85991C; J. Li et al 2013 Laser Phys. Lett. 10 055002.

[32] 400 mJ has been demonstrated by NASA Langley, and a space-capable 200mJ/5Hz laser was demonstrated in 2011. See Upendra N. Singh et al., "Twenty years of Tm:Ho:YLF and LuLiF laser development for global wind and carbon dioxide active remote sensing," Optical Materials Express **5**, 4 (2015), pp. 827-37.

pump technologies on Mercury[33] and HAPLS[34]. To date no multi-joule-class systems have been demonstrated but, if successful, this approach has the potential to provide high energy laser pulses at high repetition rate and high wall-plug efficiency. The longer wavelength does have important implications for a collider discussion: the amount of laser energy per pulse is reduced fourfold (inversely proportional to the square of the wavelength) significantly increasing the performance margin on laser damage threshold and Mean Time To Failure (MTTF) for optics. However, the number of stages is increased fourfold (proportional to the square of the wavelength), increasing greatly the number of components and staging intervals.

Two other approaches rely on coherent pulse combining of low energy laser pulses amplified in fiber based systems to generate high energy pulses. These approaches are also novel and offers the potential of high wall plug efficiency, and low laser-driver costs. Fiber based lasers operating in a continuous wave mode are commercially available at power levels of 100 kW with wall-plug efficiency approaching 45%. Significant challenges remain in combining many pulses with high pulse shape fidelity and pulse contrast but the potential benefit of such a system merit continued development as a potential candidate to meet the long term needs. In the nearer term, high-repetition-rate (>100 kHz) lasers providing tens-of-mJ pulses for non-LPA applications seem very feasible.

We next discuss each technical approach in detail, first for a near term 3 kW facility such as a test platform for high average power LPA technology as well as a demonstrator for high flux radiation sources, and second for a long term 300 kW facility such as a collider module.

4.A. Near term (0-5 years)

This section discusses near-term prospects for 3-kW high-pulse-energy lasers (k-BELLA: 3 J, 1 kHz) and low-pulse-energy lasers (30 mJ, up to 100 kHz).

4.A.1. Ti:Sa based

Ti:sapphire supports the short pulse durations required to drive the science cases of interest. The key challenges to achieve high repetition rates are the implementation of more efficient pump lasers than the present flashlamp-pumped systems, and thermal management to enable high average power. Three approaches addressing these challenges were discussed.

4.A.1.a. Incoherent combined fiber pump lasers

High-level concept: A hybrid architecture combining advanced optical parametric and Ti:Sa amplifiers leverages mature technology to realize k-BELLA performance and a facility within five years. Figure 1 illustrates the key elements. Optical parametric chirped-pulse amplification (OPCPA) is a proven technology that can be scaled to higher pulse energies and average powers

---

[33] Bayramian et al., "The Mercury Project: A High Average Power, Gas-Cooled Laser for Inertial Fusion Energy Development", Fusion Science and Technology . **52** (Oct. 2007) pp. 383-387.

[34] C. L. Haefner et al., "High average power, diode pumped petawatt laser systems: a new generation of lasers enabling precision science and commercial applications", Proc. SPIE 10241, Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers III, 1024102 (June 26, 2017); doi:10.1117/12.2281050.

with excellent beam quality using modern solid-state pump laser technology that facilitates joule-class picosecond and nanosecond OPCPA modules. High single-pass broadband gain offers experimental flexibility (including pulse duration as short as 15 fs) and ultrahigh temporal contrast needed to support a broad range of experiments. OPCPA will likely be used as a front end for any bulk laser technology to mitigate gain narrowing. Intrinsically low optical losses in OPCPA crystals nearly eliminate thermal loading and associated beam degradation; plus, power not converted to the output signal can could be reclaimed to enable high wall-plug efficiency. Alternatively, a commercial Ti:Sa based front-end system could be considered that operates at a kHz repetition rate and meets the power requirements.

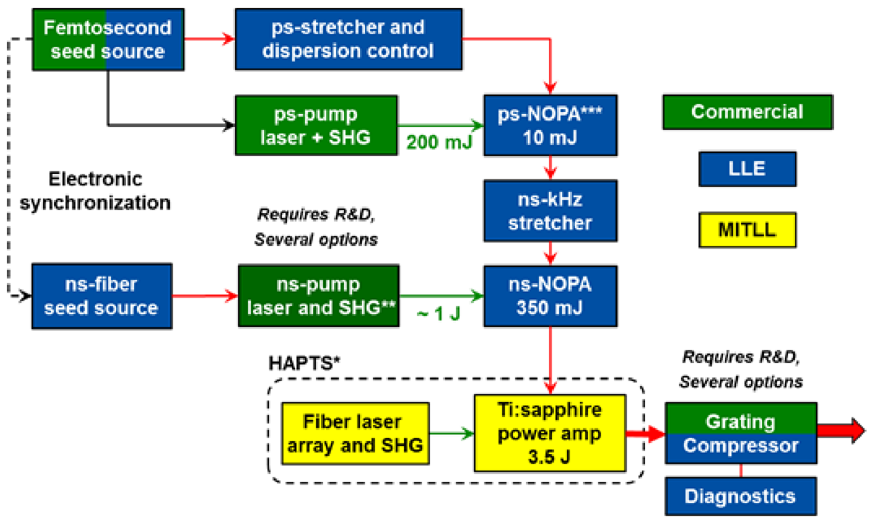


Figure 1. Schematic diagram of a hybrid OPCPA-Ti:Sa laser system for k-BELLA. HAPTS = high-average-power, fiber-laser-array-pumped Ti:Sa; SHG = second harmonic generation; NOPA = noncollinear optical parametric amplifier.

Ti:Sa laser amplification is technically very mature and minimal R&D is needed to demonstrate that it can provide ultrafast pulses at few kW level average power in the near term. A novel, fiber-based pump laser system is proposed that uses commercial-off-the shelf (COTS), telecom-grade components in a fiber array that can spatially shape the gain profile and deliver Gaussian-like focal spots. The relative cost per joule of pump energy of the fiber-based pump system would be less than 25% that of conventional pump lasers. Cryogenic cooling of Ti:Sa has been commercially demonstrated at the 5 mJ level with average power ~50 W.[35] Advanced cryogenic cooling proven in other high-average-power (HAP) lasers by the team would enable multi-kilowatt average powers. Last but not least, high-average-power gratings are a critical technology common to all technical approaches and must be advanced.

[35] For example KM Labs, RedDragon https://kmlabs.com/product/reddragon-50w/

State of the art: The OPCPA front end employs state-of-the-art technology. Broadband seed sources using white light continuum or Ti:Sa oscillators are commercially available to seed both the hybrid chirped pulse amplification and the picosecond OPCPA pump laser. Equipment and designs for grating pulse stretchers and programmable dispersion-control devices are commercially available, as are HAP Yb:YAG regenerative amplifiers and low-loss SHG crystals for OPCPA pump lasers.

Colorado State University has demonstrated multi-pass Yb:YAG amplifiers producing >1-J pulses at 1 kHz (see Section 4.a.1.b of this report) and a system with similar performance is being developed commercially by TRUMPF Scientific Lasers.[36] The latter uses industrial-grade, thin-disk laser technology deployed for 24/7 operation in factories around the world. Highly reliable, fiber-based, nanosecond seed sources that provide high-fidelity pulse shaping have been proven in laser fusion facilities, including the OMEGA Laser Facility at LLE. Ultra-broadband OPCPA systems with picosecond pumping have been commercially demonstrated at average powers up to 55 W (55 mJ at 1 kHz), and 200 W (200 mJ at 1 kHz) systems are being developed. Similar high average powers are expected for the proposed nanosecond OPCPA system.

Cryogenic cooling of Ti:Sa enables high average power output with high beam quality. Cryogenic cooling to 77 K, compared to room-temperature operation, simultaneously increases sapphire's thermal conductivity about 30× while also reducing the change of refractive index with temperature (about 7×) and the thermal expansion coefficient (about 15×). The net of all these improvements leads to an expectation that Ti:Sa lasers could operate with 200× more power at cryogenic temperatures.[37] While this provides some guidance, scaling power with cryogenic cooling depends on the cooling geometry. The room-temperature, gas-cooled slab geometry used for the HAPLS system suggests that considerable margin exists for scaling large-aperture designs to 3 kW with a cryogenically cooled gas. A similar large-aperture, high-energy system, the Yb:YAG DIPOLE laser developed at the Rutherford Laboratory, recently generated 1 kW of average power (105 J at 10 Hz) with 150 K, He-gas cooling[38] and high brightness beam output.

The relatively small aperture needed for a k-BELLA Ti:Sa laser crystal suggests that better cooling would be obtained by conduction through the side of the laser material, rather than face cooling. The crystal would be bonded to a heat sink cooled by a cryogen, such as liquid nitrogen. MIT Lincoln Laboratory (MIT LL) has considerable experience with this approach, and in older published work has reported 455 W of continuous-wave power, with high beam quality, for conduction cooled Yb:YAG crystals.[39]

The pulsed pump source would employ a multitude of individual pulsed fiber lasers that are incoherently combined to provide the needed pump pulse energy of ~13 J at a 1 kHz rate. The design pulse energy from each fiber falls in the 2.5 to 3.5 mJ range, with a nominal 100-ns-duration output pulse. These energies fall below reported values for diffraction-limited

---

[36] Personal communication.

[37] P.A. Schulz and S.R. Henion, "Liquid-nitrogen-cooled Ti:Al_2O_3 laser," IEEE J. Quantum Electronics **27**, 4 (April 1991), pp. 1039-1047.

[38] P. Mason et al., "Kilowatt average power 100 J-level diode pumped solid state laser," Optica **4**, 4 (2017), pp. 438-9.

[39] T.Y. Fan et al., "Cryogenic Yb^{3+}-Doped Solid-State Lasers, " IEEE J. Selected Topics in Quantum Electronics **13**, 3 (May-June 2007), pp. 448 (2007).

performance with 4 mJ, 50 ns pulses at 3 kHz.[40] The majority of research on pulsed, nanosecond fiber lasers seeks much shorter pulses, in the 1-10 ns range, where fiber damage and nonlinearities limit pulse energies to approximately 1 mJ.

Ti:Sa lasers currently use gold-coated gratings operating near the short-pulse fluence limit. For k-BELLA to deliver high peak *and* high average power, multi-layer dielectric (MLD) gratings with greatly reduced absorption have been developed to minimize the thermal load.[41] The trade-off for improved average power handling is a reduction in bandwidth and diffraction efficiency when they are used far from the Littrow incidence angle. One solution is to use an out-of-plane compressor design, where the four Littrow gratings are tipped for use in reflection.[42] Simulations show that new MLD gratings fabricated on thermally stable and high-conductivity substrates that are actively cooled reduce degradation of the pulse width, temporal contrast, and focal spot, and should in principle meet the k-BELLA requirements.

Technical risks and mitigation strategy

Gratings: Diffraction gratings that provide high damage thresholds and efficiency at multi-kilowatt average power and support the bandwidth required for compressing pulses as short as 30 fs are a critical technology for all HAP lasers. Proving this technology and other HAP optical components will critically depend on leveraging all available expertise in the community, and would be of benefit to all technical approaches operating near 1 µm for k-BELLA and beyond.

Modest beam sizes (~300 cm^2 or ~20 cm diameter) are required given the ~10 W/cm^2 average power handling capacity (10 mJ/cm^2 at 1 kHz) of current commercial gold grating technology.[43] LLNL recently reported a four-grating pulse compressor using multi-layer dielectric (MLD) gratings with >98% diffraction efficiency over 45 nm bandwidth operating at the Littrow angle using an out-of-plane configuration.[44] Furthermore, LLNL demonstrated active cooling gratings with size consistent with 1 PW operating and exposed to ~1kW. This technology is expected to scale to ~hundreds of kW.[45]

Initial damage testing with 80-fs pulses at low repetition rates (10 Hz) showed a 50% damage probability of 300-mJ/cm^2. The laser damage threshold reported for another broadband MLD grating design[46] is 180 mJ/cm^2. Plymouth Grating Laboratory and Horiba Jobin-Yvon are developing broadband gold-on-etched-substrate and metal-multi-layer dielectric (MMLD) gratings with similar performance. Laser damage resistance and average power handling of all

[40] J. Limpert et al., "100-W average-power, high-energy nanosecond fiber amplifier," Appl. Phys. B **75**, 4 (2002), 477.

[41] D.A. Alessi et al., "Active cooling of pulse compression diffraction gratings for high energy, high average power ultrafast lasers," Optics Express **24**, 26 (2016), pp. 30015-30023.

[42] M. Divoký et al, "Off-plane diffraction in pulse stretcher and compressor," CLEO Europe (2005), p. 432.

[43] Horiba Jobin-Yvon, private communication.

[44] D. A. Alessi, H. T. Nguyen, J. A. Britten, P. A. Rosso, and C. Haefner, "Broad-bandwidth low-dispersion multilayer dielectric diffraction gratings for 800nm pulse compression," (in preparation), and D. Alessi, and C. Haefner, "High-Average-Power Diffraction Pulse-Compression Gratings Enabling Next-Generation Ultrafast Laser," Lawrence Livermore National Laboratory report LLNL-TR-707794 (Nov. 2016).

[45] D. A. Alessi, H. T. Nguyen, J. A. Britten, P. A. Rosso, and C. Haefner, "Broad-bandwidth low-dispersion multilayer dielectric diffraction gratings for 800nm pulse compression," (in preparation). The average power capability is dependent on the MLD absorption. Modern coating technologies have demonstrated lower absorption and therefore grating absorption can be reduced from 500 ppm to 60 ppm. Even higher average power handling might be achieved with further reduction of absorption and substrates that conduct heat better.

[46] D.H. Martz et al., "Large area high efficiency broad bandwidth 800 nm dielectric gratings for high energy laser pulse compression," Optics Express **17**, 26 (2009), pp. 23809-16.

these gratings, including the influence of the vacuum environment, should be assessed to independently evaluate performance.

Gaussian focal-spot profile: Typical Ti:Sa high-energy laser systems employ flat-top pump beams, from one or a small number of pump lasers, along with a matching extraction beam, in the final-stage amplifier. However, a flat-top output beam is undesirable for the end use in driving capillary-based laser plasma acceleration, where a Gaussian near-field beam profile is much more appropriate. In conventional high-energy systems, one would expect to sacrifice extracted energy with a Gaussian beam. Using an array of many fiber-laser-based pump beams could enable a highly customizable spatial profile for the pumped region in the Ti:Sa final amplifier. This baseline approach allows maximizing the extraction efficiency from a Gaussian output beam.

The OPCPA driver system provides another level of optimization, as the input beam to the amplifier can be shaped in the early stages of the OPCPA chain to provide an optimally matched input profile to the final-stage Ti:Sa amplifier. The highly saturated amplification in the OPCPA driver system, along with the high stability provided by the fiber-laser pumping scheme, assures that the desired beam profile will have a high degree of amplitude and beam-pointing stability.

Schemes need to be explored to convert near-field beams with high fill factors to Gaussian-like far fields as they could provide an advanced approach to determining whether both desirable conditions (amplitude and beam-pointing stability) can be achieved. Design techniques employing laser beam intensity and wavefront control, which were developed to optimize beam profiles at both far and intermediate fields on the National Ignition Facility for a spot-blocking system, could be extended.[47]

Thermal effects in OPCPA chain: The thermal load in optical parametric amplifiers (OPAs) is relatively negligible compared to laser materials that rely on energy storage. Even so, absorption in OPA crystals at high average powers (HAP) may produce thermal gradients that disturb phase matching and cause gain bandwidth reductions and beam quality degradations.[48] A cw, kilowatt laser test bed is under construction as part of an LLE-MIT LL collaboration to test LBO (lithium triborate—LiB_3O_5) under HAP conditions. Sensitive interferometric and thermal imaging techniques will be used to measure temperature gradients and wavefront changes in samples with ultra-low absorption (< 3 ppm/cm). A separate 1-kHz pulsed source will be simultaneously frequency doubled as the thermal load is varied to calibrate and qualify nonlinear optical models that include finite-element modeling of the crystals.

A second test bed will be built with scaled-aperture broadband OPAs. Tests with picosecond and nanosecond pump pulses will validate point designs and be used to demonstrate techniques for optimizing efficiency by shaping the temporal pulses and near-field beams for maximum overlap between the pump and signal. A compressor will be added to demonstrate schemes to achieve adjustable temporal contrast.

Thermal effects in Ti:Sa final amplifier: As noted above, the required k-BELLA power output represents a major advance in the state of the art, and we estimate that about 2.5 kW of

---

[47] Bahk et al., "Spot-shadowing optimization to mitigate damage growth in a high-energy-laser amplifier chain"On," Applied Optics **47**, 35 (10 Dec.(1 Sept. 2008), pp. 6586- 6593.

[48] Riedel et al., "Thermal properties of borate crystals for high power optical parametric chirped-pulse amplification," Optics Express **22**, 15 (2014), pp. 17607-17619.

heat will need to be removed from the laser crystal. Fortunately, the thermal, optical and mechanical properties of sapphire are well understood over a wide temperature range, providing a firm foundation for computer-aided design work to develop an optimum heat-extraction scheme that also minimizes optical distortion of the output beam. Cooling techniques including both static and flowing liquid nitrogen designs are under consideration. They provide low-to-mid tens of W/cm^2 heat removal, and would likely require the use of heat spreaders between the laser crystal and the coolant. More advanced schemes, such as evaporative spray cooling, could enable much higher critical heat fluxes (>100 W/cm^2) and lower thermal impedance. Sub-scale amplifiers working at a nominal 300-W level would be constructed early in k-BELLA system development to test models and provide confidence in scaling to multi-kW power levels.

Fiber-laser-based pump lasers: Design trade-offs regarding fiber core size and length need to be resolved through construction of a test system and evaluation of performance against several variations in design. This would be done at an early stage of the laser construction effort to facilitate initial production of enough fiber pump lasers to build a sub-scale Ti:Sa power amplifier, as noted above, for evaluating cryogenic cooling techniques.

A preliminary assessment of the state of the art and TRL level for this approach are presented in Table VI.

Table VI. State of the art and estimated TRLs

Subsystem	Achieved performance	TRL	Reference(s)
fs seed	$\Delta\lambda$ ~ 200nm, C > 10^{12}, P ~ 1W, f_{rep} ~ MHz	9	Multiple demonstrations in literature
HAP-OPCPA:			
• TD regen • multi-pass amplifier • HAP SHG • HAP-OPCPA	• 230mJ/1ω/1ps/1kHz (CPA) • 1J/1ω/2ps/1kHz (CPA) 1J/1ω/5ps/1kHz (CPA) • 7J @ 82%, 10Hz • 500mJ @ 5Hz, $\eta_{p\text{-}s}$=37%; 55mJ @ 1kHz, ps OPA	8 4 4 4* 4* 4*	• TSL web site • TSL private communication CSU results in TA5 report • OptExpr 24, 19682 (2016) • OptLett 30, 1843 (2005); OptExpr 25, 5797 (2017)
HAPTS power amplifier:			
• ns fiber laser • fiber array • cryo Ti:S	• COTS ns fiber lasers • fiber array demonstrated • 50W avg/<25fs/5-10kHz 115W avg/5Hz (not cryo)	9 7-8 4* 4*	• Various suppliers • LL private communication • KMLabs web site CSU results in TA5 report
HAP gratings + compressor	• 50W avg/<25fs/5-10kHz • 80W avg/24.5J/30fs/3.3Hz	3*	• KMLabs web site CSU results in TA5 report
* Lower power demonstrated @ TRL8/9 but requires power scaling			

4.A.1.b. Compact bulk Yb:YAG pumped Ti:Sa active disk laser

This approach to a k-BELLA-class system relies on Ti:Sa as the gain medium and extending diode-pumped cryo-cooled Yb:YAG pump laser technology that has already been demonstrated at the kW average power level.[49] The same successfully demonstrated high capacity cryo-cooling technique can be used to solve the thermal management challenge in the 3 kW Ti:Sa amplifier for k-BELLA.

A conceptual diagram for such a 3 kW, kHz, fs laser system is shown in Figure 2. The system will be remarkably compact: it will fit on a single 5'x16' optical table.

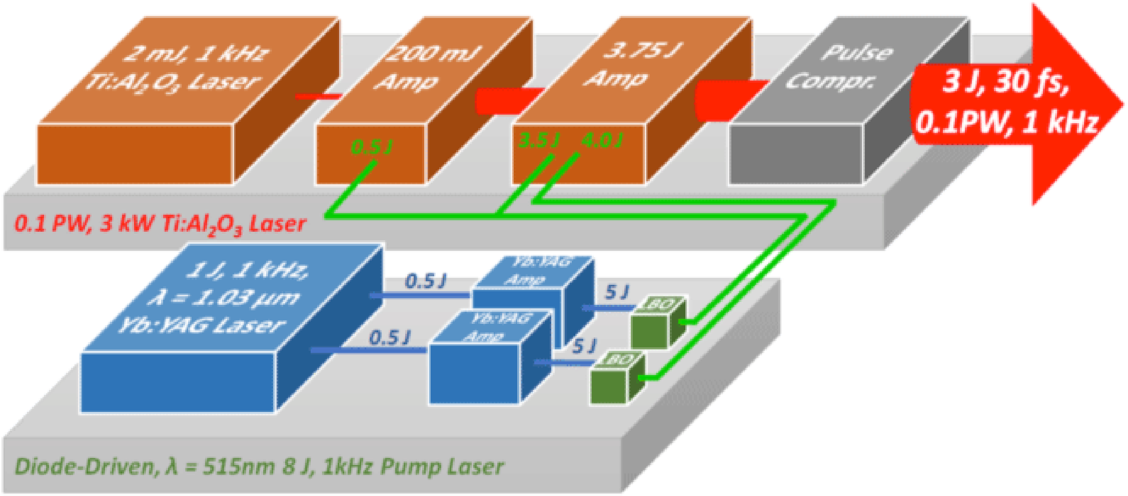


Figure 2. *Conceptual diagram of a compact 3 kW average power, 0.1 PW Ti:Sa laser pumped by two cryo-cooled bulk Yb:YAG amplifiers. The pump concept has already been experimentally proven at 1 J, 1 kW average power. A chain of two cryo-cooled Ti:Sa disk amplifiers is seeded with a conventional Ti:*Al_2O_3 *laser with XPW for improved contrast. These amplifiers are pumped by two diode-driven, bulk Yb:YAG active mirror amplifiers that are frequency doubled in LBO to generate λ = 515 nm , 8 J pulses at 1 kHz repetition rate. After compression, 3 J, 30 fs duration pulses are obtained at a 1 kHz repetition rate.*

Pulses from a commercially-available 2 mJ, 1 kHz Ti:Sa laser front end will be amplified by a chain of two multi-pass cryogenically cooled active mirror Ti:Sa amplifiers to reach an energy of 3.75 J. These multi-pass amplifiers will be pumped by λ = 515 nm pulses. The pulses are produced by frequency doubled diode-pumped bulk Yb:YAG laser amplifier modules that are based on recently demonstrated diode-pumped high power Yb:YAG active mirror cryogenically cooled amplifier laser technology. A prototype of such an amplifier module has already produced 1.5 J pulses at a 500 Hz repetition rate (750 W average power),[51] and 1 J pulses at a 1 kHz repetition rate. The cost per joule is significantly lower than other conventional pump lasers. An additional advantage of this pump laser system is its modular architecture that offers the great flexibility for scaling and reduced risk.

---

[49] Reagan, B.A. et al., "Demonstration of a 100 Hz repetition rate gain-saturated diode-pumped table-top soft x-ray laser. *Opt. Lett.* **37**, 17 (2012), pp. 3624–3626.

4. TECHNICAL APPROACHES

In the proposed concept, the output of a fully engineered version of this 1 kW average power laser will produce 1 J pulses that will be split into two amplifier units, each a scaled version of the Yb:YAG bulk diode-pumped amplifier module shown in Figure 3. Each amplifier module will produce 5 J, λ = 1.03 μm pulses at a 1 kHz repetition rate. These pulses will be subsequently frequency-doubled with 80% efficiency in Type I LBO crystals, resulting in green pump pulses at a combined 8 J. Alternatively the same pump pulse energy could be obtained using four Yb:YAG amplifier modules with half the power, or, for more margin, four 3 J amplifier modules.

A fraction will pump a Ti:Sa amplifier that will amplify the stretched pulses from the Ti:Sa front end into 200 mJ pulses at a 1 kHz repetition rate. The remaining λ = 515 nm pump energy will pump the second Ti:Sa amplifier, which will produce 3.75 J stretched pulses at a 1 kHz repetition rate. These pulses will be compressed by a grating pair to a duration of < 30 fs to deliver 3 J pulses at 1 kHz. Concept advantages are pump technology proven at the kW average power level, compactness, and cost effectiveness in term of dollars per joule of pump.

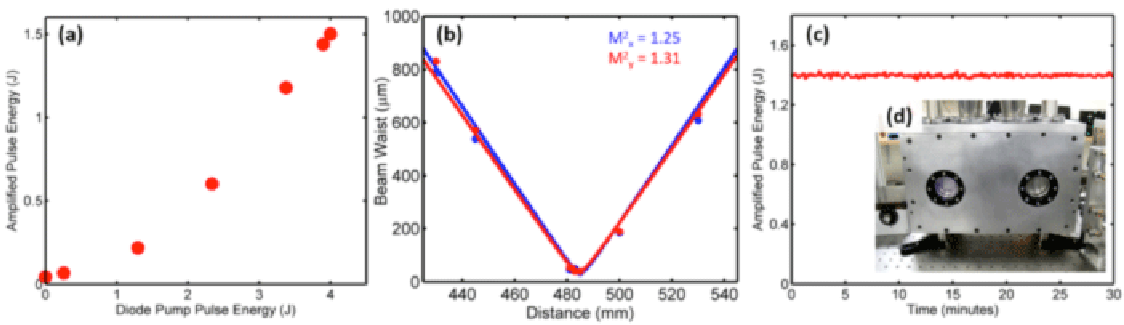


Figure 3. *Measured performance of a 1.5 J, 500 Hz repetition rate, λ = 1.03 μm chirped pulse amplification laser based on bulk, cryogenic Yb:YAG active mirror amplifiers. (a) Measured pulse energy at the output of the main amplifier as a function of pump pulse energy at 500 Hz repetition rate. (b) M^2 measurement of 1.4 J pulses exiting the at the output of the amplifier at 500 Hz repetition rate. (c) Measured output energy RMS variation of 0.75% at the full repetition rate over 30 minutes at full repetition rate. (d) Photograph of the laser amplifier module.*

State of the art: kilowatt average power diode-pumped bulk Yb:YAG laser technology

A major roadblock in the development of a joule-level, multi-kilowatt average power femtosecond laser was recently to a large extent overcome with the demonstration of joule-level, kW average power, diode-pumped cryogenically-cooled λ = 1.03 μm, Yb:YAG amplifier technology developed at Colorado State University (CSU) in partnership with XUV Lasers.[50] In 2012, an all-diode-pumped chirped-pulse amplification (CPA) laser system that produced 1-J pulses of 5 ps FWHM duration at a 100 Hz repetition rate was demonstrated and used in driving plasma-based ultrashort wavelength lasers between 10-20 nm.[51] Recently, this cryocooled thick disk technique was scaled to generate 1.5 J pulses at a 500 Hz repetition rate (0.75 kW) that were compressed to ps duration [Baumgarten, ibid.].

The performance of this compact CPA laser module as shown in Figure 3 defines the state of the art: 1.5 J at 500 Hz repetition rate (Figure 3a). The pulses have excellent beam quality (M^2 factor of ~1.3), as shown in Figure 3b. Furthermore, stable, long-term operation has been demonstrated. Figure 3(c) shows nearly 1 million consecutive 1.4 J shots at a repetition rate of 500 Hz with a shot-to-shot fluctuation of 0.75% RMS. These pulses were subsequently compressed, resulting in the generation of 1 J, 5 ps pulses at 500 Hz repetition rate. In a preliminary experiment, >70% conversion efficiency into λ = 515 nm pulses was demonstrated. This cryo-cooled active mirror module can be scaled to produce 4 J per pulse of green light at a 1 kHz repetition rate, to fulfill the requirements to pump a k-BELLA-class laser. The same cryo-cooled disk laser technique can be used to cool an active mirror Ti:Sa amplifier, with the great advantage of increased heat conductivity of Ti:Sa at liquid nitrogen temperature; or, alternatively, transmission-based disks, discussed below, could be used.

Key technical risks and mitigation strategy

Energy/Power scaling of bulk Yb:YAG pump laser modules. The cryo-cooled bulk Yb:YAG amplifier technology developed by CSU and XUV Lasers is very advanced and has already produced 1 J pulses at 1 kHz repetition rate. A rapid development strategy to reach the pump powers needed for k-BELLA is to scale these amplifiers to the 5 J, 5 kW average power level, maintaining the excellent beam quality of the current 1 kW prototype**.** Two of these compact cryo-cooled amplifiers units, frequency doubled with 80% efficiency, will be capable of pumping a 3 J, 1 kHz, 30 fs laser. The strategy is to scale the current cryo-cooled Yb:YAG system by increasing flow. A fallback strategy is to employ four 2.5 kW amplifier modules instead of two 5 kW modules, or for more margin four 3 kW amplifier modules.

Efficient frequency doubling at multi-kW average power. Pumping Ti:Sa with a diode-pumped 1 μm wavelength laser requires efficient frequency doubling at high average power. The strategy is to use low absorption LBO to demonstrate efficient doubling of an existing kW average power ,1 J, Yb:YAG laser. Obtaining 80 percent conversion efficiency is a very realistic goal. In preliminary tests, we have already obtained 70 percent doubling efficiency at lower

---

50 Baumgarten, C. et al., "1 J, 0.5 kHz repetition rate picosecond laser," *Optics Letters* **41,** 14 (2016) 3339-42.

51 Reagan, B.A. et al., "Demonstration of a 100 Hz repetition rate gain-saturated diode-pumped table-top soft x-ray laser. *Opt. Lett.* **37**, 17 (2012), pp. 3624–3626.

average powers. A risk mitigation strategy is to split the beam into multiple channels for efficient frequency doubling at lower average power per channel.

Dielectric multilayer coatings with long lifetime at high fluence**.** The efficient operation of the pump laser and Ti:Sa amplifiers requires operation at fluences above saturation. Efficient high reflector and anti-reflection coatings are required to operate at these high fluences for years at 1 kHz repetition rate and above. The strategy consists of using state-of-art ion beam deposition developed in house, combined with techniques to reduce stress, multiple diagnostics, and tests of coated optics at high repetition rate (e.g,. 1 J, 1 kHz) using our existing high power lasers.

Heat management for Ti:Sa amplifier operation at multi-kW average power. Operation of a k-BELLA class laser will require scaling by more than an order of magnitude in average power of present Ti:Sa lasers. The strategy is to employ the same cryocooling technique we currently use to remove heat and maintain high beam quality in the kW average power, joule-level, Yb:YAG amplifier. We are currently removing heat at up to an average pump intensity of 0.8 kW cm^{-2}.

In addition to the above tasks, as discussed in other parts of this report there is a need for the development of efficient diffraction gratings that can withstand the high average powers.

4.A.1.c. High repetition rate Thin Disk (TD) Ti:Sa amplifiers for sub-PW class laser systems

In this approach, thin disk (TD) laser technology was advocated as providing a path forward to higher average power. The heat from a TD is extracted in the direction of the beam propagation across the whole section of the beams, making cooling more effective and uniform due to a significantly larger cooled surface comparing to the conventional side-surface heating extraction and thus minimize thermal wavefront distortions and possible damage.[52]

Ti:Sa crystals have advantages that make this material very promising for TD lasers.[53] Ti:Sa's high emission cross section ($4\cdot10^{-19}$ cm^2) and broad spectrum (~250 nm) support high single-pass gain and 10 fs pulses. At the same time, the higher thermal conductivity of sapphire (~40 W/(m·K) at room temperature and more than two orders of magnitude higher when cryogenically cooled at 70-80 K) enables significantly increasing the crystal thickness to a few mm, which increases the single- pass gain, simplifying optical schemes by reducing number of passes and makes further scaling possible. Moreover, the thicker crystal also allows a transmission-based optical scheme. Therefore, Ti:Sa amplifiers could be developed that simultaneously achieve high peak as well as average power.

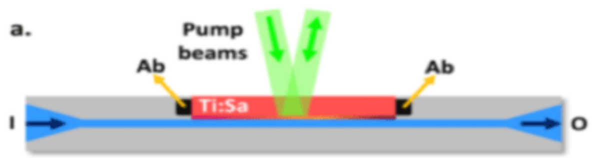
The primary challenges for TD amplifiers are suppression of transverse amplified spontaneous emission (TASE) and of parasitic generation (TPG). Extraction during pumping

[52] J. Speiser, "Scaling of thin-disk lasers—influence of amplified spontaneous emission," J. Opt. Soc. Am. B **26**, 1 (2009), pp. 26-35.

[53] V. Chvykov et al., "Design of a thin disk amplifier with extraction during pumping for high peak and average power Ti:Sa systems (EDP-TD)," Optics Express **24**, 4 (2016), pp. 3721-33.

(EDP) technology has been successfully applied to the Ti:Sa crystals[54, 55, 56] with a wide range of parameters. This allowed the reduction of connected losses even for very large crystal apertures and aspect ratio and recently resulted in the record output energy of ~200 J (~5 PW after compression).

EDP-TD: The first design of a TD Ti:Sa amplifier with EDP for high peak and average power laser systems (EDP-TD) was presented in Chvykov et al.[57] The principle of reflection based TD- Ti:Sa amplifiers is presented in Figure 4.



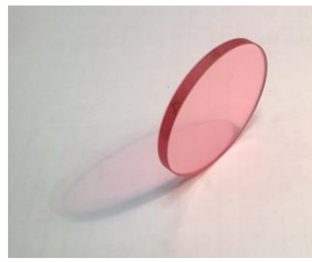


Figure 4. *(a), left: Single channel cooling with reflection based optical scheme; (b), right, Ti:Sa crystal of 35 mm diameter and 3 mm thickness.*

The final cryogenically cooled Ti:Sa amplifier of a 100 TW/10 Hz /28 fs laser system was replaced by the EDP-TD room temperature water cooled arrangement using a Ti:Sa crystal of 35 mm x 3 mm.[58] The front surface of the crystal was AR coated, while the rear side was HR coated for both the pump (532 nm) and the seed (800 nm) beams resulting in the amplifier working as an active mirror. The liquid absorber with refraction index of 1.76 for 800 nm covered the side surface of the Ti:Sa crystal to mitigate TPG. The rear surface of the crystal was cooled by water (18° C) in order to keep the maximum crystal temperature, after stabilization, under 30° C (Figure 5a).

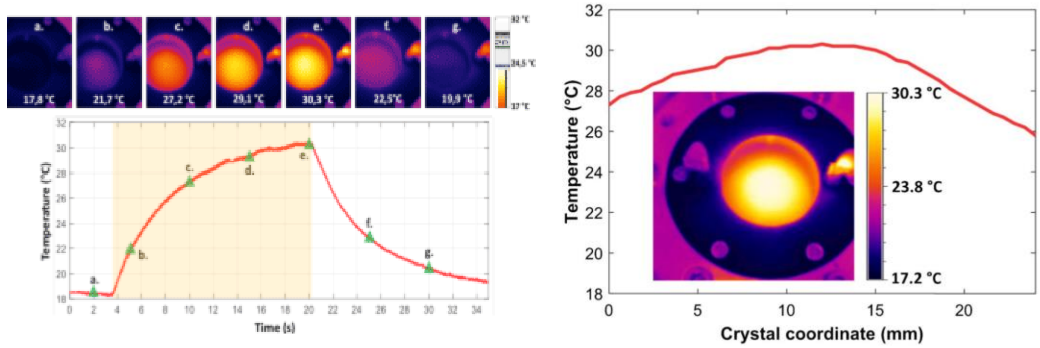
[54] V. Chvykov et al., "Suppression of parasitic lasing in multi-pass Ti-sapphire amplifiers," in Proc. CLEO 2003, Opt. Soc. Am. Technical Digest, paper CWA34.

[55] V. Chvykov and K. Krushelnick, "Large aperture multi-pass amplifiers for high peak power lasers," Optics Communications **285** (2012), pp. 2134-6.

[56] V. Chvykov, J. Jees, and K. Krushelnick, "Transverse amplified spontaneous emission: The limiting factor for output energy of ultra-high power lasers," Optics Communications **312** (2014), pp. 216-21.

[57] V. Chvykov et al., "Design of a thin disk amplifier with extraction during pumping for high peak and average power Ti:Sa systems (EDP-TD)," Optics Express **24**, 4 (2016), pp. 3721-33.

[58] V. Chvykov et al., "High peak and average power Ti:sapphire thin disk amplifier with extraction during pumping," Optics Letters **41**, 13 (2016), pp. 3017-20.



a b

Figure 5. a) *Temperature growth dynamics of the central point in the Ti:Sa crystal.*
b) *Temperature distribution through the amplifier crystal after temperature stabilization.*

The temperature variation across the pump area in the transverse direction was only 3° C (Figure 5b), which did not affect significantly the wavefront of the amplified beam. The area of 24 mm diameter was pumped by three 532-nm, 15- ns, 2-J beams, resulting in total absorption of 85%. The seed 800 nm pulse of 500 mJ energy was directed to the input of the amplifier. Despite using a liquid absorber, severe parasitic generation was revealed after pumping by 3.4 J of absorbed energy. The EDP technique allowed mitigation of parasitic lasing, reaching 2.6 J output energy when the total absorbed pump energy was 5 J. In contrast to conventional Nd:YAG or Yb:YAG TD amplifiers that require tens of passes, the Ti:Sa TD amplifier results were achieved with only three passes of the amplified and two passes of the pump beams due to the much higher emission cross section and thickness of the Ti:Sa crystal.

Despite the successful results of these experiments, several key technical risks are left, as described below, which should be solved for reaching the required k-BELLA laser system parameters.

Key technical risks and mitigation strategy

- Thermal management of gain material with 6 J/1 kHz pumping and connected temporal and spatial distortion of the laser pulse in multi-kW average power operation. *Mitigation strategy*: use an amplifier based on a transmission optical scheme with cooling of both crystal surfaces.
- Optical coating damage in long term operation. *Mitigation strategy*: Investigate the most qualified materials; choose coolant and crystal with comparable index of refraction; design the crystal holder at the Brewster angle.

The amplifier based on a transmission optical scheme is able to solve most of these problems (Figure 6a). More effective heat extraction can be accomplished by cooling both optical surfaces of the gain medium.[59] In addition, the antireflective coating of crystal surfaces can be negated if

[59] R. S. Nagymihaly et al., Optics Express **25**, 6 (2017), pp. 6664-77.

the refraction index of the chosen coolant and crystal are comparable. Finally, the requirements for crystal surface quality are much relaxed for transmission based amplifiers.

Numerical heat transfer simulations of TD Ti:Sa power amplifiers for a 100 TW-class system operating at up to a 100 Hz repetition rate were performed. Temperature distributions in the gain media were calculated for several coolant laminar flow velocities. Two Ti:Sa crystals of 35 x 6 and 35 x 4 mm were investigated. Two-side pumping of 6 J absorption was considered.

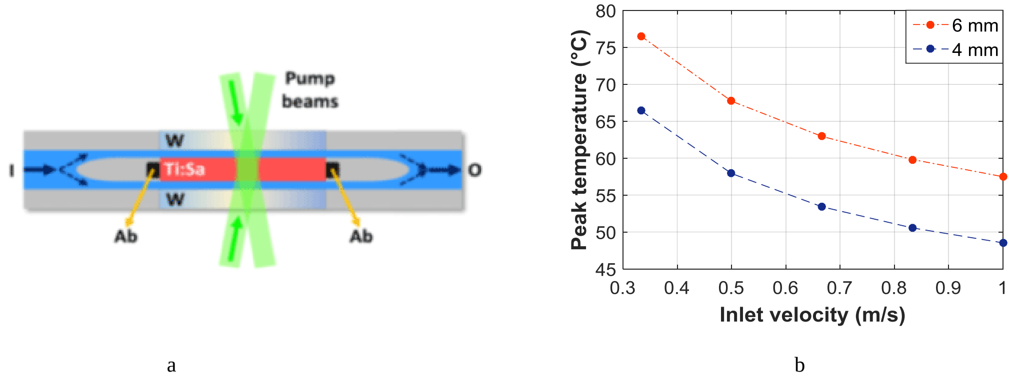


Figure 6. a) *Double channel cooling with a transmission based optical scheme* ***b)*** *Simulated peak temperatures for different coolant inlet flow velocities in case of the 6 x 35 mm (red) and 4 x 35 mm disk sizes.*

Figure 6b shows the peak temperature dependence on the flow velocity, with coolant temperature set at 15° C. The results show the great improvement of thermal behavior below 50° C achieved by switching to the 4 mm thick disk and increasing the flow velocity to 1 m/s. The optical path difference (OPD) generated by the temperature profile was calculated for both 4 and 6 mm thick gain media in case of 1 m/s inlet coolant flow velocity. OPD between the center and left edge of the pumped area was found to be 1.3 µm and 0.72 µm in case of the 6- and 4-mm-thick crystals, respectively. The wavefront distortion by the coolant flow was measured (RMS-0.36 um; P-to-V – 0.08 um) and was found to be comparable to the temperature effect.

Further numerical as well as experimental research of the EDP-TD Ti:Sa amplifier based on the transmission optical scheme will be required for 1 kHz and beyond. Temporal and spatial diagnostic of the compressed pulse will also be essential.

Replacing the conventional amplifiers with TD units would allow significant reduction of the total material volume in the laser system. Consequently, it will give the ability to reduce the chirped pulse duration at the same factor to few tens of ps. This pulse with initially negative chirp could be compressed in the bulk of glass + chirp mirrors, avoiding the grating compressor and associated losses, and increasing—perhaps doubling—the output power.

4.A.2. Ultrafast Fiber Lasers for the Near Term (5 Years, 3 kW Average Power)

State-of-the-art femtosecond fiber systems based on coherent combination of 8 individual large core fibers offer pulse energy up to 12 mJ at 60 kHz, i.e. an average power as high as 700 W at

~1 µm wavelengths.[60] The newest lab results have pushed this average power to 1.85 kW. The pulse duration out of those systems is around 200 fs. The gain bandwidth of ytterbium-doped fused silica fibers supports pulse durations in the order of 100 fs;[61] however, pulse durations as short as 30 fs require additional bandwidth broadening and post-compression. Femtosecond fiber lasers with pulse energies up to 10 mJ and average power up to 1 kW are commercially offered today.[62]

Based on the concept of coherent pulse addition of spatially and temporally separated amplification schemes, it can be foreseen that within the next 5 years (Table VII), pulse energies of 30 mJ at 100 kHz repetition rate (i.e., 3 kW of average power) will be available. Such parameters require more a technological development than strong R&D efforts. A 16-channel FCPA system allows the extraction of 30 mJ (compressed and combined) without damage issues or excessively strong nonlinearity in the fibers. An average power of 3 kW can be handled by suitable optical components with advanced coating technology. R&D is needed to address pulse durations shorter than 100 fs and higher pulse energies. Nonlinear post-compression in hollow core fibers works well up to a pulse energy of 5 mJ.[63] Above 5 mJ, ionization effects limit effective transmission through the hollow core waveguide. One possible approach is a spatially and/or temporally separated nonlinear compression[64] followed by coherent combination, which is rather straightforward at 30 fs pulse duration.

Alternatively, the 2 µm wavelength region can be addressed by thulium-doped fibers which have already produced 1 mJ pulse energy at 50 kHz repetition rate (50 W average power) in combination with sub-100-fs pulse duration.[65] The gain bandwidth of thulium-doped fibers supports roughly a factor of 2 shorter pulses that ytterbium-doped fibers at 1 µm wavelength. The concept of coherent pulse addition can be applied at 2 µm wavelength as well,[66] and pulse energies in excess of 30 mJ appear feasible within the next 5 years. No further post compression is required as, for the envisaged application, 60 fs at 2 µm is equivalent to 30 fs at 1µm.

Pulse energies above 1 J appear require long-term development as detailed in the section below, and appear unrealistic with the next 5 years. For this reason, this approach is considered for long-term systems. It would however be a competitive solution in the near term for low energy systems that operate at high repetition rates, such as those needed for light source pump-probe experiments.

---

[60] Marco Kienel, Michael Müller, Arno Klenke, Jens Limpert, and Andreas Tünnermann, "12 mJ kW-class ultrafast fiber laser system using multidimensional coherent pulse addition," Optics Letters **41**, 14 (2016), pp. 3343-3346.

[61] L. Lavenu, M. Natile, F. Guichard, Y. Zaouter, M. Hanna, E. Mottay, and P. Georges, "High-energy few-cycle Yb-doped fiber amplifier source based on a single nonlinear compression stage," Optics Express **25**, 7 (2017), p. 7530.

[62] www.afs-jena.de

[63] S. Bohman, A. Suda, T. Kanai, S. Yamaguchi, and K. Midorikawa, "Generation of 5.0 f s, 5.0 mJ pulses at 1 kHz using hollow-fiber pulse compression," Optics Letters **35**, 11 (2010), pp. 1887- 1889.

[64] Arno Klenke, Steffen Hädrich, Marco Kienel, Tino Eidam, Jens Limpert, and Andreas Tünnermann, "Coherent combination of spectrally broadened femtosecond pulses for nonlinear compression," Optics Letters **39**, 12 (2016), pp. 3520-3522.

[65] C. Gaida, M. Gebhardt, F. Stutzki, C. Jauregui, J. Limpert, and A. Tünnermann, "Thulium-doped fiber chirped-pulse amplification system with 2 GW of peak power," Optics Letters **41**, 17 (2016), pp. 4130-4133.

[66] C. Gaida, M. Kienel, M. Müller, A. Klenke, M. Gebhardt, F. Stutzki, C. Jauregui, J. Limpert, and A. Tünnermann, "Coherent combination of two Tm-doped fiber amplifiers," Optics Letters **40**, 10 (2015), pp. 2301-2304.

Table VII. Summary: feasible parameters within 5 years with fiber laser technology.

λ	E_P	P_{AVG}	f_{REP}	Δτ	Comment
1 μm	30 mJ	3 kW	100 kHz	100 fs	direct from FCPA
1 μm	30 mJ	3 kW	100 kHz	30 fs	with post compression
2 μm	60 mJ	6 kW	100 kHz	60 fs	direct from FCPA

4.A.3. Thulium-based Concepts

4.A.3.a. Very High Average Power, Single Aperture, Diode Pumped Solid State Laser Solutions (0-5 years perspective)

Scaling the technology of high peak power lasers to higher average power while maintaining key technological performance requirements is challenging. Pulsed high energy solid state lasers have demonstrated continuous operation at energies ~100 J and repetition rates up to 10 Hz (e.g., DiPOLE100 and the High Repetition Rate Advanced Petawatt Laser System, aka HAPLS). Solid state lasers with average power in the petawatt class and pulse energies exceeding 10 J have reached an instantaneous power of tens of watts (BELLA), with HAPLS on the trajectory to 300 W. Improvements in average power of ultrafast lasers on the order of -1000× are needed to realize the potential future applications and their associated benefits. With the increases in average power, both the optical-to-optical and the overall wall-plug efficiency of the laser system becomes increasingly important: the laser cooling capacity and complexity of the laser amplifier design scales with the amount of energy directly converted into heat in the laser gain medium.

The output energy of a diode pumped laser system can be written as:

$$E_{out} - E_{in} = \eta_{DC}\eta_{P}\eta_{EO}\eta_{PT}\eta_{abs}\eta_{QD}\eta_{decay}\eta_{ext}\eta_{MO}\eta_{trans}E_{elec}$$

where

$$\eta_{optical\text{-}to\text{-}optical} = \eta_{QD}\eta_{decay}\eta_{ext}\eta_{MO}\eta_{trans}$$

and η_{DC} is the overall efficiency of the laser diode power supply; η_P is the efficiency of the pulse forming network for pulsed laser diodes; η_{EO} is the electrical to optical efficiency of the laser diode arrays; η_{PL} is the pump light transfer efficiency to the amplifier gain medium; η_{abs} is the gain medium absorption efficiency; η_{QD} is the laser gain medium quantum defect efficiency; η_{decay} is the decay efficiency, defined as the fraction of the excited upper-state population that remains at the end of the pump pulse; η_{ext} is the fraction of the excited-state population that is extracted on each pulse; η_{MO} is the pump-to-extraction mode coupling efficiency; η_{trans} is the passive optical system transmission efficiency; and E_{elec} is the electrical input energy. The product of the nine efficiency terms is the wall-plug efficiency of the final amplifier, and E_{in} is the pulse energy injected into the final amplifier.

For architectures that rely on laser-pumped-lasers (e.g., Nd:YAG pumped Ti:Sa systems), efficiencies for each laser, frequency converter and optical transfer efficiencies must be included. These generally large laser losses associated with the pump-laser point us strongly in the direction of eliminating pump lasers and using direct short pulse chirped pulse amplification in a single beam line is desirable in order to achieve high wall plug efficiency. For comparison of system efficiency for a cw diode pumped, direct CPA laser system vs. a diode pumped, indirect CPA laser system, the energy losses per joule of output energy are shown in Figure 7, where estimated losses have been grouped into logical categories to emphasize waste heat pathways. The efficiency impact of the pump laser have been grouped into a single term, η_{ICPA} (ICAP = indirect CPA), which has the value ~0.1 for the Ti:Sa example. Finally, to calculate the overall wall-plug efficiency of the laser, the power consumption of the laser support systems (e.g., cooling and the laser control system) must be factored in. It is important to note, that the cooling system size and cost, power consumption, and overall contribution to the system wall plug efficiency scale with the waste heat to output energy ratio.

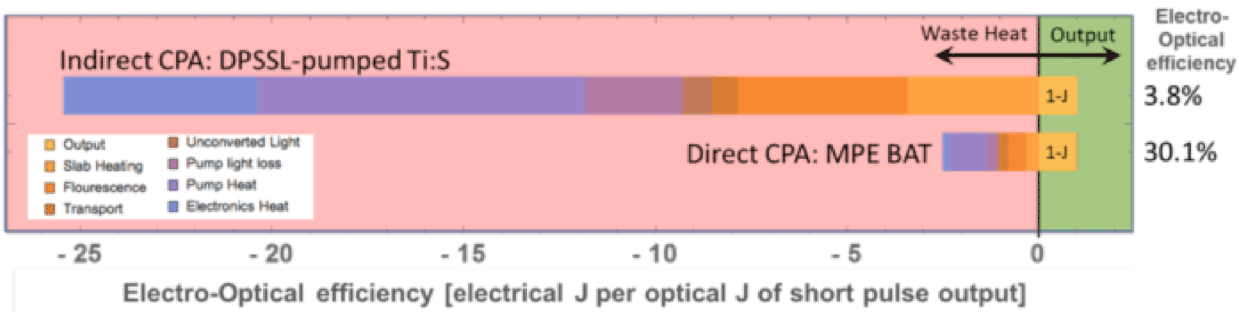


Figure 7*. Wall-plug efficiency comparison between direct CPA (here: Multi-Pulse-Extraction, Big Aperture Thulium (BAT) laser architecture utilizing multi-pulse extraction) and a pulsed, diode pumped, indirect CPA system (here based on Nd:xxx pumped Ti:Sa).*

Over 80 known laser gain media were analyzed for maximum net efficiency and suitability for laser diode pumping (long upper-state lifetime), along with lasing properties consistent with the applications described in this and previous workshop reports (**Figure** 8, left). Net efficiency, η_{net}, is defined as the product of the three efficiency terms that are the most affected by the choice of gain medium (η_{QD}, η_{ICPA}, and η_{EO}).

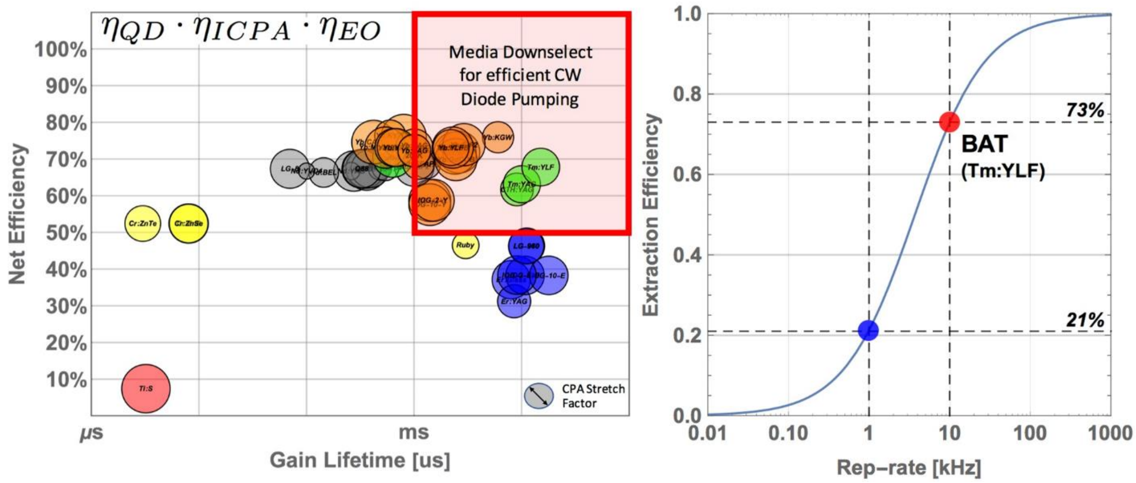


Figure 8. *Left: Net efficiency (quantum defect x indirect CPA efficiency x electro-to-optical efficiency) vs. gain lifetime of various laser gain media. For the Ti:Sa case,* η_{ICPA} *is 0.XX while for the other cases, which use direct CPA designs, ,* η_{ICPA} *is unity. Laser media were down-selected for net efficiency (>50%) and diode pumping suitability (gain lifetime >1 ms). Right: Extraction efficiency (stimulated emission rate divided by the sum of stimulated emission rate and spontaneous decay rate). In multi-pulse extraction, higher repetition rates (while maintaining the extraction fluence) are beneficial to the overall wall plug efficiency.*

At repetition rates for which the excited state lifetime exceeds the time between extraction pulses dramatically—by an order of magnitude or more—efficient laser architectures can be designed that use cw laser diodes to energize the gain media and that operate in the aptly named "multi-pulse extraction" regime. In the multi-pulse extraction mode, stored energy is extracted from the gain medium over multiple, low fluence pulses (e.g., <10% of the saturation fluence) with an efficiency that is as high as might be achieved in a single, high fluence pulse (Figure 9). The extraction time in the multi-pulse extraction mode must be less than the storage lifetime. This allows for the efficient use of low-gain/high saturation fluence materials while still heeding conventional ns-scale optical damage limitations.

As shown in Figure 9 left, thulium (Tm) doped gain media offer significant lifetime advantage over the well-established Yb doped materials traditionally used for diode pumped fiber and bulk systems. Tm multi-pulse extraction becomes efficient at repetition rates > 3-5 kHz (see **Figure** 9 right). In comparison, Yb materials require repetition rates > 50-100 kHz.

To be relevant for sub-100-fs applications, the gain bandwidth of Tm in the chosen laser host material must be >50 nm, which is satisfied by most of the host materials.

Among the relevant host materials, YLF offers several attractive properties, including a negative and low dn/dT, low linear and nonlinear refractive indices, and natural birefringence. These properties support laser architectures that exhibit

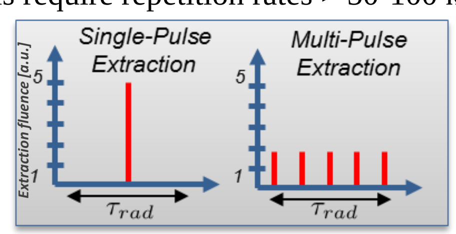


Figure 9. *In multi-pulse extraction mode, the same stored energy is extracted from the gain medium over multiple, low fluence pulses vs. extracting the energy in a single, high fluence pulse. The extraction time in the multi-pulse extraction mode must be less than the storage lifetime.*

high fidelity laser pulses with very low nonlinear phase accumulation, low wavefront aberration, and high polarization purity at very high average power (hundreds of kW). The Tm dopant in YLF lases at ~1.9 µm, and has a long upper-state lifetime (15 ms). Due to the well-known cross-relaxation process, pumping in the ~800 nm band yields approximately two excited state ions per pump photon, resulting in an effective quantum defect of ~84% (depending on doping), comparable to Nd lasers, so only 16% of the pump energy is converted to heat.[67, 68] Therefore, Tm:YLF is amenable to pumping with commercially available, custom-off-the-shelf, technologically-mature high-brightness continuous-wave laser diodes that operate at 800 nm. CW pumping of the gain material eliminates laser diode pulse forming networks (pulsers) and associated electrical losses. Furthermore, the overall brightness requirement is reduced due to the longer time available for storing the pump energy in the gain media. Tm:YLF is commercially available in boule sizes consistent with 300 kW average power operation of a 30-50 J short pulse laser (see Figure 10).

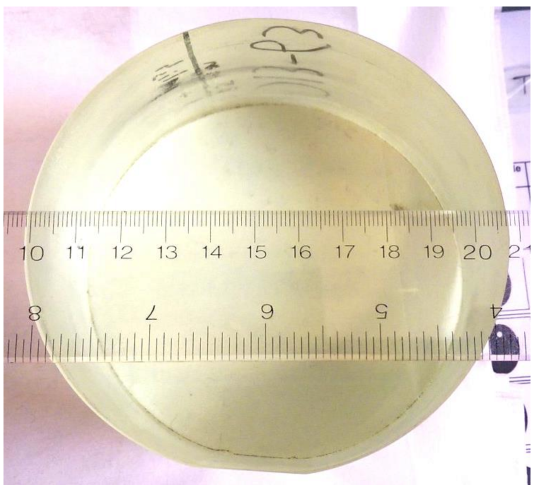


Figure 10: *Recently grown Tm:YLF crystal for the Big-Aperture-Thulium Laser (BAT). The crystal has a diameter of ~11 cm, consistent with operation at high pulse energies (>50 J)*

These considerations led to the choice of considering Tm:YLF as the laser amplifier medium for a laser concept consistent with the requirements for secondary source generation and specifically for an efficient laser wakefield driver.

4.A.3.b. Big-Aperture Thulium (BAT) Laser Concept

The BAT laser main amplifier is designed to deliver 30-J pulses at a repetition rate of 10 kHz from a single ~7x7 cm aperture to address long term laser needs for colliders. The beam could be round or rectangular depending on the application. The average power of this laser system would be 300 kW, the center wavelength at 1900 nm, and the pulse duration can be potentially as short as 40 fs. The electrical true wall-plug efficiency, including laser cooling and controls, is

[67] Honea, E.C. et. al. "115-W Tm:YAG Diode-Pumped Solid-State Laser," IEEE J. Quantum Electronics **33**, 9 (September 1997), pp. 1592-1600.

[68] Dergachev, A. et al., "Review of multipass slab laser systems," IEEE Journal of Selected Topics in Quantum Electronics **13**, 3 (May/June 2007) pp. 647-60.

estimated at 20% (see for comparison of electrical-to-optical efficiencies between the direct CPA BAT technology and the indirect CPA, aka "laser-pumped-laser," Ti:Sa technology). Owing to the multi-pulse extraction technique, the resulting fluence would be less than 1 J/cm^2. The total nonlinear phase retardation (B-integral) would be less than 0.1 rad,[69] supporting excellent compressed-pulse fidelity and coherent pre-pulse contrast.

At current (2017) market prices, the costs for the laser diodes required for the BAT laser are approximately $8M for the large amplifier operating at 10 kHz. This is only ~2x higher than the published costs of laser diodes installed in the Ti:Sa based HAPLS laser, while providing capability for 1000× the average power of HAPLS.

The miniBAT architecture to meet the near-term need for a kW-class system is downscaled from the BAT architecture and is designed to deliver 3 to 6 joules from an ~30×30 mm^2 single aperture with a 10 kHz repetition rate, equivalent to 30 to 60 kW. MiniBAT and BAT can also be operated at lower repetition rates (≥1 kHz), lowering the capital investment for the laser diode arrays; however, the net efficiency will be reduced (see **Figure** 9, right).

The miniBAT and BAT laser front-end relies on the Innoslab technology pioneered by Fraunhofer Institute for Laser Technology in Germany. It has demonstrated parameters at 1 µm similar to parameters needed for seeding the mini-BAT stage and also has demonstrated transferability to the 1.9 µm wavelength thulium technology. The front end itself consists of 3 stages (see Figure 11): (a) A low power, short pulse seeder including pulse-shaping, pulse-picking and stretching to ~100 ps. (b) A low power, high gain multipass preamplifier. (c) A high power Innoslab stage.

Low power seed sources with pulse energy ~10 nJ are commercially available. High stability regenerative amplification of ps pulses in the 2 µm wavelength range from nJ to mJ has been demonstrated at kHz repetition rates,[70] and can be considered to be technologically very similar to proven 1 µm regenerative amplifiers as all required optical elements, especially electro-optical switches are available for 2 µm in a similar quality and similar performance. In the final front-end stage the energy is brought up from ~1 mJ to ~300 mJ using several directly diode-stack pumped Tm:YLF Innoslabs.

Innoslab amplifiers allow for a high amplification factor without regenerative amplification. Innoslab amplifiers are similar to the slab amplifier technology and offer a straightforward power scaling capability with the crystal width. At 1 µm wavelength the technology has demonstrated output powers exceeding 1 kW at below picosecond pulse duration and MHz rep rate,[71] as well as high pulse energy capability exceeding 500 mJ energy per pulse[72] at ns pulse durations. Systems delivering > 300 W of average power at several 100 ps pulse duration, 160 mJ pulse energy and 2 kHz rep rate were produced and installed at customer sites [Russbueldt, op. cit.].

---

[69] Ti:Sa laser systems that deliver pulses with 100 TW – 1P W typically accumulate 1-2.5 radians of nonlinear phase shift (B) in the laser chain.

[70] P. Kroetz et al., "Ho:YLF Regenerative Amplifier with 6.9 mJ at 1 kHz Overcoming Bifurcation Instability," in Advanced Solid State Lasers, OSA Technical Digest (online) (Optical Society of America, 2015), paper ATh3A.4.

[71] P. Russbueldt et al., "Innoslab Amplifiers," in IEEE Journal of Selected Topics in Quantum Electronics **21**, 1 (Jan.-Feb. 2015), pp. 447-463.

[72] J. Löhring et al., "Demonstration of a 500 mJ InnoSlab-amplifier for future lidar applications," Solid State Lasers XXV: Technology and Devices, Proc. SPIE **9726** (March 16, 2016), 97260M.

Furthermore the technology has been commercialized by two different companies, and scaling of this technology to Tm:YLF has been demonstrated with 200 W of cw output.[73]

Amplification and pulse compression to 30-J pulses would be accomplished in three amplification stages with output energies of 300 mJ (preamplifier), 3 J (Mini-BAT), and 30 J (BAT). The preamplifier would rely on an extension of proven Multipass and Innoslab [Russbueldt, op. cit.] technologies developed by the Fraunhofer Institute for Laser Technology (ILT). The power amplifiers (mini-BAT and BAT) would rely on LLNL's multipass, gas-cooled amplifier technology (Figure 11).

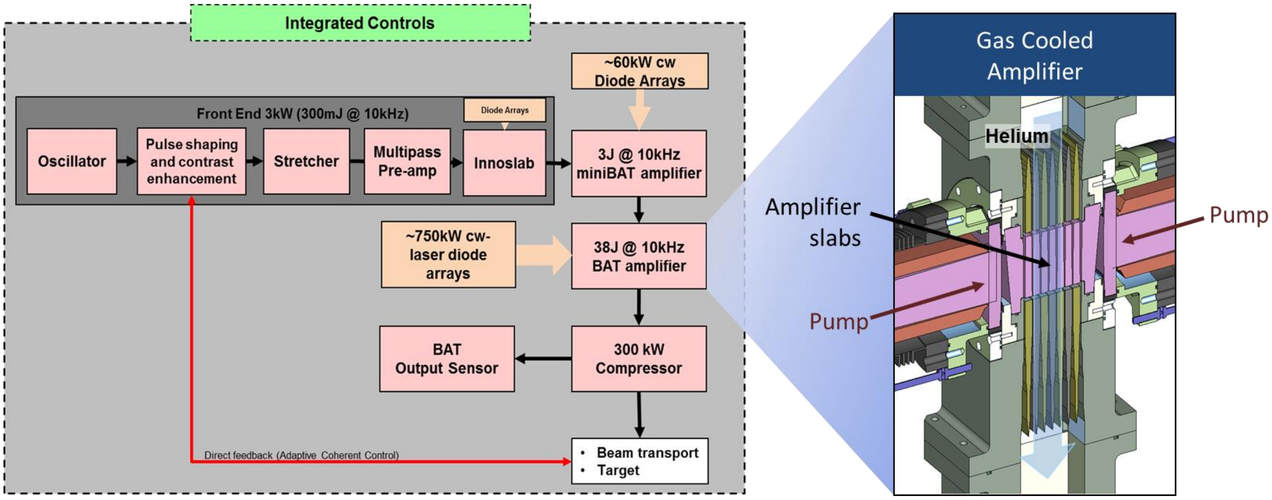


***Figure 11**. BAT schematic diagram.*

The main BAT amplifiers leverage the 4-pass passively switched architecture developed for the kilowatt pump laser on HAPLS. Minor modifications are required for short pulse operation, such as reflective imaging optics to maintain the proven fully relay-imaged, angularly multiplexed and polarization switched two-amplifier head cavity design. The change to reflective optics on this short pulse laser system follows the same design reasoning as was demonstrated on the HAPLS short pulse laser system.

Thermal management and residual heat removal in BAT would be accomplished through a modest extension of LLNL's amplifier helium gas-cooling technique. Pioneered at LLNL in the 1980s,[74] this is an established heat removal method that has been adopted by multiple groups worldwide. The method was reduced to practice on several high energy, high average power laser systems (Mercury Laser,[75] LLNL, 2005; HAPLS, LLNL, 2016[76]; DiPOLE10, CLF, 2014;

[73] Meissner, A. et al., "200-W Tm:YLF INNOSLAB Laser," Solid State Lasers XXII: Technology and Devices, Proc. SPIE **8599** (2013), 85991C.

[74] Emmet, J.L., Krupke, W.F., Sooy, W.R., "The Potential of High-Average-Power Solid State Lasers", UCRL-53571 (Sept.1984), https://www.osti.gov/scitech/servlets/purl/6294772

[75] A. Bayramian et al, "The Mercury project: A high average power, gas-cooled laser for inertial fusion energy development," Fusion Sci. Tech. **52**, 383-387 (2007).

[76] C. L. Haefner et al., "High average power, diode pumped petawatt laser systems: a new generation of lasers enabling precision science and commercial applications", Proc. SPIE **10241**, Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers III, 1024102 (June 26, 2017); doi:10.1117/12.2281050

DiPOLE100, CLF 2016[77]) and for various gain media: Yb:SFAP, Nd:glass[78], Ti:Sa, and cryo Yb:YAG.

4.A.3.c. Development path for a kW laser system

Advancing understanding and development of high-flux laser wakefield accelerators and other secondary sources require an increase of repetition rate from today's laser capabilities. k-BELLA is an intermediate facility envisioned as operating at the 1 kHz, 100 TW level with sufficient machine flexibility to support broad exploration of target parameters. The miniBAT laser supports these requirements and may even be operated at higher repetition rates. Furthermore, it reduces to practice and informs the strategic path for a technology that has the potential to be extended to to the full performance – 10 kHz, 30 J – required for the injection and amplification stages of a laser-based electron collider. The BAT and miniBAT laser designs rely largely on technologies that have already been reduced to practice at relevant scales. The technical readiness level of MiniBAT is estimated at TRL 4. It could be constructed in three years (like HAPLS) after a two-year technology maturation phase that develops and reduces to practice key aspects of the architecture outlined below.

The key remaining technical risks can be addressed via technology development efforts focused on:

- Heat removal: The BAT laser design relies on a moderate scaling of 10× from previously-demonstrated helium gas cooling techniques. This requires scaling to higher mass flow while maintaining the mechanical stability and integrity of the amplifier slabs. Theoretical models that have been benchmarked on various other lower power systems support this extension. A subscale amplifier model that demonstrates optical pumping and efficient heat removal should be developed to provide information on the architecture scalability and benchmark the simulation results.
- 2-μm optical coatings: Optical coatings at 2 μm are becoming widely available from multiple vendors. For high repetition rate, laser-induced damage testing and understanding optical damage initiation and growth is important to develop robust coatings consistent with large MTTF. Efforts to study gigashot laser damage are ongoing for visible/near-infrared optics.[79] A facility-class 2-μm laser operating at 10 kHz will accumulate ~10 terashots over its operational lifetime. Further study of optic survivability under these conditions is required.
- Finishing and robustness of the gain material: Growth of YLF boules at sizes consistent with BAT is well understood by commercial industry. LLNL has obtained Tm:YLF with ~10.5cm diameter. This size is sufficient for the 300 kW BAT design and there is near-term commercial capability to further scale up to 120 mm diameter crystals. Growth of Tm:YLF crystals is expected to be easier than Nd:YLF because Tm ions are closer in size to the yttrium atoms (16 angstroms larger vs. 4 angstroms smaller) that they replace in the YLF

---

[77] P. Mason et al., "Kilowatt average power 100 J-level diode pumped solid state laser," Optica **4**, 4 (2017), pp. 438-9

[78] A. Bayramian et al., "High energy, high average power, DPSSL system for next generation petawatt laser systems," 2016 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, 2016, pp. 1-2.

[79] Ly, S. et al., "Gigashot optical degradation in silica optics at 351 nm," *Optics Express* **23**, 4 (2015), pp. 4074-91.

host crystal, making the distribution coefficient approximately equal to unity and making doping-induced crystal strain/defects very low. Fabrication, finishing and coating of YLF-crystals is also well understood by industry. Although the material is available, the boule must be characterized for quality, homogeneity, doping uniformity, etc., and fabrication, finishing and coating of amplifier slabs must be demonstrated.

- Direct CPA architecture and temporal contrast: Direct CPA architectures with longer energy storage lifetimes require additional steps to manage the energy pre-pulse contrast (aka ASE background). Several technologies have been developed and applied to large, high peak power, direct CPA laser systems, such as short pulse optical parametric amplifier (SPOPA) – e.g., LLE's Omega EP and LANL's Trident laser, now decommissioned; XPW pulse cleaner (commercially available technology deployed on many systems); repetitive plasma mirror (LBNL's TREX laser); and saturable absorber (older technology with tens-of-ps gating time). These techniques have been mainly developed for wavelengths around one micron and need to be scaled to 2 microns.
- 2-μm wavelength, average-power-capable gratings: High efficiency multilayer dielectric (MLD) gratings have been demonstrated in the ~1 and 2 μm spectral region with up to 50 nm of bandwidth.[80] Active cooling of MLD gratings has been developed for HAPLS. Experimental results at the kW laser level have been obtained and it is projected that active cooling can support average powers in the hundreds of kW.[81] MLD grating designs for the 2 μm wavelength have been demonstrated in a CPA system with ~25 nm of bandwidth.[82] Scaling of existing broadband MLD designs to the mid-IR is expected to achieve the required bandwidth.
- Front end lasers: Commercial short pulse front-ends in the 2-micron wavelength range are available but have not been optimized for seeding a petawatt class laser chain. Basic front-end energy capabilities are well developed in Thin Disk and Innoslab lasers. [Russbueldt, op. cit.] Architectures need to be scaled to the 1.9 μm seed wavelength and in average power and energy. However, laser systems with performance close to the requirements for the BAT front-end have already been demonstrated by the Innoslab technology at 1 μm. [Russbueldt, op. cit.] The capability of this platform to produce high output power with Tm:YLF at 1.9 μm was demonstrated [Meissner, op. cit.] and needs to be extended to the amplification of chirped pulses. Pulse shaping/picking and stretching and the high gain regenerative/multipass amplifier are envisioned to be straightforwardly scalable to 1.9 μm wavelength; however, pulse contrast (as addressed above concerning direct CPA) and acquired nonlinearity in the regenerative amplifier need to be assessed.

[80] Martz, D.H et al., "Large area high efficiency broad bandwidth 800 nm dielectric gratings for high energy laser pulse compression," *Opt. Exp.* **17**, 26 (11 Dec. 2009), pp. 23809-16.

[81] Alessi, David A.; Rosso, Paul A.; Nguyen, Hoang T.; et al. "Active cooling of pulse compression diffraction gratings for high energy, high average power ultrafast lasers," Optics Express 24, 26 (19 Dec. 2016), pp. 30015-23.

[82] Stutzki, F. et al., "152 W average power Tm-doped fiber CPA system," Optics Letters **39**, 16 (5 August 2014), pp. 4671-4.

4.B. Longer term (0-15 years): beyond k-BELLA – 30 kW and 300 kW class

4.B.1. Ti:Sa approaches

4.B.1.a. Hybrid OPCPA/Ti:Sa with incoherently combined fiber pump lasers

The ultimate collider application is particularly sensitive to wall-plug efficiency due to the cost associated with operating many accelerator stages. Paths to evolve both OPCPA and Ti:Sa technologies for meeting these long-term requirements are outlined below.

The present hybrid OPCPA/Ti:Sa design has the potential for scaling by an order of magnitude in power beyond k-BELLA by increasing the pump rate to 10 kHz with the proposed number of Ti:Sa pump fiber lasers. A short pulse (~30fs) laser could serve as the drive laser for the first stage (injector) of a TeV collider or stand-alone LPA modules, albeit at low wall plug efficiency. Such future designs would depend on risk reduction planned for k-BELLA to provide a firmer basis for their own planning.

The pump laser system for k-BELLA requires each fiber laser to operate at a very modest IR power of about 3.5 W at a 1-kHz rate using a nominal 10-W pump laser. At a 10-kHz rate with the exact same design, the average fiber-laser power would approach the 6-7 W expected for a cw-like laser. Increasing the fiber-laser power to 35 W to maintain the pulse energy from the Ti:Sa laser would require replacing the single 10-W pump with a 50-W pump, which is readily available from several vendors at somewhat higher $/W than for k-BELLA. The still modest average power from each fiber source would not require a major redesign in the rest of the pump system, but would need more robust air cooling.

The major risk is the limit in average power possible from a single, cryogenically cooled Ti:Sa crystal. The design used for k-BELLA does not appear to have a hard limit at the 3.5 kW level of output power, but no models or experimental data are presently available. In the worst case, amplification could be accomplished with multiple crystals operated in series.

High-repetition-rate OPCPA pump lasers are commercially available, and scaling to higher energies and repetition rates is already underway. Continuous-wave pumping supports efficient multi-10-kHz operation with less complexity compared to the pulse-pumped lasers that would be used for k-BELLA. Scaling modular laser systems to pump higher-average power OPCPA amplifiers is relatively straightforward by applying narrowband coherent beam combining techniques. Relatively few lasers would need to be coherently combined, which results in substantially reduced system complexity and improved reliability compared to fiber laser schemes that would need to combine femtosecond pulses with much lower energies.

Scaling another order of magnitude, to 300 kW of average power, poses more fundamental changes to the hybrid OPCPA/Ti:Sa technology. Wall-plug efficiency poses the greatest challenge. The effective quantum defects are high for traditional implementations of both types of amplifiers but novel schemes can reduce the negative impact. Reclaiming residual pump and idler power leaving OPCPA crystals is a promising approach to significantly improve efficiency that would require optimizing photovoltaic cells for these wavelengths. In parallel, the emergence of high-efficiency green-wavelength diode lasers to pump Ti:Sa would provide a path to improved pumping efficiency, but fundamental materials improvements in GaN semiconductors would be required. Given the widespread adoption of GaN-based lighting, there is at least some hope that significant investments in commercial GaN sources could lead to this improvement.

A more likely scenario for the long term is that OPCPA would continue to provide the most effective front-end and driver technology, but the final amplifier would need to employ gain media directly pumped by high-efficiency diode lasers. Research and development for this was discussed in an earlier section.

EDP-TD Ti:Sa amplifiers are able to achieve a much higher average power (tens of kW) if cryogenically cooled. As was noted above, the thermoconductivity of sapphire is more than two orders of magnitude higher when cryogenically cooled at 30-80 K. We calculated the temperature field in the 20x2 mm Ti:Sa crystal that was designed for a reflection based scheme with cryogenic cooling at 77 K and also 30 K coolant temperatures. The crystal is pumped from one side by pump pulses with energy of ~10 J.

The maximum temperature difference in the case of 70 K coolant temperature at 1 kHz repetition rate is 18 K. In the case of 30 K coolant temperature, the same temperature difference is reached at a 6 kHz repetition rate. Therefore the repetition rate can be greatly increased with a lower-temperature coolant. Nevertheless, more detailed modeling of the different amplification schemes, as well as crystal holder design and experiments, are required. Deploying such lasers at tens of kW average power is however limited due to the low wall plug efficiency.

4.B.1.b. Cryo-cooled disk pump technology for 30 kW, 10 kHz, Ti:Sa lasers

The compact cryo-cooled bulk Yb:YAG pump laser technology outlined in Section 4.A.i.b, suitable for pumping a femtosecond laser for k-BELLA, is modular and therefore scalable. The thick disk laser technology discussed above could be used to generate 80 kW average power level of λ=515 nm light required to pump a 30 KW, 10 kHz, sub-30 fs Ti:Sa laser. In the most conservative approach. the same 5 kW Yb:YAG laser modules (4 kW frequency doubled) developed for a k-BELLA-type laser could be used in a series/parallel combination to achieve the necessary pump power (Figure 12). In this scheme, the bulk Yb:YAG pump laser would be used as a front end to seed 20 of the same 5-kW amplifier modules in parallel. The approach resembles that currently used to pump the 1 Hz BELLA, in which 12 Nd:YAG pump lasers are used in parallel. Moreover, future improvements in laser optical coatings, laser gain and frequency doubling materials, and gratings could significantly reduce the number of modules. This approach would require the same advances to thermal management and possible beam combination, and would be subject to the same limits on efficiency, as outlined in the previous paragraph.

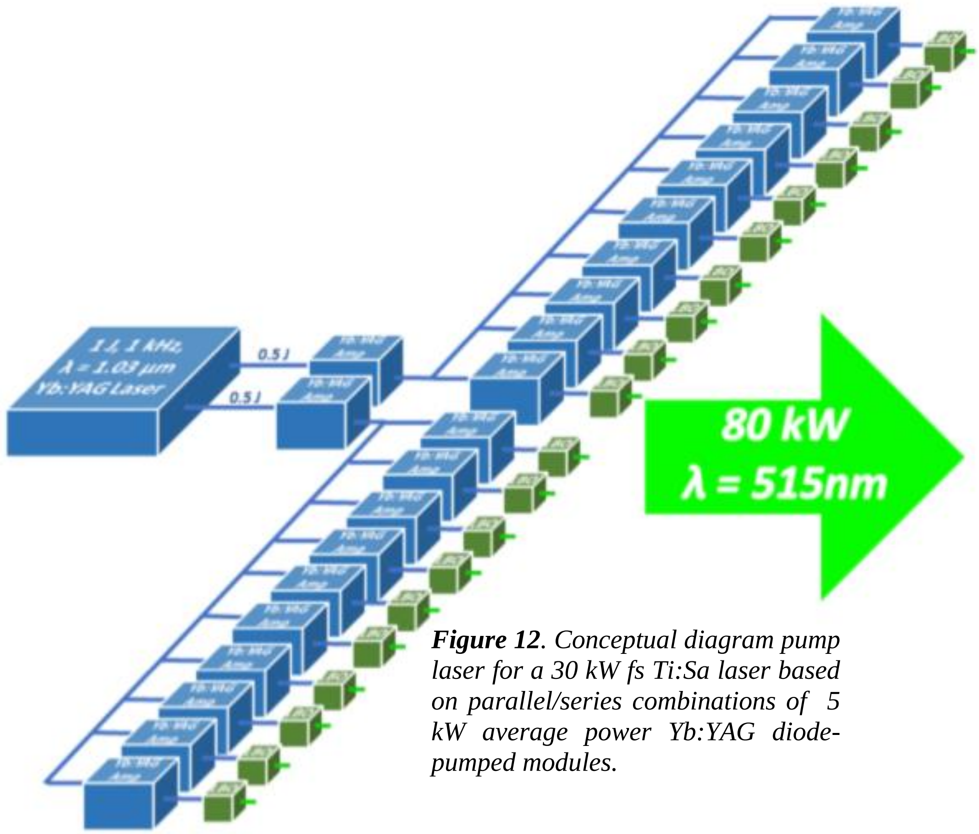


Figure 12. *Conceptual diagram pump laser for a 30 kW fs Ti:Sa laser based on parallel/series combinations of 5 kW average power Yb:YAG diode-pumped modules.*

4.B.2. Direct CPA based on Tm:YLF for a 30-300 kW laser system

The BAT concept has been laid out to meet the final application requirements of 300 kW, 30 J per pulse, but provides through aperture (energy) and repetition rate (average power) inherent flexibility for a variety of applications, for example a 3-TW/1-MHz configuration could be of great interest for future high-rep-rate x-ray FELs. Notably, higher wall plug efficiencies can be achieved at the greater rep rates.

Significantly, key operating performances of a full performance (300-kW) BAT can be effectively anchored on the performance of a 10× down-scaled prototype BAT laser (a.k.a. miniBAT), with lower pulse energy and average power but identical fluences and aereal thermal loadings, and allows for a credible and cost-effective development path. The miniBAT platform will reduce to practice all relevant physics and engineering aspects of the energy/aperture scaled full BAT. Importantly, once miniBAT is fully operational and has validated system performances, it can serve as the preamplifier for the full BAT system.

The BAT system amplifies the short pulse directly in the primary laser chain using chirped-pulse amplification (i.e., direct CPA), avoiding laser-pumped-laser architectures that have significantly higher energy loss inherently (i.e., indirect CPA). Therefore, BAT can operate at electrical-to-optical efficiencies >30% and true wall plug efficiencies of 20% or better. It can be directly pumped by commercially available, inexpensive CW laser diodes at ~800 nm, eliminating the need for an additional laser system to deliver pump light to the final amplifier. Furthermore, through a cross-relaxation process it is possible to excite two Tm ions with a given pump photon, decreasing the effect of the quantum defect. Finally, high repetition rates enables efficient extraction over many pulses at a lower fluence per pulse and at lower amplifier gains, providing for a more robust and tolerant system design. This technique maintains high contrast, while efficiently extracting the stored energy.

Operating directly at 2 μm, BAT operates at reduced accumulated nonlinear phase retardation, or B integral, which scales as $1/\lambda^2$. Together with the wavelength scaling the low-gain BAT architecture maintains a total B <0.1 in the amplifier. This low total B, together with the relay-imaged architecture produce high stability, high beam quality and contributes to maintaining the high contrast of the front end through the power amplifier. In addition to desired PW-class secondary-source applications, the scalability of the system to higher pulse energy and average power at 2 μm also presents opportunities for additional applications in medicine, non-destructive-evaluation, radiation testing, machining, and other applications.

Table V summarizes the top level performance parameters for LLNL's diode pumped Ti:Sa HAPLS laser and laser concepts building on its technologies, specifically, amplifier heat removal through gas cooling.

Table V: Top level performance parameters, system technical-readiness-values, integration challenge and delivery horizon for gas-cooled lasers and concepts.

System	Type	TRL Estimate	Integration Challenge	delivery horizon	E (J)	t (fs)	P_{av} (kW)	P_{peak}(PW)
HAPLS	DPSSL+TiS	7	Low	today	30	<30	0.3	1
SHARC	DP CPA Nd:Glass	6	Low	3yrs	150	150	1.5	1
Mini-BAT	DP CPA Tm:YLF	3-4	Medium	3-5yrs	3	40 or 100	3	.075
BAT	DP CPA Tm:YLF	3	Medium	5-7yrs	30	40 or 100	300	.75

4.C. Fiber Based Concepts

4.c.1. Fiber based lasers with coherent combining, pulse stacking, and spectral combining

High-Level Concept

Fiber lasers are the most efficient high average power laser technology demonstrated to date. Their small cores and long fiber lengths offer two key benefits. First, the small cores lead to high intensities that ensure high laser efficiency. Second, the small cores and long lengths facilitate excellent beam quality at high average power. This is a result of the small core acting as a continuous spatial filter with a high surface area to volume ratio for simple thermal management. An additional benefit of fiber lasers is that the emission spectrum of rare earth ions in glass is homogeneously broadened, leading to large gain bandwidths intrinsically compatible with 30-100-fs range pulses.

However, the small cores and long lengths of optical fibers generate two key barriers to addressing the collider and LPA radiation source laser requirements. First, pulse energy is directly related to aperture size and the required pulse energy for many of the proposed applications (joules) is significantly in excess of the attainable pulse energy from a single fiber (tens of millijoules). Second, the long fiber lengths have linear dispersion terms much greater than other proposed systems, and combined with high intensities, this generates nonlinearities that limit the quality of the compressed optical pulses at the laser output.

Figure 13 shows a notional architecture that exploits the advantages of fiber laser technology while addressing the drawbacks. As with all other approaches, chirped pulse amplification (CPA) is employed to address amplification of high peak power pulses. While development is required to realize each part of this architecture, this may provide the path to the highest efficiency for collider and high flux light source applications.

In addition to CPA, fiber lasers will also require coherent and possibly spectral beam combination in order to attain the required pulse energies. A reasonable upper bound on pulse energy from a single fiber laser is in the order of 10-30 mJ. Approximately 100 fiber lasers will need to be spatially combined into a single beam per joule of required laser energy in the application. Further, CPA alone is insufficient to mitigate nonlinearities due to the high peak powers; thus coherent pulse stacking is required to extract the full 10-30 mJ per amplifier whilst keeping the peak intensity sufficiently low to enable pulses to be recompressed with acceptable temporal fidelity.

Additionally, gain narrowing in fiber amplifiers creates challenges in exploiting the full gain bandwidth of the fiber amplifier. Pulses of 300 fs can be achieved in a straightforward manner, but to date there is only one very recent report of a 130-fs amplified pulse. It is an open question whether or not a single set of fiber amplifiers can attain the required pulse width. Thus the notional laser architecture includes a provision for coherent spectral beam combination where two or more spectral channels are employed to provide sufficient spectral bandwidth to enable the pulse width required for the application. Coherent spectral pulse combination may enable pulses as short as 30-50 fs, and potentially shorter if more than one fiber gain medium (e.g., Yb- and Nd-doped) were used.

Finally, pulse temporal quality issues associated with dispersion of the system, relevant nonlinearities, and interactions (not yet fully understood) between these effects must be addressed. To this end the notional laser architecture will need to include components to pre-correct the phase of the chirped pulse and may require post-compression pulse cleaning, a technology that would need to be developed.

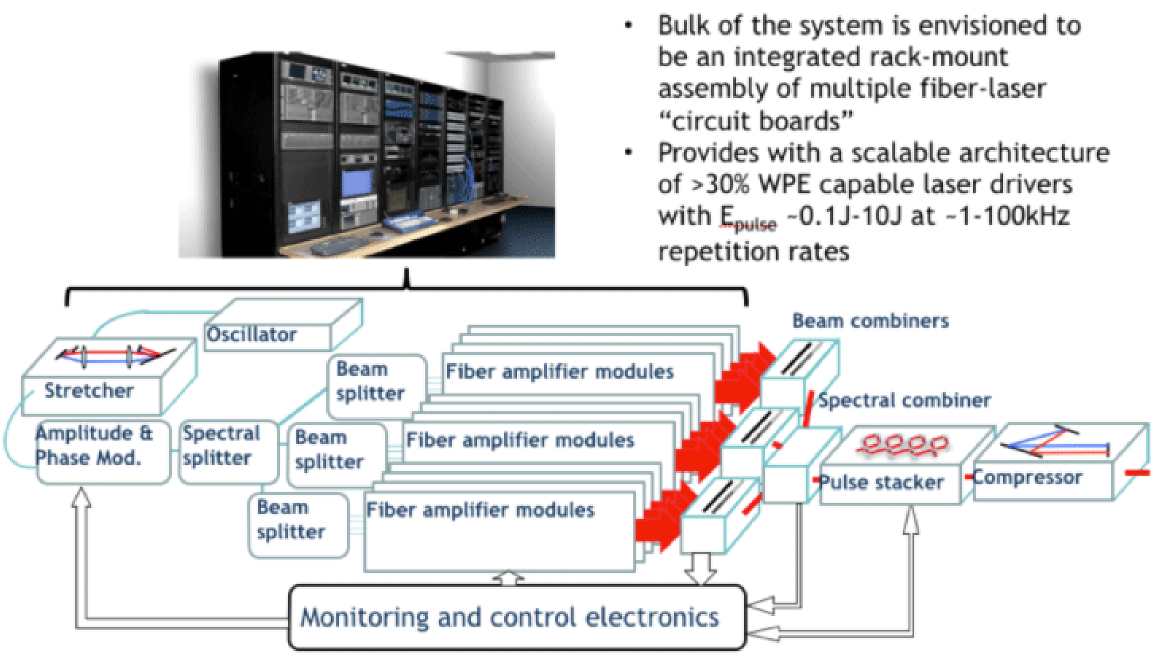


Figure 13. *Concept for a high energy, high average power laser system based upon fiber laser technology.*

Consider the notional laser architecture in Figure 13, which uses all three abovementioned coherent beam combination strategies to combine hundreds of unit cells into a single high-energy, high peak- and average-power pulse train. The system starts with a high quality, high repetition rate (1-4 GHz) short pulse oscillator. The pulses from this oscillator are stretched from ~100 fs to ~1 ns by a conventional optical stretcher. The pulse train is then amplitude and phase modulated to pre-correct for distortions in the system. The amplitude modulation also forms the pulse train into macropulses at the required system repetition rate.

Each macropulse is a train of ~81 micropulses. The pulse train is then spectrally split into 2-6 channels (if needed). After the spectral splitting each spectral channel is split into the required number of spatial channels required to attain the desired system pulse energy, where again this corresponds to a system total of ~100 channels per joule of energy. The pulse train is then amplified to 10-30 mJ/macropulse of pulse energy in a parallel set of fiber amplifiers. This distributed amplification will take place at average power levels per amplifier that have been proven to be easily manageable with current fiber laser technology. Post-amplification, the pulse trains will be recombined, first spatially, then spectrally. Finally a pulse stacker will combine the 81 micropulses into a single macropulse that is compressed by conventional pulse compressor into a single high energy, high peak and average power beam. The key advantage provided by the coherent pulse stacking amplification technique is that the extracted energy per fiber-rate channel is at least an order of magnitude higher than with other techniques. We anticipate that this will lead to a very rapid experimental advance in increasing fiber-array pulse energies. It is reasonable to expect that within 2-3 years this technique will be able to reach 100 mJ pulse energies, and to achieve TW peak and kW average powers.

The important aspect of this modular architecture is that each "unit cell" in the system consists of a monolithically spliced specialty large-core fibers, which enables very compact, integrated-board style packaging of each individual module. These individual unit cells then can be aggregated into electronic-rack type of assemblies, thus allowing very compact, easily scalable, and cost-effective laser systems. Additionally, due to the distributed heat removal from each module individually, this architecture eliminates all challenging thermal management issues.

State of the Art

An existing effort funded by the DOE Accelerator Stewardship Program is studying the notional laser architecture in Figure 7. The effort is currently focused primarily on coherent temporal pulse stacking, and has coherently stacked bursts of 81 pulses at a 1 kHz macropulse repetition rate to attain up to 10 mJ of stacked pulse energy with ~500 fs compressed pulse duration, from the first-generation 85 µm core diameter chiral coupled core fibers.[83] R&D is in progress to further improve stacking stability and fidelity. The program has also developed concepts for spatial beam combination methods using diffractive optical elements that overcome issues associated with employing these diffractive optical elements with broad spectrum pulses. The funded program is also making good progress toward developing a sophisticated model of dispersion and non-linear impacts on recompressed pulse quality. Spectral beam combination is not currently being addressed, but was previously demonstrated at a conceptual level.[84]

In Europe, there is significant work of a similar nature at the Institute of Applied Physics, Friedrich-Schiller-Universitat Jena. The group there is focusing on employing photonic crystal rods with ~100-µm cores. Divided pulse amplification is being studied as means of implementing temporal pulse stacking. The Jena team is also employing a cascade of polarizing beam splitters to achieve spatial multiplexing. A spatial light modulator is employed to correct for pulse phase errors affecting pulse quality.

The Jena group has combined 8 channels with 4-pulse macro-packets to attain 12-mJ pulses at a 56-kHz repetition rate for 700 W of compressed signal power with a beam combination efficiency of 78%.[85] These pulses were approximately 267 fs pulse width and had excellent beam quality (M^2<1.2). Nearly two orders of magnitude (18 dB) of pre-pulse suppression was attained. They are currently developing a 16 channel system and have preliminary results of 1830 W, 796 kHz, 2.3 mJ, 235 fs and $M^2 < 2$. The power amplifiers for the system fit on a 4'x8' optical table. Significant engineering effort is being applied to the set-up. Thermal effects in the beam combination system are being studied and mitigated.

---

[83] Almantas Galvanauskas et al., "Coherent Pulse Stacking Amplification – Extending Chirped Pulse Amplification by Orders of Magnitude" (invited talk), CLEO 2017 (May 14 -19, San Jose, CA), SM4I.1.

[84] Wei-zung Chang, Tong Zhou, Leo A. Siiman, and Almantas Galvanauskas, "Femtosecond pulse spectral synthesis in coherently-spectrally combined multi-channel fiber chirped pulse amplifiers," Optics Express **21**, 3 (2013), p. 3897.

[85] M. Kienel et al., "12 mJ kW-class ultrafast fiber laser system using multidimensional coherent pulse addition," Optics Letters **41**, 14 (2016), pp. 3343-6.

A French team[86] has attained a record-breaking 130-fs amplified pulse train with 250-µJ pulses at 200 kHz from a single channel fiber laser system. This is the current record for pulse width in an amplified fiber laser system. and is promising in that it may portend a notional fiber laser architecture that does not require spectral beam combination for many of the proposed scientific applications.

Yb fiber laser systems have the highest efficiencies and operate at 1µm. However, there are some advantages to Tm fiber laser systems. In particular, 95-fs pulse widths have been attained from a Tm system.[87]

A key challenge of fiber laser systems is coherent pulse pedestal. Specifically, in the 50 ps preceding the main pulse, pulse power contrast is typically on the order of 10^{-2} to 10^{-4}. Over a 500 ps - 50 ps window preceding the pulse, this coherent pedestal drops to 10^{-6}. For applications such as ion acceleration using target-normal sheath acceleration (TNSA), this is a significant problem. It may be less of an issue for other applications. However, it will at least have an undesired impact on overall system efficiency and may limit coherent combination efficiency. On the bright side, it is possible that coherent combination will reduce the coherent pedestal significantly, providing the phase errors are generated in each amplifier and not common to all pulses. Further out in time, the pulse power contrast will be dominated by amplified spontaneous emission between pulses. This may be managed as it is in other systems by employing double chirped pulse amplification (CPA), which limits system gain and associated amplified spontaneous emission (ASE). Fiber lasers systems employing double CPA have attained more than 7 orders of magnitude of ASE power contrast (75 dB).[88]

4.C.2. Ultrafast Fiber Lasers, Medium Term (10 Years, 30 kW Average Power)

As was just described, coherently combined fiber lasers will advance within the next 10 years. The physical approach that appears most promising is to arrange multiple cores in a single fiber, i.e., a multicore fiber.

We developed a concept of coherent beam/pulse addition from a multicore fiber over recent years (Figure 14) and proceeded with several proof-of-principle demonstrations, which included a compact and efficient 1-to-n beam splitter / combiner for high power ultrashort laser pulses based on segmented mirrors, the realization of a 16-element piezo array for phase length stabilization, and a photo-diode array for phase error detection. In addition, the first multicore ytterbium-doped fibers have been realized; they possess a core arrangement adapted to the segmented mirror beam splitter/combiner.

Hence, it can be foreseen that with considerable R&D effort this concept will demonstrate its potential within the next 10 years. Assuming a 16 core fiber and up to 8 mJ pulse energy per core (8 ns stretched pulse duration), one multicore fiber will deliver 128 mJ pulse energy, with 90% combination efficiency, resulting in 115 mJ usable energy at a 10 kHz repetition rate (i.e., 1.15

[86] L. Lavenu et al., "High-energy few-cycle Yb-doped fiber amplifier source based on a single nonlinear compression stage," Optics Express **25** , 7 (2017), pp. 7530-7.

[87] C. Gaida et al., "Towards sub-100 fs multi-GW pulses directly emitted from a Thulium-doped fiber CPA system," in Fiber Lasers XIV: Technology and Systems, Proc. SPIE **100830C** (2017).

[88] Jay W. Dawson et al., "High-Energy, Short-Pulse Fiber Injection Lasers at Lawrence Livermore National Laboratory," IEEE Journal of Selected Topics in Quantum Electronics 15, 1 (January/February 2009), pp. 207-19.

kW average power). Thirty-two such multicore fibers would be needed to generate >30 kW average power and >3 J of pulse energy at pulse durations in the range of 100 fs. Table VI summarizes the prospects.

The approach requires R&D on coating technology that can handle 30 kW average power, as well as R&D on fiber technology to mature ytterbium-doped fibers with large multiple cores.

A very similar approach would be feasible with thulium-doped fiber. However, taking into account the weaker efficiency of thulium-doped systems, the 2 μm wavelength path might not be the best choice on a longer time scale.

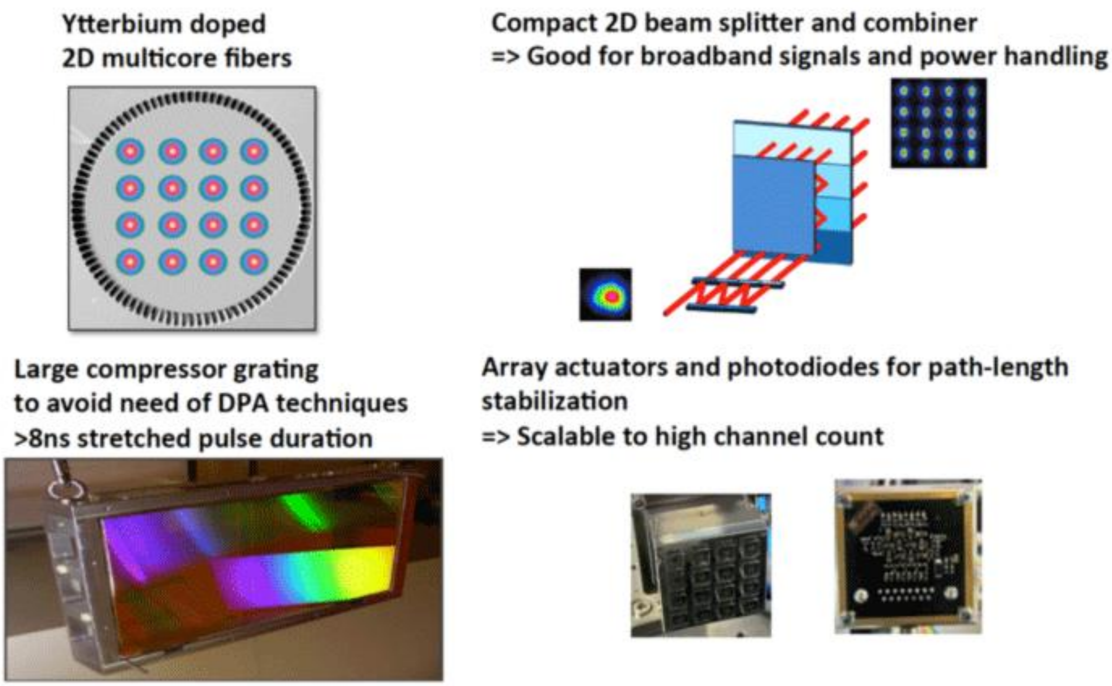


Figure 14. *Essential parts of the proposed concept.*

Table VI. Summary of feasible parameters within 10 years with fiber laser technology.

λ	E_P	P_{AVG}	f_{REP}	Δτ	Comment
1 μm	30 mJ	30 kW	1 MHz	100 fs	direct from FCPA
1 μm	3 J	30 kW	10 kHz	100 fs	direct from FCPA

4.C.3. Ultrafast Fiber Lasers, Long Term (15 Years, 300 kW Average Power)

The concept of coherently combined multicore fibers will also be pursued to address the long term goal. A 6x6 (36) core fiber,will be the basis for a single amplifier module. Assuming again a stretched pulse duration of 8 ns, each core will provide 7.8 mJ energy at close to a 50 kHz repetition rate, i.e., 370 W of average power. With 90% combining efficiency, one such multicore can deliver 12 kW average power and 251 mJ pulse energy. The emissions of 32 such compact multicore emitters will be combined again with 90% combination efficiency (in addition to a 90% compressor throughput efficiency), resulting in 6.5 J energy and 310 kW average power. The number of cores in a single fiber and resulting number of separate fibers can be adapted to hit the sweet spot in terms of production complexity, price, etc. The pulse duration can be in the range of 100 fs. Figure 15 summarizes the scaling concept.

Figure 15. Summary of projected parameters. Blue: from a single core, green: from one multi-core fiber, red: from 32 combined multicore fibers.

Table VII: Summary of feasible parameters within 15 years with fiber laser technology.

λ	E_P	P_{AVG}	f_{REP}	$\Delta\tau$	Comment
1 µm	6 J	300 kW	50 kHz	100 fs	direct from FCPA
1 µm	3 J	300 kW	100 kHz	100 fs	direct from FCPA

Significant R&D is required to realize optical components able to handle 300 kW average power from energetic femtosecond pulses. In addition, some efforts in fiber technology are needed in order to advance multicore fiber structures. This approach might allow for a wall-plug efficiency as high as 40-50% and can be very compact (less than 2 m^3 volume).

Scaling to 30 J of pulse energy appears realistic as well by, e.g., increasing the core count of a multicore fiber (e.g. 10 × 10 = 100 cores) or by increasing the number of combined multicore fibers.

Similar parameters will be feasible with thulium-doped fiber and the same approach; however, an efficiency penalty of a factor of 2 has to be taken into account. (Concerning combination efficiency and compressor throughput efficiency, there is no difference between 1 µm (ytterbium) and 2 µm (thulium) systems. However, the gain fibers have different efficiencies. Record slope efficiencies of high power ultrafast thulium-doped fiber amplifiers are in the range of 40%, whereas for ytterbium that value is as high as 80%, i.e., a 2x penalty for thulium systems. Certainly there is room for optimization, but they will never have the same efficiency.)

Furthermore, the same power, pulse energy, pulse duration, and efficiency performance can be achieved with a modular architecture shown in Figure 13. From an engineering point of view, however, this architecture might have multiple advantages. Since each parallel channel is built using monolithically integrated circuit-board modules, it allows for a great degree of flexibility, graceful scalability in array size and total power, and distributed heat management. Note that this architecture is already used in commercially available continuous-wave 100-kW fiber laser systems, which already have proven significant cost, efficiency, power scalability, and robustness advantages over conventional solid-state type architectures. Since every 300 kW LPA driver could be assembled from standardized subsystems, this should significantly reduce overall cost of each driver.

Risks, Mitigation Strategy, and Resources Needed

The following key risks were identified for this technological approach at the workshop as the highest priority for R&D investment in the near to mid term.

- Basic R&D on ultrashort pulse and beam coherent combining.
- Maturation of concepts (independently, and integrated) to achieve high fidelity performance.
- Combining optics at relevant powers and pulse energies.
- Development to maximize efficiency of the coherent combination optics.
- Basic R&D needed on pulse contrast issues and possible impact on efficiency and beam combination.
- Development of low cost, high reliability unit cells for scalable large-core fiber arrays, and maximizing pulse energy and average power per stage.
- System engineering studies.
- Assess methods to deal with complexity of the approach, and scalability of control systems.
- Projection of system costs and attainable total efficiency.

These risks were mapped into a proposed program plan with estimated funding levels required to make progress on a timeframe consistent with the DOE roadmap for laser-based accelerators. This proposed program plan is illustrated graphically in Figure 16 below. The proposed roadmap starts with the current Accelerator Stewardship Program investment in the LBNL-University of Michigan-LLNL collaborative effort on the notional architecture in Figure 13. It presumes this group will attain 10-mJ stacked pulses and a single channel theoretical model of pulse quality by the end of the effort. Note that the Jena group demonstrated spatial combination of 8 units in 2016.

4. TECHNICAL APPROACHES

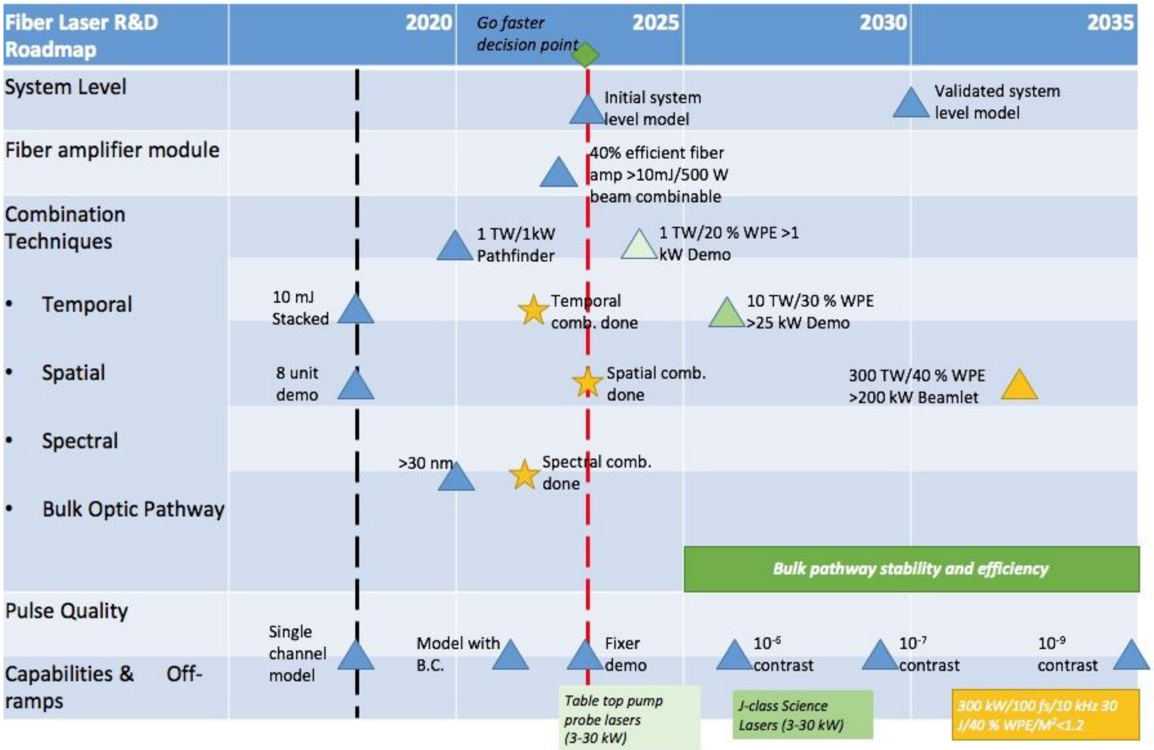


Figure 16. Fiber laser technology development roadmap.

The current effort is not funded at a sufficient level to make progress at a rate consistent with the DOE roadmap for laser based particle acceleration. To accelerate to a pace consistent with this roadmap will require a funding investment of several million dollars per year over the next five years (FY18-FY23). An investment at this level would enable many of the risk issues identified above to be addressed. Each of the three proposed combination techniques (spatial, spectral and temporal) could be demonstrated in isolation and ultimately as an integrated system.

Pulse quality issues must be addressed both via theory and benchmarked experiments to fully understand risks and achievable mitigations surrounding this issue. Fiber amplifier technology would be matured to enable a high wall-plug efficiency fiber modulate capable of producing >10mJ/macropulse, pulse trains with >500 W of average power with 40% wall plug efficiency and sufficiently low nonlinearities to allow beam combining. A low power breadboard system demo at the end of this phase would provide a go/no-go decision point for this technology.

Assuming key issues have been addressed, there would be sufficient technological support for a more robustly funded program ($10-30M/year) to address remaining science and engineering issues needed to mature this technology to the point where reliable facility class laser systems meeting the required specifications could be addressed in a series of demonstrator laser stepping stones. These stepping stones would notionally mature the technology one TRL level per step (starting at TRL 3-4) and nominally an order of magnitude of pulse energy and average power per step.

5. R&D ESSENTIAL TO ADVANCING THE STATE OF THE ART

5.A. Near Term (0-5 years)

We discussed the following R&D areas that are common to all technical approaches:

5.A.1. Development and high average power testing of optical components:

- Operation at high average power of essential laser components of short pulse lasers must be demonstrated. This includes gratings, mirrors, beam splitters, non-linear optical components, gain media, polarizers, etc.
- High peak and average powers and heat load per volume need to be tested, and mitigation strategies for deleterious effects (e.g., reflectivity degradation due to carbon contamination, deformation of optical surfaces…) need to be developed. In addition, long term lifetime of such components at high energy and repetition rates needs to be studied, and improved if needed.
- Operating non-linear optical components and gain media requires R&D, particularly including cooling strategies.

5.A.2. High efficiency spatial mode shaping and control

Research on the development of laser plasma accelerators using the BELLA laser has identified laser transverse model shaping and control, to ensure high efficiency guiding in plasma channels, as one of the key challenges. Significant progress has been made on developing plasma waveguides that can guide very high peak power structures that contain higher-order modes. However, developing methods for producing Gaussian-like far-field profiles from flat-top near-field profiles would provide very significant benefits to the operation of LPAs, which may be important to achieving collider efficiency targets.

5.A.3. Modeling and simulation tools for laser or system design

The development and engineering of complex state-of-the-art laser systems capable of delivering new levels of performance requires sophisticated computational design tools and predictive models. As existing and emerging missions and applications continue to drive advances in the technology, they are pushing—and in some cases exceeding—the existing state of the art in laser modeling capability.

Laser modeling and design tools have greatly benefited from—and to a significant extent reflect—the long history of developing high-energy and high-peak power lasers for inertial confinement fusion (ICF) research, both in the U.S. and abroad. Traditionally, this work has relied on combinations of specialized tools developed to answer specific design optimization questions about critical subsystems, the results of which are connected to other tools or to larger integrated performance models through manual interfaces. An example would be calculating the pump distribution and amplified spontaneous emission (ASE) inside an amplifier, then calculating the effective gain distribution in the amplifier, and finally feeding the gain distribution into an integrated propagation model for a chain of amplifiers. Some of these tools are commercial (raytracing to calculate ASE) and others are homegrown (calculating the pump light distribution in large amplifiers). Integrated end-to-end models for these systems are currently addressed using the quasi-4D and full-4D capability of codes developed at LLNL (Prop, VBL) and CEA (MIRO), which in their current form handle many but not all important aspects of the performance space. More complex architectures, such as laser pumped short pulse lasers, large-bandwidth short-pulse CPA high intensity laser systems, HAP systems, etc., tend to be addressed with individual tools and/or subsystem models integrated by experienced subject matter experts.

Better positioning our capabilities to support the next generation of high-intensity (large bandwidth) systems and/or high-average power systems will require additional code development/integration, as well as the incorporation of additional laser physics. Some of the needed physics includes, but is not limited to:

- Spatiotemporal coupling effects in diffractive grating compressor.
- Effects of thermal stress induced birefringence in average power amplifiers.
- Transient thermal effects on gain; these are beyond our current capability (can only do steady-state or cold).
- Statistical variations in component properties (system optimization, e.g. flaw distribution, diode array pump uniformity).
- Fully integrated amplifier models including temperature-dependent physical properties (thermal conductivity, birefringence….) and laser properties (cross-section, lower level absorption, population inversion…).
- Light induced damage mechanisms in optical materials.
- Comprehensive databases for materials and material properties.

Better code integration will allow for a more comprehensive parametrization and optimization of integrated system design (architecture iteration) and quantification of cost vs. performance.

5.A.4. Coating challenges for high peak and high average power

An identified common bottleneck for all high average and high peak power lasers is the damage threshold of coatings. For femtosecond laser damage, current state-of-the-art high-reflection (HR) optics for ~1 μm coatings have a maximum laser-induced damage threshold (LIDT) of ~80J/cm^2 (3.5ns)[89] and 10 J/cm^2 for stretched pulses (150 ps);[90] 1 J/cm^2 for shorter pulses (40 fs);[91] significantly below 0.5 J/cm^2 for few cycle pulses (5 fs, near-IR);[92, 93] and around 0.2 J/cm^2 (15 – 200 fs) for broadband pulse compression gratings.[94, 95, 96] Several other parameters

---

[89] Bellum, John, et al., "Chapter 2: Production of optical coatings resistant to damage by petawatt class laser pulses," in K. jakubczak, ed., *Lasers—Applications in Science and Industry* (InTech, 9 December 2011).

[90] C. J. Stolz et al., "150-ps broadband low dispersion mirror thin film damage competition," in *Laser-Induced Damage in Optical Materials 2015*, Proc. SPIE **9632** (2015) 96320C.

[91] R.A. Negres et al., "40-fs broadband low dispersion mirror thin film damage competition," in *Laser-Induced Damage in Optical Materials 2016*, Proc. SPIE **10014** (2016) 100140E.

[92] K.R.P. Kafka et al., "Few-cycle pulse laser-induced damage of thin films in air and vacuum ambience," in *Laser-Induced Damage in Optical Materials 2016*, Proc. SPIE **10014** (2016) 100140D.

[93] K. Kafka et al., "Few-cycle pulse laser induced damage threshold determination of ultra-broadband optics," Optics Express **24**, 25 (2016), pp. 28858–68.

[94] Nicholas Bonot and Jérôme Neauport, "Diffraction gratings: from principles to applications in high-intensity lasers," Advances in Photonics and Optics **8**, 1 (2016), pp. 156-99.

play significant roles in determining the real operating fluence for an optic: beam quality and spatial contrast (peak-to-mean fluence distribution); temporal pulse shape; bandwidth; residual transmission and interferometric superposition of beams and ghost beams; polarization; wavelength (shorter wavelengths have significantly lesser LIDTs); operating environment; repetition rate, etc. Developing tools to fully understand and optimize the effective pulse profile that an optic sees, and increasing the damage threshold, are critical and will have very significant benefits, including size and cost reduction of the laser systems as well as reliability and longevity. Adequate testing capability that mimics real-world laser system conditions, and establishment of controlled processes and test protocols, are mandatory to optimize laser architectures, reduce cost and develop affordable maintenance plans. For high repetition rate systems, very limited test capability is available and will need strategic investments.

Finally, designing robust optics lasting billions of shots requires the development of predictive modeling of laser damage of multi-layer dielectric[97] and hybrid systems. including space-time-resolved short-pulse electromagnetic interaction; ionization;[98] non-equilibrium heating with electron-electron and electron-lattice coupling;[99] shock propagation with hydrodynamic modeling;[100] and finally material modification and ablation/removal.[101] A comprehensive model or a suite of models would also have to tackle significant lowering of damage threshold fluence with increasing pulse number,[102] and surface contaminant effects[103, 104] of various kinds that may seriously hamper robust operation at high repetition rates.

Femtosecond-laser-induced damage modeling[105, 106, 107, 108] is extremely challenging due to the extremely large time scale that the process covers, from incident pulse interaction with material (femtoseconds) and ionization/transition to conduction band, laser to electron energy

---

[95] P. Poole et al., "Femtosecond laser damage threshold of pulse compression gratings for petawatt scale laser systems," Optics Express **21**, 22 (Nov. 2013), pp. 26341–51.

[96] E. Chowdhury et al., "Damage testing of critical optical components for high power ultra-fast lasers," Proc. *SPIE* **7842** (2010), pp. 78421Y–78421Y–9.

[97] M. Mero et al., "Scaling laws of femtosecond laser pulse induced breakdown in oxide films," Physical Review B **71** (2005) 115109.

[98] B. Stuart et al., "Nanosecond-to-femtosecond laser-induced breakdown in dielectrics," Physical Review B **53** (15 January 1996), pp. 1749-61.

[99] S. Wellershoff, J. Hohlfeld, J. Güdde, and E. Matthias, "The role of electron–phonon coupling in femtosecond laser damage of metals," Applied Physics A **69, Supplement 1** (December 1999), pp. S99-107.

[100] J. Colombier et al., "Hydrodynamic simulations of metal ablation by femtosecond laser irradiation," Physical Review B **71**, 16 (15 April 2005) 165406.

[101] E.G. Gamaly, a. V. Rode, B. Luther-Davies, and V.T. Tikhonchuk, Physics of Plasmas **9**, 3 (Feb. 2002), p. 949.

[102] M. Mero et al., "On the damage behavior of dielectric films when illuminated with multiple femtosecond laser pulses," Optical Engineering **44**, 5 (May 10, 2005), 51107.

[103] T. Jitsuno et al., "Progress in research on laser damage mechanisms and contamination problem," in *Pacific Rim Laser Damage 2014: Optical Materials for High-Power Lasers*, Proc. SPIE **9238** (22 Sept. 2014), 923802.

[104] T. Jitsuno et al., "Source of contamination in damage-test sample and vacuum," in *Pacific Rim Laser Damage 2016: Optical Materials for High-Power Lasers*, Proc. SPIE **9983** (9 August 2016), 998316.

[105] S.I. Anisimov, B.L. Kapeliovich, and T.L. Perelman, "Electron emission from metal surfaces exposed to ultrashort laser pulses," Journal of Experimental and Theoretical Physics **66**, 375 (August 1974), p. 776.

[106] L.V. Zhigilei, P.B.S. Kodali, and B.J. Garrison, "Molecular Dynamics Model for Laser Ablation and Desorption of Organic Solids," J. Physical Chem. B **101**, 11 (1997), pp. 2028-37.

[107] P. Lorazo, L.J. Lewis, and M. Meunier, "Thermodynamic pathways to melting, ablation, and solidification in absorbing solids under pulsed laser irradiation," Phys. Rev. B 73, 13 (2006), pp. 1–22.

[108] P. Ji and Y. Zhang, "Femtosecond laser processing of germanium: an ab initio molecular dynamics study," Journal of Physics D: Applied Physics 46, 49 (2013), p. 495108.

coupling, electron-electron (fs to ps) and electron-lattice coupling (ps), and finally material modification and/or removal (ns to ms).[109]

So far, efforts have been limited to modeling the entire interaction[110] and comparing the results with experimental observation using fitting parameters[111, 112] (molecular dynamics methods usually incorporates energy coupling from laser *ad hoc*, rather than through direct electromagnetic field equations). Modeling efforts have primarily used rate equations, a Drude model and multiple fitting parameters, and it is only recently that self-consistent E-M field damage simulation, from fs to ns timescales, in an approach with no fitting parameters, has been benchmarked against precision experiments, albeit on simple systems.[113, 114, 115]

To improve optics performance, next generation models would have to cover basic material physics research to expand the choice of dielectric layers (e.g., choosing the best individual materials and combinations of high- and low-index materials beyond the conventional range); layer adhesion and dynamics under field ionization and non-thermal energy density load; deformation; damage and ablation of layer systems; and finally, the role of grating nanostructures in field enhancement, ionization and non-thermal/resistive heating (for dielectric/metal gratings). In addition to the modelling efforts, it is also important to understand the relative contribution of various precursors and early signatures of the damage mechanisms, as observed in real environments. The comparison of these observables with modelling and mirror/grating/coating preparation techniques, environmental conditions, and long-term MTBF (mean time between failures) studies is required in order to further improve the reliability of these optics.

5.B. Long Term

5.B.1. Improving Wall Plug Efficiency (WPE), diode efficiency, and electrical efficiency

Improving the efficiency of diode lasers will be essential to achieving the wall-plug efficiency figure-of-merit of all laser systems stated herein as they are all driven by laser diodes.

The importance of diode laser efficiency becomes even more evident when considering the system size, weight, power consumption, and cost (SWaP-C) of high average power lasers. High

---

109 S.K. Sundaram and E. Mazur, "Inducing and probing non-thermal transitions in semiconductors using femtosecond laser pulses," Nature Materials **1**, 4 (2002), pp. 217-24.

110 T. Apostolova and Y. Hahn, "Modeling of laser-induced breakdown in dielectrics with subpicosecond pulses," Journal of Applied Physics **88**, 2 (2000), p. 1024.

111 P. Balling and J. Schou, "Femtosecond-laser ablation dynamics of dielectrics: basics and applications for thin films" (invited), Reports on Progress in Physics **76**, 3 (2013), 36502.

112 Alexander A. Manenkov, "Fundamental mechanisms of laser-induced damage in optical materials: today's state of understanding and problems," Optical Engineering **53**, 1 (Jan. 9, 2014), 010901.

113 R.A. Mitchell, D. Schumacher, and E.A. Chowdhury, "Using particle-in-cell simulations to model femtosecond pulse laser damage," *Laser-Induced Damage in Optical Materials 2014*, Proc. SPIE **9237** (2014), p. 92370X.

114 R.A. Mitchell, D.W. Schumacher, and E.A. Chowdhury, "Modeling crater formation in femtosecond-pulse laser damage from basic principles," *Optics Letters* 40,10 (2015), pp. 2189-93.

115 A.M. Russell, K.R.P. Kafka, D.W. Schumacher, E.A. Chowdhury, "Direct Testing against Experiment of a Fundamental Ultrashort Pulse Laser Damage Simulation Technique with Utility for the Modeling of Nanostructure Formation," arXiv.org (24 April 2017).

efficiency at the front end of the laser system has a far-reaching implication for the system's SWaP-C.

Diode laser beams must be formatted in one way or other for all the laser applications discussed in this report, which reduces efficiency. For example, fiber-coupled efficiency of laser diodes is approximately 50% when used to pump large-mode-area fibers. Efficiency can and must be further increased in the laser gain medium (by using strained quantum wells or quantum dots), and slow-axis brightness must be improved. For total wall-plug efficiency, even the efficiency of laser diodes play a role, and integration of more efficient diode drivers will enable high efficiency laser systems.

Additionally, submount/heatsink materials that combine better thermal conductivity with matching coefficients of thermal expansion (CTE) must be used, and other improved thermal management techniques, such as integrated two-phase cooling, are needed. Finally, improved fiber-coupling techniques are necessary.

5.B.2. Developing engineered gain media: Host and dopant characteristics, overcoming bandwidth limitations using material and system approaches, reduction of quantum defect

Looking beyond k-BELLA to "stepping stone" and collider systems proposed in the laser accelerator road map,[116] attention to laser driver efficiency becomes paramount to achieving the targeted system wall-plug efficiencies of 3% and 40%, respectively. Efficient laser diode arrays (i.e., a diode pumped solid state laser, or DPSSL) will most certainly be employed in powering the drivers. InGaAs laser diode arrays emitting in the near infrared (~940 nm) have achieved an efficiency of 68% at room temperature and ~85% at cryogenic temperatures.

At the conceptual level, a future collider laser driver comprises a chain of stages, each successively compressing in time the laser pulse duration from the previous stage. Inevitably, an efficiency decrement will occur at each compression event, so minimizing the number of stages in the driver system is critical.

Directly-diode-pumped, ytterbium (Yb^{3+}) doped bulk crystalline gain media are nearly ideal, since only one power conversion step is needed between an efficient InGaAs pump diode array and amplification in a gain medium with a low quantum defect (fractional energy difference between pump and laser output photon of typically ~10%). Yb-doped bulk crystal DPSSLs have achieved very high efficiencies operating in a continuous-wave mode[117] and similar performance might be achieved for systems producing ultrafast femtosecond pulses. Serious attention should be devoted to identifying and resolving efficiency limitations under ultrafast pulse operation, and to identifying more optimum Yb^{3+} ion and crystalline host combinations with effective gain bandwidths that support the required ~100-fs pulse durations.

The spectroscopic parameter values characterizing the Yb^{3+} ion in the host material are constrained by the physical "Einstein" relationship attendant to an electric dipole transition, $\sigma \cdot \tau \cdot \Delta\nu = \lambda^2/8\pi n^2$, where σ is the laser transition stimulated emission cross-section, τ is the

[116] Advanced Accelerator *Development Strategy* Report, DOE HEP (2016).

[117] Qi et al., "Nd:YAG ceramic laser obtained high slope-efficiency of 62% in high power applications," Optics Express 13, 22 (2005), pp. 8725-9.

radiative lifetime of the laser transition, Δν is the spectral width of the laser transition, λ is the laser transition wavelength, and n is the bulk index of refraction of the host material. For the Yb ion, λ ~ 1000 nm, and bulk crystal materials manifest n values between 1.4 (fluorides) and 1.8 (oxides) and the triple product σ·τ·Δν takes a value in the narrow range of 5.9-6.9 × 10^{-21} cm-sec. Additionally, a successful crystalline gain medium must possess physical, optical, thermal, and mechanical characteristics amenable to designing amplifier cooling systems that adequately remove waste heat while preserving output laser beam quality.

Thus, the working question is whether a suitable Yb-doped crystalline gain medium can be found that:

1. results in an adequately low saturation fluence (which scales as 1/σ);
2. results in an adequately long energy storage lifetime (that scales as τ), for efficient and economic use of diode pump arrays; and
3. provides adequate gain bandwidth (that scales as Δν) to support amplification of 100 to 130-fs pulses.

Additionally, host crystals will need to possess lattice crystal fields of sufficient symmetry and strength for Stark level splittings that in turn are sufficiently large to permit efficient pulse energy extraction in accordance with detailed balancing considerations. Presently known Yb-doped gain crystals do not provide an optimum apportionment of values among the "triple product" parameters σ, Δν, and τ, nor optimum Stark level splittings. However, a directed "guided" search for a more optimum Yb doped gain crystal for use in stepping stone and collider drivers seems prospective and warranted.

A second approach to a directly diode-pumped ultrafast gain medium and system architecture that is potentially suitable for stepping stone and/or collider applications was described in the Workshop by LLNL. LLNL studied over 100 gain materials for suitability for a k-BELLA or LPA collider laser driver, specifically with respect to wall-plug efficiency and capability to scale to the most challenging requirements for a collider module. The Big Aperture Thulium (BAT) laser approach is based on the "two-for-one" (pump quantum efficiency ~ 2) property possessed by the thulium ion (Tm^{3+}) doped lithium yttrium fluoride (YLF) crystalline gain medium. This QE~2 scheme enables pumping Tm:YLF with efficient AlGaAs laser diode arrays at ~ 800 nm, while sustaining a rather small effective quantum defect energy for a laser output wavelength of ~1910 nm.

The rather small laser transition stimulated emission cross-section of ~2.5×10^{-21} cm^2 (corresponding to a saturation fluence of 47 J/cm^2) and rather small overall Stark level manifold splitting would be challenging for traditional architectures with low repetition rate (single shot to hundreds of Hz) pumped amplifiers. However, the multipulse extraction technique of the BAT concept takes actually advantage of this fact: at repetition rates >1 kHz, efficient energy extraction at low fluence per pulse is accomplished, thereby eliminating laser optical damage issues. Multipulse extraction, combined with cw pumping and high repetition rate spreads the ground state absorption loss over the gain lifetime, effectively minimizing this loss to < 1%. Tm:YLF optimizes this advantage with one of the longest reported lifetimes for Tm in a host (see Section 4.A.3.a). Given the time scale to realize stepping-stone and collider solutions, a guided search for a more optimum Tm^{3+} ion-doped crystalline "two-for-one" gain medium could be undertaken. In general, the development of engineered materials including gain materials and non-linear optics could potentially benefit greatly from emerging computational tools.

For systems relying on coherent stacking and beam combining of fiber based lasers, the following areas were identified:

- Continue research on developing efficient and high fidelity coherent combining of short pulses at high average power levels.
- Understanding pulse contrast in short pulse fiber systems at fs coherent time scales as well as ps, ns time scales and develop methods for high efficiency pulse cleaning and/or pulse shaping.
- Development of extra-Large Mode Aperture (XLMA), fiber array, and multicore fiber technology for more efficient and cost effective unit cells - higher energy and average power per fiber.

Other areas of research include:

- High repetition rate diagnostics for controls systems.
- Laser energy recovery: techniques for increasing the overall system efficiency by recovering unused laser pulse energy via photovoltaic cells or other direct conversion into electrical power.

APPENDIX A: WORKSHOP AGENDA

ATAP
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

Laser Technology for k-BELLA and Beyond Workshop

chaired by Wim Leemans (LBNL)

from Tuesday, 9 May 2017 at **08:00** to Thursday, 11 May 2017 at **12:00** (US/Pacific)
at **Building 71 (264)**
LBNL 1 Cyclotron Road

Manage

Description As detailed in the downloadable Charge for the Workshop, several important applications would greatly benefit and/or require a significant increase in the repetition rate of the drive lasers. In this workshop we will discuss technological solutions towards ultrafast lasers that could operate in the multi-kW to even 10's of kW average power range. The key output of the workshop will be a report documenting several specific findings.

Attendance is by invitation only. There is no registration form; Giselle Jiles (GTJiles@lbl.gov) will contact invitees for confirmation. Attendance is free, but attendees must arrange and pay for their own transportation, lodging, and other expenses.

Working lunches will be provided on Tuesday and Wednesday, and a working dinner will be held on Tuesday night at Namaste Madras Cuisine. These events are hosted (that is, no charge to attendees). AM and PM refreshments will also be provided.

Material: Attendees | Charge | Dinner Menu | Group Photo | Key Laser Parameter | Report of Workshop

Support: Giselle Jiles ***Email:*** GTJiles@lbl.gov ***Telephone:*** +1 510.486.6344

Go to day

Tuesday, 9 May 2017

08:30 - 08:45 Welcome and discussion of charge *15'*
Speaker: Dr. Wim Leemans (LBNL)
Material: Leemans

08:45 - 09:00 Questions *15'*

09:00 - 09:40 Laser parameters for accelerator and radiation source applications *40'*
Speaker: Carl Schroeder (LBNL)
Material: Schroeder

09:40 - 09:55 Questions *15'*

09:55 - 10:05 Laser parameters for other applications *10'*

10:05 - 10:15 Questions *10'*

10:15 - 10:35 Break - 20 min

10:35 - 11:20 Current state of the art in ultrafast high power lasers *45'*
Speaker: Dr. Peter Moulton (MIT Lincoln Laboratory)
Material: Moulton

11:20 - 11:35 Questions *15'*

11:35 - 11:55 Update on high average power fiber lasers in Europe *20'*
Speaker: Jens Limpert (Institute of Applied Physics)
Material: Limpert

11:55 - 12:00 Questions *5'*

APPENDIX A: WORKSHOP AGENDA

12:00 - 13:00	Working Lunch *Continue discussion of morning session - Wim Leemans*
13:00 - 13:45	Technical approach 1 (TA1) -- Introduction *45'* Speaker: MIT-LL/URochester LLE team Material: **MIT-LL**
13:45 - 14:00	Questions *15'*
14:00 - 14:45	Technical approach 2 (TA2) -- introduction *45'* Speaker: UMichigan/LBNL/LLNL team Material: **Galvanauskas**
14:45 - 15:00	Questions *15'*
15:00 - 15:30	Break - 30 min
15:30 - 16:15	Technical approach 3 (TA3) -- Introduction *45'* Speaker: LLNL team Material: **Haefner**
16:15 - 16:30	Questions *15'*
16:30 - 16:50	Technical approach 4 (TA4) -- Introduction *20'* Speaker: Jens Limpert (IAP) Material: **Limpert**
16:50 - 17:00	Questions *10'*
17:00 - 17:20	Technical approach 5 (TA5) -- Introduction *20'* Speaker: Jorge Rocca (Colorado State University) Material: **Rocca**
17:20 - 17:30	Questions *10'*
17:30 - 17:50	Technical approach 6 (TA6) -- Introduction *20'* Speaker: Vladimir Chvykov (ELI-HU) Material: **Chvykov**
17:50 - 18:00	Questions *10'*
18:45 - 19:45	Working Dinner *Working dinner-discuss Laser Technology solutions & Laser Performance parameters.* *Namaste Madras Cuisine* *2323 Shattuck Ave, Berkeley, CA 94704*

Appendix A: Workshop Agenda

Wednesday, 10 May 2017

08:00 - 10:00	Response to charge questions Q1 and Q2 *2h0'* Speakers: Eric Esarey (LBNL), Craig Siders (LLNL)
10:00 - 10:30	Break - 30 min
10:30 - 12:30	Response to charge questions Q3 and Q4 *2h0'* Speakers: Cameron Geddes, Alan Fry (SLAC) Material: **Geddes-Fry** **TRL Status & Progress Plans**
12:30 - 13:15	Working Lunch *Continue discussion of morning session - Wim Leemans*
13:15 - 15:15	Response to charge questions Q5 and Q6 *2h0'* Speakers: Bill White (SLAC), Enam Chowdhury (OSU) Material: **White & Chowdhury**
15:15 - 15:45	Break - 30 min
15:45 - 16:45	Industry perspective *1h0'* *(M. Arrigoni (Coherent), M. Kanskar (nLight), B. Krupke (WFK), B. Tulloch (Coherent), J. Kafka (Newport), S. Backus (KM Labs), J. Limpert (IAP))* Speaker: Wim Leemans (LBNL) Material: **Arrigoni** **Backus** **Kafka** **Kanskar** **Sipes**
16:45 - 17:45	Prepare summaries for close-out and further discussions *1h0'*

Thursday, 11 May 2017

08:30 - 10:30	Finalize summaries *2h0'* Speakers: Wim Leemans (LBNL), Team Leads
10:30 - 11:00	Break - 30 min
11:00 - 12:00	Round table discussion on next steps *1h0'* Material: **White - Chowdhury**

APPENDIX B: WORKSHOP ATTENDEES

ATAP ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

Laser Technology for k-BELLA and Beyond Workshop

Last Name	First Name	Affiliation	E-Mail Address
Arrigoni	Marco	Coherent	Marco.Arrigoni@coherent.com
Anders	Andre	Lawrence Berkeley National Laboratory	AAnders@lbl.gov
Backus	Sterling	KM LAbs	sbackus@kmlabs.com
Bromage	Jake	University of Rochester Laboratory for Laser Energetics	jbro@lle.rochester.edu
Campbell	Mike	University of Rochester Laboratory for Laser Energetics	mcamp@lle.rochester.edu
Chowdhury	Enam	The Ohio State Univesity	echowdhury.laserjck@gmail.com chowdhury.24@osu.edu
Chvykov	Vladimir	ELI-HU Non-Profit Ltd.	Vladimir.Chvykov@eli-alps.hu vchv@umich.edu
Dawson	Jay	Lawrence Livermore National Laboratory	dawson17@llnl.gov
Dong	Liang	Clemson University, Dept. of Electrical & Computer Engineering	dong4@clemson.edu
Esarey	Eric	Lawrence Berkeley National Laboratory	EHEsarey@lbl.gov
Fan	T.Y.	Lincoln Laboratory Massachusetts Institute of Technology	fan@ll.mit.edu
Fry	Alan	SLAC National Accelerator Laboratory	alanfry@SLAC.Stanford.edu
Galvanauskas	Almantas	Center for Ultra Optical Science University of Michigan	almantas@umich.edu
Gaume	Romain	CREOL	gaume@creol.ucf.edu gaume@ucf.edu
Geddes	Cameron	Lawrence Berkeley National Laboratory	CGRGeddes@lbl.gov
Haefner	Constantin	Lawrence Livermore National Laboratory	haefner2@llnl.gov
Kafka	Jim	Newport Corporation	jim.kafka@newport.com
Kanskar	Manoj	nLight Corporation	manoj.kanskar@nlight.net
Krupke	Bill	WFK Laser, LLC	bkrupke@comcast.net
Leemans	Wim	Lawrence Berkeley National Laboratory	wpleemans@lbl.gov

Appendix B: Workshop Attendees

Limpert	Jens	Institute of Applied Physics	Jens.Limpert@uni-jena.de
Moulton	Peter	Lincoln Laboratory Massachusetts Institute of Technology	Peter.Moulton@ll.mit.edu
Payne	Steve	Lawrence Livermore National Laboratory	payne3@llnl.gov
Richardson	Martin	Laser Plasma Lab Townes Laser Institute, College of Optics & Photonics	mcr@creol.ucf.edu
Rocca	Jorge	College of Engineering	rocca@engr.colostate.edu
Schenkel	Thomas	Lawrence Berkeley National Laboratory	T_Schenkel@lbl.gov
Schroeder	Carl	Lawrence Berkeley National Laboratory	CBSchroeder@lbl.gov
Siders	Craig	Lawrence Livermore National Laboratory	siders2@llnl.gov
Sipes	Donald	Optical Engines Inc.	Don.sipes@opticalenginesinc.com
Toth	Csaba	Lawrence Berkeley National Laboratory	CToth@lbl.gov
Tulloch	Bill	Coherent	William.Tulloch@coherent.com
White	Bill	SLAC National Accelerator Laboratory	wewhite@SLAC.Stanford.edu
Wilcox	Russell	Lawrence Berkeley National Laboratory	rbwilcox@lbl.gov
Zuegel	Jon	University of Rochester Laboratory for Laser Energetics	zuegel@lle.rochester.edu