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Title: ULTRAFAST TERAWATT LASER SOURCES FOR HIGH-FIELD PARTICLE ACCELERATION AND SHORT WAVELENGTH GENERATION

Author(s): Michael C. Downer and Craig W. Siders

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LosAlamos Los Alamos National Laboratory
Los Alamos,New Mexico 87545

Ultrafast Terawatt Laser Sources for High-field Particle Acceleration and Short Wavelength Generation

M. C. Downer
The University of Texas at Austin
Department of Physics

C. W. Siders
Los Alamos National Laboratory

INTRODUCTION AND OVERVIEW

The Laser Sources working group (a.k.a. working group 7) concerned itself with recent advances in and future requirements for the development of laser sources relevant to high-energy physics (HEP) colliders, small scale accelerators, and the generation of short wavelength radiation. We heavily emphasized pulsed terawatt peak power laser sources for several reasons. First, their development over the past five years has been rapid and multi-faceted, and has made relativistic light intensity available to the advanced accelerator community, as well as the wider physics community, for the first time. Secondly, they have strongly impacted plasma-based accelerator research over the past two years, producing the first experimental demonstrations of the laser wakefield accelerator (LWFA) in both its resonantly-driven [1] and self-modulated [2] forms. Thirdly, their average power and wall-plug efficiency currently fall well short of projected requirements for future accelerators and other high average power applications, but show considerable promise for improving substantially over the next few years. A review of this rapidly emerging laser technology in the context of advanced accelerator research is therefore timely.

With the help of T. Tajima (U. Texas), our working group began by estimating the laser peak power, average power, efficiency, and channeling length requirements for its most ambitious, long-term projected application: a laser-driven plasma-based electron-positron linear collider beyond the Next Linear Collider (NLC). C. Clayton (UCLA) and R. Freeman (LLNL) then reviewed terawatt laser requirements for a nearer term application: γ-ray generation via Compton scattering from the proposed NLC beam for a projected γ-γ collider. W. Leemans (LBL) and P. Chen (Stanford) discussed terawatt laser requirements, respectively, for x-ray generation near $\lambda = 1$ angstrom, and for a proposed fundamental study of Unruh radiation generated by relativistically accelerated electrons in the 100 eV range. The laser requirements for short-wavelength generation experiments were both more modest and more predictable than those for an e^+e^- collider, but motivate laser development in the same general direction. We then examined recent, current, and planned development of terawatt laser sources at several institutions, including both compact solid state table-top-terawatt (T^3) laser systems operating at wavelengths near $\lambda = 1$ μm [U. Michigan (G. Mourou), U. California-San Diego (C.P.J. Barty), and the Japan Atomic Energy Research Institute (JAERI- K. Tani)], and a terawatt CO_2 laser system operating near 10 μm under development at Brookhaven National Laboratory (BNL, I.V. Pogorelsky). Potential advantages of 10 μm radiation for the inverse Cerenkov accelerator (ICA) and the inverse free electron laser (IFEL) were emphasized by W. D. Kimura (STI Optronics) and A. van Steenbergen (BNL). Laser pulse shaping and sequencing schemes for optimizing laser-plasma coupling efficiency for the LWFA were presented by P. Chen (Stanford), I. V. Pogorelsky (BNL) and D. Umstadter (Michigan). The current status and near term research problems facing optical guiding of high intensity pulses in preformed plasma channels were presented by S. Nikitin and H. M. Milchberg (U. Maryland).

These presentations showed that current technologies for ultrashort pulse, peak power generation and pulse shaping already meet the requirements of laser-driven accelerators, but that average power and efficiency fall short of projected requirements by several orders of magnitude. Several speakers discussed key enabling technologies which are opening prospects for multi-kilowatt average power, high efficiency terawatt lasers, including laser diode array pump sources, high energy storage laser crystals and glasses amenable to diode pumping, phase conjugate mirrors and adaptive optics to correct thermal distortions, new cooling technologies, beam multiplexing and combining techniques, wide bandwidth CO_2 amplifiers, and high average power compressor gratings. Rapid development of these technologies, coupled with simultaneous driving by applications in materials processing and atmospheric sensing, justifies cautious optimism that terawatt laser sources which meet the average power and efficiency requirements of future accelerators will become available within the next decade.

TERAWATT LASER REQUIREMENTS FOR HEP COLLIDERS

The 1996 Snowmass meeting projected that an e^+e^- collider beyond the NLC must provide a center of mass energy of 5 TeV and luminosity at the interaction point (IP) of 10^{35} cm^{-2}s^{-1}. In order to help estimate the laser requirements for such a collider, T. Tajima presented a "strawman" scenario, described in more detail in a separate paper in this volume, which envisioned that such a collider would be a LWFA driven resonantly in a well-controlled linear regime of laser-plasma interaction to a plasma wave amplitude approaching the cold wavebreaking (WB) limit $\delta n_e/n_e \sim 1$. Collider parameters were chosen to satisfy known collider physics requirements. In particular, bunch size was limited to 10^8 e^- in order to hold IP beamstrahlung losses and collective instabilities to acceptable levels. Preference was given to small individual stage acceleration lengths ($L \sim 1$ m) by assuming acceleration gradients (~ 10 GeV/m) well beyond the limit of conventional rf accelerators, thus dictating a plasma density $n_e \sim 10^{17}$ cm^{-3} , for which $L_{\mathrm{dephasing}} = L_{\mathrm{pump\ depletion}} = 1$ m and $E_{\mathrm{WB}} = 10$ GeV/m. The plasma wave was assumed to transfer its stored electrostatic energy to beam energy with an efficiency of 10%. Small beam size and therefore emittance ($e_{yn} = e_{xn} = 2 \times 10^{-7}$ m-rad) were assumed achievable and appropriate to a small radius acceleration channel driven by a short wavelength ($\lambda \sim 1$ μm) laser source. Finally 500 MW of electrical power were assumed to be available for the lasers. See the paper by M. Xie *et al.* in this volume for further discussion and justification of the assumed parameters. From the above scenario, one can straightforwardly derive the terawatt laser requirements shown in the second column of Table 1 and compare them with the capabilities of existing solid state and CO_2 laser technology shown in the fourth and fifth columns. Because of uncertainty in the underlying assumptions, the figures in the second column should be treated as, at best, order of magnitude estimates.

A parallel set of laser requirements can be derived, with much less uncertainty, for γ-ray generation at NLC for a γ-γ collider. In this case the laser requirements are dictated directly by known e^- beam characteristics. First, the pulse format of the laser must follow that of the

Parameter	5 TeV LWFA	NLC γ-γ	Solid St.		CO_2	Units
λ	1–10	1	0.8	1.06	10	μm
E	1	1	0.1	20	15	J
τ	100	1000	20	1000	3000	fs
P_{peak}	10	1	5	20	5	TW
f_{rep}	60	15	50×10^{-3}	10^{-5}	10^{-4}	kHz
P_{avg}	60	15	5×10^{-3}	2×10^{-4}	1.5×10^{-3}	kW
$\eta_{\text{wall-plug}}$	0.1	——	$< 10^{-4}$	$< 10^{-4}$	~ 0.01	

Table 1: Laser Requirements for a 500 stage, 5 TeV LWFA and NLC-based γ-γ collider (85 bunches/macropulse at 180 Hz macropulse rate) and current state of the art for solid-state, i.e. Ti:S (0.8 μm, [3,4]) or Nd:x (1.06μm, [5]), and CO_2 systems [6]. For the NLC γ-γ collider, current efficiencies are adequate since only one laser system is needed.

e^- bunches, which at NLC consists of macropulses of 120 ns duration at 180 Hz repetition rate, each consisting of 85 micropulses separated by 1.5 ns. Second, the lower limit of laser wavelength is set by the need to avoid e^+e^- pair production by secondary rescattering of γ-ray photons with incident laser photons ($\gamma + \omega_0 = e^+ + e^-$), as dictated by the inequality $\omega_0\omega_\gamma < m^2c^4$, or equivalently $\lambda > 4.2\ E_0$[TeV] μm. For NLC ($E_0 = 0.25$ TeV), this implies $\lambda > 1$ μm, an appropriate wavelength for solid state TW laser technology. For a future higher energy collider (e.g. $E_0 = 2.5$ TeV), the same inequality implies $\lambda > 10$ μm, appropriate for CO_2 technology. Thirdly, the required pulse duration $\tau \sim 1$ ps is determined by matching the longitudinal e^- bunch profile, while the pulse energy $E \sim 1$ J is set by requiring unity conversion efficiency of optical to γ-ray photons. These requirements are summarized (peak power 1 TW, average power 15 kW, at 1 μm wavelength) in the third column of Table 1.

Several broad conclusions emerge from these intellectual exercises. First, starting with the good news, the individual laser pulse requirements ($E_{\text{pulse}} \sim 1$ J, $\tau_{\text{pulse}} \sim 0.1$–$1$ ps, $P_{\text{peak}} \sim 1$–10 TW) for both the e^+e^- and γ-γ collider scenarios have already been met by existing 1 μm solid state T^3 laser technology, as described in more detail in the next section. Subpicosecond terawatt CO_2 sources appear poised to meet such requirements in the near future. Secondly, the estimated number of acceleration stages (500), and therefore laser systems, for the e^+e^- collider appears to be within the budget (~\$200 million) of a large national or international collider facility, assuming current prices (~\$400K) for terawatt laser systems. For the γ-γ collider, only two such laser systems would be required. Thirdly, the laser-plasma coupling efficiency $\eta_{\text{laser-plasma}} \sim 10\%$ required by the LWFA-based e^+e^- collider scenario appears reasonable provided the required channeling lengths can be achieved, and that pulse shaping techniques discussed further in the next section are fully exploited.

At the same time, the collider scenarios reveal several aspects of terawatt laser technology which are in need of substantial further development. First, the IP luminosity requirement for the e^+e^- collider dictates that 1 J, 100 fs pulses must be delivered at a repetition rate $f \sim 60$ kHz, corresponding to an average power of $P_{\text{avg}} \sim 60$ kW. This, as well as the 15 kW requirement of the γ-γ collider, both exceed the current capability of solid state terawatt laser systems by over three orders of magnitude. CO_2 technology has demonstrated multi-kilowatt average powers, but so far only for pulses of nanosecond or longer duration. The physical causes of the current limitations and efforts in progress to overcome them are described in the next section. Secondly, the available electrical power for a e^+e^- collider dictates wallplug-laser efficiency near 10%, again several orders of magnitude beyond the capability of current solid state laser technology. High power CO_2 lasers achieve efficiency near the required 10% level, but this needs to be demonstrated for subpicosecond pulse duration. For the γ-γ collider, and other short-wavelength generation applications, current wall-plug efficiency levels are tolerable because of the much smaller number of laser systems.

TERAWATT LASER TECHNOLOGIES IN HAND

Over the past ten years, the dual emergence of Ti:sapphire and other solid-state vibronic media as high-quality, ultrabroadband, high energy storage amplification materials and of chirped pulse amplification (CPA) techniques [7] have spurred the generation of multi-terawatt ultrashort pulses near 1 μm wavelength in table-top laser systems around the world. In CPA, low energy short duration seed pulses are expanded several thousand-fold in duration by chirping, thus enabling amplification at high fluences without intensity-dependent damage of the solid-state amplifier components. Early CPA systems achieved peak powers near 1 TW in the form of 0.1 to 1 J pulses of 100 to 500 fs duration. Later refinements to CPA included the development of seed pulse oscillators at the 10 fs level, development of high order dispersion compensation techniques, and the development of passive spectral shaping elements to compensate spectral gain narrowing in the amplifier. These refinements have resulted in generation of ultrashort laser pulses with peak power higher than 100 TW. These single pulse properties exceed projected requirements for plasma-based particle accelerators and gamma ray sources of interest to the high energy physics community. The dramatic recent developments in solid state TW laser technology have been reviewed in detail by Barty [4] and by Mourou and Perry [8].

Participants in the Laser Sources working group pointed out emerging solid state technologies likely to lead to still further improvements in multi-TW peak power generation. G. Mourou described several potential advantages of Yb:glass as an amplifying medium for CPA. The glass host is cheaper and scalable to larger sizes than crystalline hosts. Moreover, Yb:glass, which has a gain bandwidth sufficient for 30 fs pulse amplification, offers much higher energy storage capacity (30 J/cm^3) than most ion-doped crystals, although limitations to usable fluence set by optical damage must be carefully evaluated. Other possible advantages of Yb:glass are discussed in the next section. C.P.J. Barty, on the other hand, emphasized that CPA based on now standard, wider bandwidth Ti:S crystals, which support amplification of pulses as short as 10 fs, could be scaled to pulse energies as high as 40 J at repetition rates of 6 Hz by exploiting recent advances in phase-conjugated Nd:glass pump lasers. For example, eight such lasers each providing 25 J at 532 nm, simultaneously pumping a Ti:S final amplifier stage would be adequate to produce a 40 J pulse. K. Tani described plans to construct a system similar to this at the Japan Atomic Energy Research Institute, where generation of pulses approaching the 1 PW level at 5 to 10 Hz repetition rate is anticipated by the year 2000.

While solid state CPA systems are currently the most advanced sources of TW laser pulses, I. V. Pogorelsky described a novel TW picosecond CO_2 laser system now under development at the Brookhaven Accelerator Test Facility (ATF). Conventional subnanosecond, multi-GW CO_2 lasers have been, and continue to be, used successfully in laser beatwave accelerator (LWBA) experiments, where externally-injected electrons have been accelerated to energies as high as 30 MeV [9,10]. The projected generation of ps, multi-TW CO_2 pulses will not only upgrade ongoing far field (inverse Cerenkov and inverse FEL) experiments, but will open application of CO_2 lasers to plasma-based LWFA schemes for the first time. Pogorelsky, A. Van Steenbergen, and W. D. Kimura emphasized several advantages which the 10 μm wavelength of the CO_2 laser can offer in these applications. In far field accelerators, the long wavelength lengthens the phase slippage distance between particles and oscillating fields, reduces sensitivity to bunch smearing and gas scattering, and increases the achievable longitudinal accelerating field compared to a shorter wavelength driver. For the LWFA, a 10 μm driver pulse produces a hundred-fold higher ponderomotive potential in the plasma, resulting in a higher axial accelerating field E_z than for a 1 μm pulse of the same intensity and duration. For plasmas of the same density this advantage is offset by the shorter phase slippage distance ($L_{\text{dephasing}} \sim \lambda_p^3/\lambda^2$) for the 10 μm driver, caused by its smaller group velocity in the plasma. However, a practical10 μm driven LWFA would probably operate with lower plasma density and looser focus than its 1 μm counterpart, in which case the $L_{\text{dephasing}}$ disadvantage is reduced or eliminated. For the self-modulated LWFA, drivers of equivalent relativistic self-focusing power $P[\text{GW}] = 17(\omega/\omega_{\text{p}})^2$ may provide the most relevant comparison. From this point of view, the CO_2 driven accelerator operates at hundred-fold lower plasma density than, and $L_{\text{dephasing}}$ equivalent to, the short wavelength driven accelerator, and thus provides greater total acceleration $E_z L_p \sim \lambda$ over a dephasing length [12]. Emittance degradation from electron beam scattering should also be reduced at lower plasma density. The paper by Pogorelsky *et al.* in this volume discusses these comparisons further.

A 10 GW (1 J, 100 ps) CO_2 laser is currently operational at the ATF. The basic technologies for upgrading the current system to multi-TW (15 J, 3 ps) power exist, and are being combined and implemented at BNL. Semiconductor switching techniques [11] will be used to generate picosecond 10 μm seed pulses. Isotopic mixing and high pressure ($\sim$ 10 atm) collisional broadening are being used to broaden and smooth the CO_2 gain spectrum into a 1 THz bandwidth continuum which supports 0.5 ps pulse amplification. A high volume-penetrating x-ray pre-ionizer and fast energy loading from a 1 MV Marx generator will be used to achieve a spatially uniform discharge in the large active volume ($\sim$ 10 liter) required to reach TW power levels in the small energy storage density ($\sim 10^{-2}$ J/cm^3) CO_2 medium. Initial repetition rate of 0.1 Hz is anticipated. The ATF laser is expected to be available as a user facility by 1998. Further details of the upgrade parameters and schedule are presented in the paper by Pogorelsky *et al.* in this volume.

In addition to high peak power generation, several working group participants emphasized the importance of temporal shaping and sequencing of TW pulses for optimizing laser-plasma coupling efficiency in plasma-based advanced accelerators. P. Chen predicted analytically that an asymmetric temporal pulse profile consisting of a slow rising edge and a sharp falling edge maximizes efficiency for driving the LWFA with a single pulse in the linear regime. A similar conclusion based on PIC simulations [12] was presented by I.V. Pogorelsky, who noted that nearly optimized pulse shapes can be produced by the semiconductor switching system used to seed picosecond CO_2 amplifiers. For a more strongly driven LWFA, D. Umstadter presented 1D simulations showing that short pulse trains with pulses spaced by approximately a plasma period improve driving efficiency over a single pulse [13]. In an optimized pulse train, the pulse spacing increases and pulsewidth decreases as the plasma amplitude grows. These optimized LWFA driving schemes have not yet been demonstrated in the laboratory. Such experiments are needed to determine their sensitivity to jitter in pulse shape and spacing, to plasma density nonuniformity, and to radial pulse structure. Nevertheless the technology for shaping and optimizing ultrashort pulses and pulse sequences has been developed in other contexts. Programmable liquid crystal displays or acousto-optic modulators placed in the Fourier plane of the stretcher of a CPA system modulate the spatially dispersed frequency components of a short pulse to produce the desired temporal shape and/or sequence after the amplifier and compressor [14,15]. Temporal features on a 20 fs times scale has been demonstrated [15], and appears adequate for LWFA applications. Pulse sequencing challenges beyond the single- or several-pulse regime which arise in multi-kilohertz repetition rate applications such as the γ-γ collider are discussed in the next section.

For resonantly-driven LWFAs based in plasmas of density less than several 10^{18} cm^{-3}, the driving pulse or pulse sequence must be optically guided at peak intensities of 10^{18} W/cm^2 over distances much longer than its vacuum Rayleigh length in order to convert plasma electrostatic energy efficiently into beam energy. Leemans *et al.* [16] have carried out a detailed design study of guiding requirements for next generation LWFA experiments. The guide length should be approximately equal to the phase slippage length λ_p^3/λ^2, which ranges from several cm to several meters for typical resonantly-driven LWFA schemes. The U. Maryland group of H. Milchberg has pioneered the development of preformed plasma waveguides which have guided pulses as intense as 5×10^{15} W/cm^2 over several hundred Rayleigh lengths (3 cm) [17]. The waveguide is created by bringing a 100 ps, 1 μm, 0.5 J pulse to a cylindrically symmetric focus using an axicon lens. A density cavity with wavelength-independent optical guiding properties evolves on a nanosecond time scale as a shock wave driven by axial electron heating propagates radially outward. The Maryland group has characterized the radial mode structure of guided pulses [18] and has analyzed the temporal evolution of the waveguide structure using folded wavefront interferometry [19]. The experimental approach and theory of a guiding technology relevant to plasma-based accelerators is thus already well-developed. Nevertheless several problems still need to be addressed. Guiding properties must be experimentally tested at the intensity and pulsewidth (10^{18} W/cm^2, 100 fs) required by the LWFA . Distortions induced on both the waveguide and the intense driving pulse by relativistic nonlinearities may become significant and must be carefully evaluated. Moreover the input and output coupling efficiency, and shot-to-shot pointing stability, will have to be evaluated at high intensity. Waveguide-induced slowing of the group velocity will degrade phase slippage distance, and will have to be figured into the accelerator design. Finally, waveguides of 10 cm to 1 m length will require laser pulses of 1 to 20 J energy to form the channel. Such lasers become a major fraction of the power consumption of any accelerator scheme, and will face the same difficulty in scaling to higher repetition rates as the lasers which power CPA systems. These issues will be key subjects of near-term research in plasma channeling for accelerator applications.

Several short wavelength sources driven by visible and near infrared TW or multi-GW laser pulses have been developed in the past few years. Incoherent picosecond soft x-ray pulses have been produced by the interaction of intense high-contrast pulses with solid targets [20–22]. Coherent XUV radiation has been generated by TW-pulse-driven laser action [23] and by high order harmonic generation [24] in gases. Of particular relevance to the advanced accelerator community is the recent generation of fs x-ray pulses by 90 degree Thomson scattering of a TW laser pulse (100 fs, 40 mJ, 800 nm., 10^{15} W/cm^2) from electron pulses (1.5 nC, 15 ps, 50 MeV) in the injector linac at the Berkeley Advanced Light Source [25]. Initial experiments have produced 10^5, 30 keV x-ray photons in a pulse of 200 fs duration with an angular divergence of 10 mrad. A similar physical interaction scaled to higher electron energy (.25 to 2.5 TeV) and laser pulse energy (1 J), involving similar laser-electron pulse synchronization issues, underlies proposed γ-ray generation schemes for future γ-γ colliders [26], as discussed further in the next section. P. Chen and T. Tajima also proposed to the working group that existing or near-future TW lasers (10–100 TW, 10 fs, 10 μm focus guided over 1 cm) could generate detectable ($\sim$ 100 photons) Unruh radiation [27] in the 100 eV range because of perturbation of the vacuum by relativistically accelerated electrons in the laser pulse front. Thus within the last few years TW laser technology has introduced not only a variety of promising new short wavelength sources, but the promise of new table-top physics experiments at the most fundamental level.

Most of the laser technologies and applications outlined above have developed since 1991, demonstrating that progress can be very fast. We can thus approach remaining problems in terawatt laser technology with some confidence that they, too, can be overcome on a reasonable time scale.

TW LASER TECHNOLOGIES NEEDING MAJOR DEVELOPMENT

The principal shortcomings of current TW laser technology for projected collider applications are low average power and, for solid-state lasers, low wall-plug efficiency. These limitations originate from several sources. Current solid state TW laser systems are very inefficiently pumped. Typical Ti:sapphire oscillators are pumped by an argon laser which consumes > 10 kW of electrical power to produce a 5 W output beam before pumping the oscillator with 15% efficiency. Flash-lamp-powered Nd:YAG lasers, which often pump the Ti:sapphire amplifier crystals and the plasma channelling system, typically operate with about 1% wall-plug efficiency. In such lasers the flashlamps convert about half of the electrical input power to a blackbody output spectrum of which only 10–20% falls within the absorption bands of the laser rod. Of this useful fraction, typically 10 to 20% will appear as laser output, depending on material parameters of the gain medium, geometrical factors, and optical losses, while the rest is dissipated as heat [28]. Similar ratios apply for flashlamp-pumped Nd:glass amplifiers, where the poor thermal conductivity of glass results in slower heat removal. Thermal stressing and thermo-optic beam distortion from cumulative heating limit the repetition rate to tens of Hz for typical (10 W average power, 1 cm beam diameter, Q-switched) Nd:YAG pump lasers. In fact the average power of nearly all high peak-power solid-state laser systems, from Nova-scale down to short-pulse oscillators does not exceed approximately 10 Watts. The currently highest power CPA systems (5–50 J/pulse) use cylindrical Nd: glass rods of several cm diameter in the final stage, where heat removal limits the repetition rate to as little as two to three pulses per hour.

For a simple pulsed amplifier this "10 Watt limit" is straightforwardly rationalized. The repetition rate f is inversely proportional to the cooling time $\tau_{\text{th}} = (x_0^2 c\gamma)/\kappa$, where c is the heat capacity, γ the mass density, κ the heat conductivity, and x_0 is a scale length for heat flow. For a simple cylindrical rod amplifier cooled about its sides, x_0 would be proportional to the radius r_0. The damage fluence, $F_{\text{dam}} \sim 1$ J/cm^2, for both the amplifier media and associated optical elements (mirrors, lenses, etc.). In order to accommodate large pulse energies E with a cylindrical amplifier, the beam must have an area $A \geq E/F_{\text{dam}}$, and therefore the average power $P_{\text{avrg}} = E \cdot f \sim F_{\text{dam}}\kappa/c\gamma$ is constant. For typical solid-state laser hosts, e.g. sapphire and YAG, this constant is on the order of a few watts. For glass hosts, which can be made in large slab geometries, the significant increase in extracted energy is offset by the $\sim 50\times$ smaller heat conductivity, leading coincidentally to the same few watt limit. Similar results hold for quasi-CW operation, in which a more careful analysis of the heat flow must be performed. The figures used above represent conservative estimates.

CO_2 lasers can operate with 15 to 20% efficiency with 50 kilowatt average power for CW discharges and nearly 1 MW for gas-dynamic lasers [29]. For long pulses, they can operate at 1 kHz with several kW average power. The TW peak power, subpicosecond pulsed laser now under construction at BNL will initially operate with unoptimized repetition rate (0.1 Hz), average power (1.5 W), and wall-plug efficiency (0.01), which are adequate for its intended use for proof-of-principle high field physics experiments. However, in the future it should be feasible to scale these numbers significantly upward, using known technologies, while maintaining the 10 liter volume of the gain medium. Pogorelsky estimates that repetition rates of 1 kHz, limited by the power supply and the speed of gas exchange through the discharge region, should be feasible with 50 TW peak power, limited by window damage, 10 kW average power and 0.5 to 0.8 ps pulse duration. The initial wall-plug efficiency is limited by the weakess of the x-ray (compared to e-beam) preionization, which necessitates a higher than optimum discharge voltage, and by the window damage threshold and an unoptimized optical configuration. Efficiency of stored energy extraction can be improved several-fold by amplifying a 100 ns train of 1 ps pulses instead of a single 1 ps pulse. Pogorelsky estimates that efficiencies approaching 20% are achievable in ps TW mode.

DRIVING APPLICATIONS

Shortcomings in efficiency and repetition rate are not unique to TW lasers or to advanced accelerator applications, but currently limit many high average power laser applications [26]. For example, TW lasers scaled to multi-kilohertz repetition rates could provide a compact, bright, inexpensive source of soft x-rays for photolithographic manufacture of future submicron integrated circuits [30]. Atmospheric sensing applications, including global wind measurements for weather modelling and local diagnostics of wind shear near airports and vorticity in tornado-prone areas [31], generation of pulsed laser guidestars [32], and laser ranging and targeting applications are driving development of high average power, nanosecond-pulse solid state lasers in the near infrared. Since such lasers often pump solid state TW lasers, scaling of their repetition rate and average power will directly benefit TW technology. Nanosecond CO_2 lasers, which can operate at high efficiency (10–20%) and average power (multi-kilowatt) compared to their long-pulse solid-state counterparts, are also becoming increasing attractive for remote sensing applications as new nonlinear optical materials are developed [33] for efficiently frequency doubling their output into the atmospheric propagation window at 4–5 μm. Finally, materials processing applications such as welding, cutting and annealing also increasingly require kilowatt average power lasers of various wavelengths and pulse durations. Femtosecond laser micromachining [34] and 3D optical storage inside transparent materials [35] are emerging applications which will also benefit from higher average power sources. Since the driving applications are numerous, the community-wide motivation for overcoming current limitations to TW technology is high.

ENABLING TECHNOLOGIES

Group 7 participants outlined the key enabling technologies which are now being developed to achieve efficient high repetition rate laser operation. The first two of the following technologies – efficient pumping and improved thermal management – apply primarily to solid state lasers. The third – beam multiplexing – applies equally to solid state and CO_2 lasers.

1. Diode array pumping. The replacement of flashlamps and argon lasers by laser diode arrays promises to have an impact on solid state laser technology in general, and TW laser technology in particular, as profound as the replacement of vacuum tubes by solid state integrated circuits. The ability to fabricate linear bars and 2D arrays with tight control of material composition, layer thickness and device geometry has progressed significantly during the past decade with advances in epitaxial semiconductor growth techniques such as metal organic chemical vapor deposition (MOCVD). The excellent spectral match between their output and the absorption bands of solid state gain media renders essentially all of the radiation useful. Consequently pumping efficiency is greatly increased, while thermal loading is reduced compared to flashlamp pumping, thus permitting an increase in repetition rate and average power. For example, diode-array pumped Nd:YAG lasers with cylindrical rods have already been operated with wall-plug efficiencies of 8% at 0.8 J/pulse, average powers 160 W, repetition rate 200 Hz [28]. Longer lifetime (10^9 shots) and reduced system maintenance compared to flashlamps (10^7 shots) also result from the reduced thermal loading and negligible UV output. The principal current drawback of diode arrays is their high cost resulting from customized, labor-intensive manufacturing. However, R. Freeman estimated during group 7 discussions that high demand would reduce their cost 10- to 100-fold within the next several years.

Group 7 participants described several ways in which laser diode arrays could impact TW laser systems. C.P.J. Barty emphasized their role in scaling Nd:YAG and glass lasers for use as high average power pump sources for wide-bandwidth Ti:sapphire gain crystals, which because of short fluorescence lifetime cannot be directly diode-pumped. In a similar vein, K. Tani described extensive use of diode-pumped Nd:YAG lasers for pumping a planned high repetition rate TW Ti:sapphire system at JAERI while R. Freeman and C. Clayton emphasized the central role of diode-pumped Nd lasers in planned γ-γ collider development. G. Mourou, on the other hand, emphasized the potential role of laser diodes as direct pumps of wide bandwidth gain media such as Yb:glass, which have storage times as long as 2 ms. This approach favors overall system compactness, although the problem of heat removal from glass must be addressed, as discussed further below. The emergence of femtosecond oscillators based on Nd:glass and Cr:LiSaF which can be directly laser-diode pumped [36], though not presented at AAC, is also enabling more efficient and compact laser sources for advanced accelerators by replacing inefficient argon lasers.

2. Thermal management. Even with efficient diode pumping, the scalability of solid state amplifiers to higher average power is still limited by residual thermal distortions in the solid state gain medium. Methods for management of and compensation for these residual thermal effects therefore complement diode pumping as a key enabling technology in high average power generation. Face-pumped slab gain medium architectures, employing a zig-zag optical path to suppress thermal distortions present in cylindrical rod geometries, have been a subject of active research and development since their original proposal in 1972 [37]. Residual thermal distortions from edge and end effects set the practical performance limits of such systems, and place a premium on uniform pumping deposition, uniform cooling and optimized slab design [28]. Scalability of such systems to kilowatt average power has been demonstrated for long pulse operation. For example, a diode-array-pumped Nd:YAG slab laser has generated 1 kW average power in 150 microsecond pulses at 2 kHz repetition rate, although with poor beam divergence [38]. Improvements to this design are expected to achieve 10% wall-plug efficiency [28]. To improve output beam quality, several groups have supplemented slab amplifiers with active correction of thermal wavefront distortions by optical phase conjugation [39]. For example, a diode-pumped Nd:YAG slab laser using phase conjugate mirrors based on stimulated Brillouin scattering (SBS) has produced 100 W average power in the form of 1 J pulses at 100 Hz [40]. Even in flashlamp-pumped Nd:glass amplifiers, SBS phase conjugation has enabled unprecedented generation of 30 J, 14 ns pulses at > 150 W average power (6 Hz repetition rate) [41]. Although the powers and repetition rates achieved to date are lower than in uncorrected lasers, these phase conjugated systems have produced nearly diffraction-limited output beams. The bandwidth of available phase conjugate nonlinear media may limit their direct use in TW CPA systems, where they must respond to extremely broadband, sub-nanosecond stretched pulses whose re-compressibility is very sensitive to material dispersion. In these cases alternative adaptive optic technologies such as deformable mirrors may provide the required wavefront correction. According to K. Tani, extensive use of adaptive optic technologies is planned in the high average power TW systems at JAERI.

G. Mourou described an alternative thermal management approach appropriate for media such as Yb:glass, which have poor thermal conductivity but can be scaled to large sizes. In this scheme, diode-pumping and amplification are restricted to a region near the edge of an Yb:glass cylinder, which is then continuously rotated during amplification so that a cooled region of the gain medium is presented to each pulse. The center of the cylinder can be hollowed to provide a channel for coolant flow.

3. Beam multiplexing. Efficient pumping and good thermal management may push solid state TW technology one to two orders of magnitude beyond the "10 watt limit". However, further progress will require beam multiplexing. G. Mourou, R. Freeman, and C. Clayton each independently described one generic approach to beam multiplexing. In their scheme, a single pulse from a low repetition rate preamplifier is divided into numerous individual beam lines, each containing one thermal- and fluence-limited $\sim$ 10–100 W T^3 amplifier. After recombination, the copropagating but temporally separated pulses form a "brigade" of pulses with a net average power in the multi-kW regime. C. Clayton described a variety of specific methods for dividing and recombining the pulse train. The simplest approach uses a passive cascade of beam splitters and optical delay lines. An alternative active approach traps the low repetition rate input pulses in an optical storage ring in which the pulses can be regeneratively amplified and shaped while the pulse frequency is multiplied. Frequency-domain multiplexing is also possible. These multiplexing schemes can be used not only to increase the repetition rate, but also to produce a desired laser pulse format. For example, to produce gamma rays by Compton backscattering from the NLC beam, the laser pulses must be synchronized with an electron pulse format consisting of 120 ns. macrobunches at 180 Hz repetition rate, each containing approximately 85 pulses at 1.5 ns separation. These various approaches to multiplexing are described in more detail in [26].

A long-range proposal for a more ambitious multiplexing scheme, discussed by C.W. Siders, utilizes the r_0^2 dependence of the cooling time, combined with a monolithic amplifier consisting of, for example, 10 μm diameter × 1 cm long amplifier rods in a 5000 × 5000 (10 cm × 10 cm) array, to achieve up to MHz repetition rates with MW average powers. Rather than multiplexing in the time domain, this scheme would utilize a microlens array to coherently separate, amplify, and recombine tens of millions of individual "microbeams". Optical pumping could be achieved either via dichroic longitudinal pumping with a large array of fiber-coupled diode lasers or, perhaps, via diode lasers embedded in the monolithic structure and with transverse gradient-index coupling to the amplifier rods. Though this scheme has considerable attraction as a compact (100 cm^3) "single-stage" amplifier, considerable engineering would be required in the area of coolant flow within the structure and subsequent heat dissipation. Nevertheless, similar designs have been successfully used for $\sim$ 10 MW operation in commercial nuclear power station fuel bundles and design work has been performed on similarly compact MW-class fission-fragment-pumped lasers [42].

CONCLUDING REMARKS AND PROSPECTUS

Rapid developments in solid-state terawatt laser technology within the past five years have already met the single pulse requirements for a variety of laser-driven advanced accelerator schemes. A new CO$_2$ terawatt technology is now emerging, and promises to complement the capabilities of solid state sources in many advanced accelerator applications. The basic technologies for improving average power and (for solid state lasers) efficiency by as much as two or three orders of magnitude are now rapidly being developed in numerous laboratories. It appears likely that kilowatt average power, terawatt peak power lasers which meet the basic requirements for developing a γ-γ collider in conjunction with the NLC or other linear collider can be developed within the next decade. A future high luminosity, laser-driven e^+e^- collider will require hundreds of such laser systems. Wall-plug efficiencies of at least 10% will therefore be essential to contain power consumption costs. There are grounds for optimism that this efficiency requirement can also be met. Nevertheless simultaneous unprecedented requirements for multi-stage alignment and beam emittance in such a collider will raise new technological challenges which have yet to be seriously addressed.

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