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High-Power Lasers for Science and Society

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Executive Summary

Since the first demonstration of the laser in 1960 by Theodore Maiman at Hughes Research Laboratories, the principal defining characteristic of lasers has been their ability to focus unprecedented powers of light in space, time, and frequency. High-power lasers have, over the ensuing five and a half decades, illuminated entirely new fields of scientific endeavor as well as made a profound impact on society. While the United States pioneered lasers and their early applications, we have been eclipsed in the past decade by highly effective national and international networks in both Europe and Asia, which have effectively focused their energies, efforts, and resources to achieve greater scientific and societal impact. This white paper calls for strategic investment which, by striking an appropriate balance between distributing our precious national funds and establishing centers of excellence, will ensure a broad pipeline of people and transformative ideas connecting our world-leading universities, defining flagship facilities stewarded by our national laboratories, and driving innovation across industry, to fully exploit the potential of high-power lasers.

Introduction: a survey of forty years of high-power lasers

Forty years ago, the Department of Energy's national laboratories aggressively initiated research and development on high peak-power lasers for laser fusion. Similar scale efforts in laboratories in Europe (notably the UK and France) and Asia soon joined in, with record peak powers rapidly scaling to the 10-TW level, followed by a decades-long increase to the 100-TW level. Twenty years ago, Lawrence Livermore National Laboratory's petawatt (PW) laser based on kilojoule Chirped Pulse Amplification (CPA) applied to the NOVA fusion laser, represented a further decadal leap in peak power. "The PW," as it was called, opened our eyes to the science frontiers that high-intensity petawatt lasers offered (10^{21} W/cm^2).

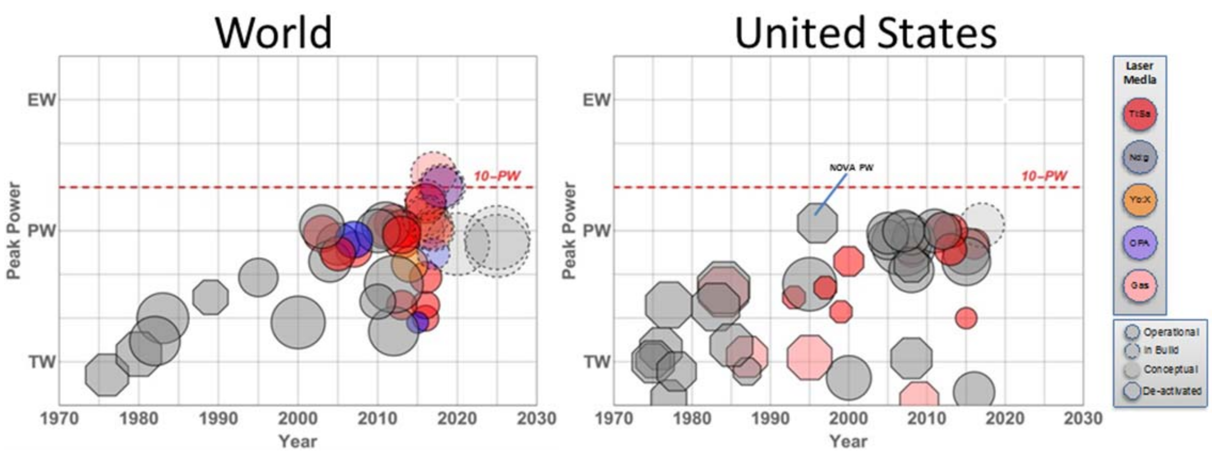

Figure 1: Evolution of high-peak power lasers (>100-GW) in the world and in the US over the last twenty years. Systems that are currently operating are shown as circles with solid border; systems that were operating in the past but are now de-activated are show as octagons with solid borders; and systems actively funded and being built are shown as circles with dashed border. The diameter of the symbol is logarithmically proportional to laser pulse energy and the color indicates the laser media used in the final amplifiers: Ti:Sapphire, Nd:glass, Yb:X, Optical Parametric Amplification (OPA), or gas (KrF and CO_2). The 1995 ~10^{21} W/cm^2 point is the original petawatt laser demonstrated at LLNL. As of early 2016, no high-power system has exceeded the 10-PW limit, even though there are several funded projects underway in Europe and Asia to break this barrier.

Beyond achieving its anticipated goals of reaching the threshold to the ultra-relativistic regime, wherein a free electron oscillating in the laser field is accelerated to near the speed of light (peak intensity $>10^{18}$ W/cm^2), unexpected discoveries such as the production of ions at multi-MeV energies, which have since become standard probes for high-energy density science, further enhanced its impact[1-3]. Of great importance, the success of the PW was a direct result of innovations born by academic researchers at the University of Rochester – such as CPA and associated laser pulse stretching/compressing technologies – and carried forward by a multi-disciplinary national lab team to scales beyond that achievable in the university environment.

High-energy short-pulse laser systems operating at PW peak powers (e.g. from 30-Joule/30-femtoseconds to kiloJoule/picosecond) have in the intervening two decades enabled a wide range of new high-energy (keV-GeV) particle and radiation sources for single shot discovery science[4,5] and have fed back from the national labs to university laboratory capability – the most striking example being the Texas PW at the University of Texas at Austin, which was literally born of parts of the NOVA laser and further refined by university innovators.

An examination of the average powers (Figure 2) of the operating and planned PW facilities across the world show that average powers span from ~100 milliwatts (notionally a kJ shot per hour), where a large amount of global follow-on PW capability exists, to state-of-the-art sub-kilowatt, with the operating ~50W flashlamp pumped PW-laser BELLA made by French defense company Thales, and LLNL’s ~half kilowatt High-repetition-rate Advanced Petawatt Laser System (HAPLS) laser (currently under construction and for delivery to the European Extreme Light Infrastructure) leading the pack.

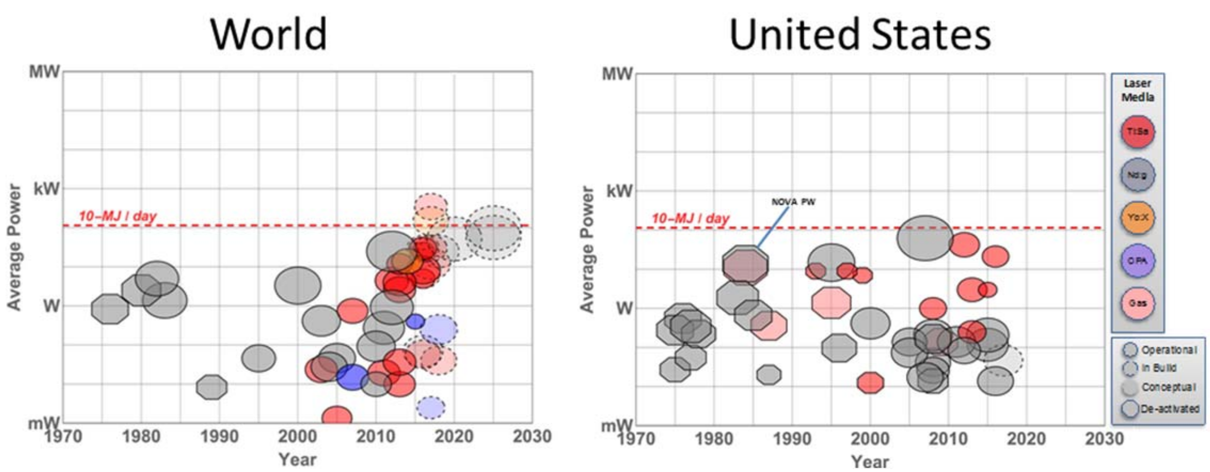

Figure 2: Evolution of the average power of high-peak-power lasers (with peak power >100-GW) in the world and in the US over the last twenty years. For known secondary source conversion factors the average power directly corresponds to the dose delivered, or number of experiments conducted. Note that as of early 2016, no high-power system has exceeded 10-MJ/day.

The high-repetition-rate (10 Hz) of the HAPLS system is a watershed moment for the community, as it reaches the point at which sophisticated feed-*back* control systems, as opposed to the feed-*forward* designs of the past, can optimize and maintain the spatial focusing and temporal compression of the laser output to near-diffraction-limit values. Indeed, they allow for feed-back from the sample or target itself (whether in an academic or industrial application) to dynamically optimize the laser system performance based on the end-product performance.

Practical applications of such PW-class-driven capability include the development

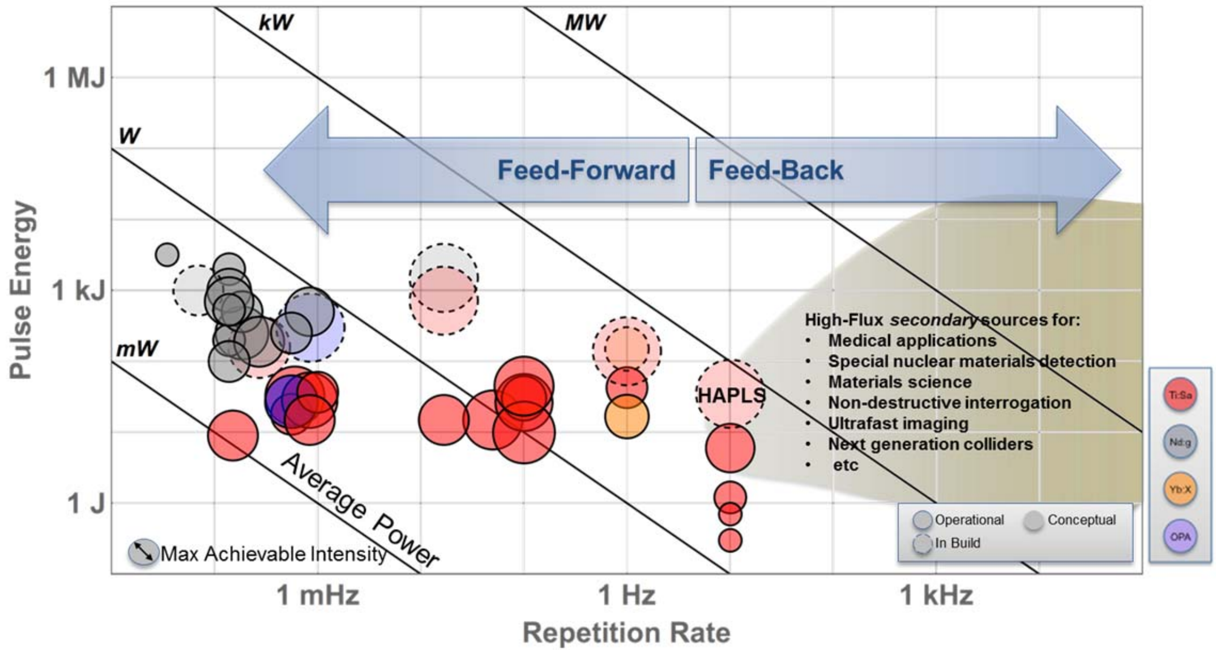

Figure 3: Pulse energy vs repetition rate for high peak power laser systems. Laser driven secondary sources such as electron, neutron, proton, ion, x-ray and gamma beams are promising candidates for various future applications where proof-of-principle experiments have demonstrated key physics. However, the energy delivered times the repetition rate is proportional to the secondary source luminosity; most applications will require average power levels of typically hundreds of Watts to tens or hundreds of kiloWatts. Furthermore, feed-back methods for dynamic source optimization become feasible at repetition rates >5 Hz.

of proton and ion sources for medical applications including cancer therapy; high-flux neutron sources for neutron radiography, special nuclear materials detection and materials science; high-brightness x-ray/gamma-ray sources for non-destructive interrogation and evaluation, medical diagnostics, ultrafast imaging at the molecular and atomic level, and nuclear photonics; and electron particle accelerators for next-generation colliders. The ultimate realization of these applications will require even higher repetition rates and higher average powers – beyond the “kW Barrier” to 10’s of kW and ultimately 100’s of kW[4,6-10] (Figure 3).

Also of note over the past two decades of high-power lasers is the fact that achievable peak powers have remained relatively stagnant, and the peak focal intensities achieved (Figure 4) went from ~10^{21} to ~10^{22} W/cm^2. However, the useable intensities for experiments have been typically an order of magnitude less than this, partly due to a lack of emphasis on the integrated capabilities required for practical exploitation, as opposed to academic demonstration. Notably, these peak intensity demonstrations occurred at both the Rutherford Appleton Lab Nd:Glass-based “Vulcan PW” laser in the United Kingdom, and the Ti:Sapphire-based HERCULES laser at the NSF Center for Ultrafast Optical Science in Michigan.

The decade following these groundbreaking systems saw the development of a great many systems, including the Omega EP system at Rochester/LLE, with similar peak intensity and power performance. Indeed, the ICUIL organization (ICUIL.org) is tracking *more than a hundred operational petawatt-class lasers* globally by the end of 2017. The majority of these new installations still relies on mostly 1990s laser technology and as Figure 2 shows, low-average power and repetition-rate and hence aimed at proof-of-principle science.

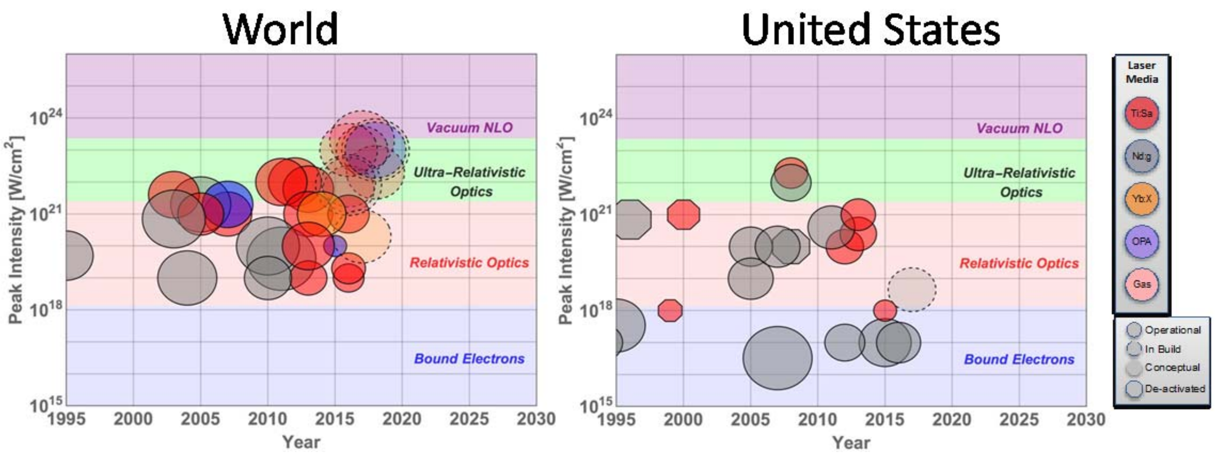

Figure 4: Evolution of high-intensity lasers (with peak power >100-GW) in the world and in the US over the last twenty years. The color bands show the following intensity-thresholds: for intensities >10^{15}W/cm^2 the atom Coulomb potential is suppressed by the laser field (field ionization, strong field regime); for intensities >10^{18} W/cm^2 the quiver energy of the electron becomes comparable to its rest energy (511keV) and the electron motion becomes relativistic; for intensities >10^{21} W/cm^2 the quiver energy of the proton becomes comparable to the rest energy of the electron; for intensities >10^{24} W/cm^2 the quiver energy of the proton becomes comparable to its rest energy and the proton motion becomes relativistic; and at 10^{29} W/cm^2 (not shown here) electron-positron pairs can be directly produced in the laser field.

The latter half of the 2010s will see a half-dozen systems commissioned with goals of a further 10-fold increase in peak focal intensity, reaching ~10^{23} W/cm^2. Two approaches are being pursued: 1) 10x energy scaling to 10-PW operated with low repetition rate (up to few shots/hour), and 2) 10x average power and rep-rate scaling at fixed PW peak power. The latter, which include the HAPLS system designed and built by LLNL, are engineered to achieve these intensities through an increase in precision and pulse fidelity enabled by system-in-the-loop active feedback control. Active feedback demonstrated on low energy systems to date allows significant intensity enhancements by gains in focusing and laser pulse compression. The former are flashlamp pumped architectures, while the latter are diode-pumped with consequently higher pulse fidelity and pulse stability, as well as greater system efficiency. Though the late-decade achieved performance of these new systems will point to the route for 100-PW and beyond, it is anticipated that the route will center on further energy/aperture scaling of diode-pumped high-rep-rate technology with its genesis in rep-rated fusion laser technologies.

The successful development and effective use of these discovery science and application-enabling high-power lasers requires multi-disciplinary teams that encompass state-of-the-art engineering and systems engineering, laser science and technology R&D, advanced performance modeling and computer controls and safety systems, material and optical materials science, skilled commissioning and operation staff and professional project management. The size of these teams and the operation of these highly-complex machines are typically beyond the capabilities of our national research universities, though they depend critically upon the scientists and engineers, both young and old, from there. Our national laboratories and industry have ably demonstrated their capability to design, construct, and operate high-utility world-leading laser light sources such as NIF, Omega, ALS, and LCLS, along with a multitude of high average-power defense systems. Together, this critical pipeline of people and innovative ideas from academia, through the Labs, and to the commercial world can deliver high impact societal applications.

Three key observations on domestic high-power lasers

Figure 5 integrates the data over time shown in Figure 1 and Figure 2 and illustrates a remarkable increase in peak and average powers. Notably, this includes fusion lasers, which have consistently climbed in both attributes through aperture scaling and multi-beam architectures – a direct result of long-term programmatic funding by the DOE and considerable engineering effort by the national laboratories.

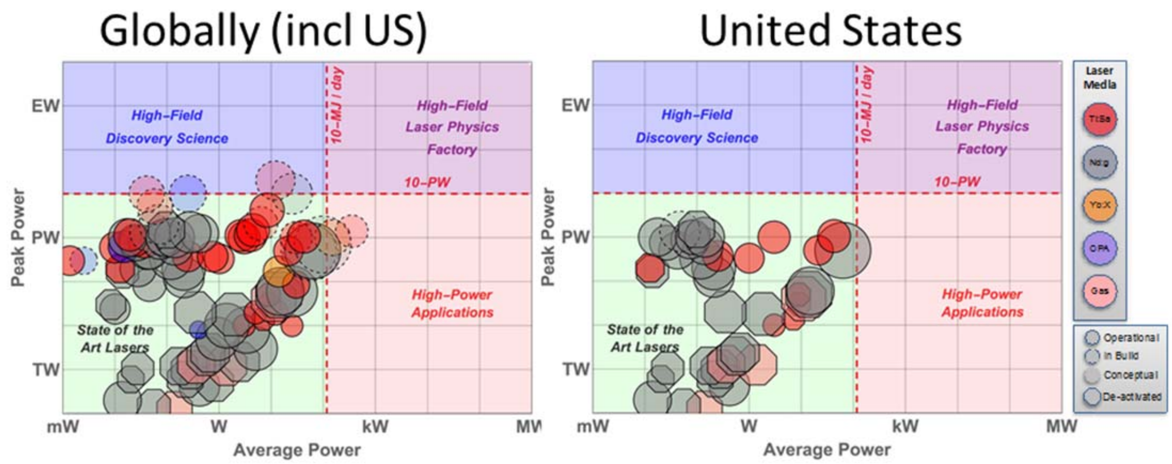

Figure 5: Comparison of laser systems and facilities globally and in the US. Peak power vs average power, with both the 10-MJ/day and 10-PW demonstration limits shown. Note that the highest average power 1-PW and 10-PW systems on this chart are being designed, developed, and delivered to ELI by LLNL and National Energetics, respectively.

Even a cursory examination of Figure 1 and Figure 5 reveals the following key observations:

1) The US is approaching the conclusion of the past decade's remarkable high-energy high-power laser development efforts, with commissioning of the LLNL ARC laser to higher peak power, consistent with stated programmatic needs – one of the few high-energy, short-pulse laser development activities still ongoing, as shown in Fig 2.
2) US facilities, though pioneering with the Nova Petawatt, the Texas Petawatt, Omega EP and HERCULES, are effectively absent in the global efforts to directly explore beyond a PW and 10^{22} W/cm^2.
3) The US, through LLNL's HAPLS laser and National Energetics' 10-PW ELI-L4 laser, are at the forefront of *development* of high-average and high-peak power laser construction but is sacrificing ownership, since these systems are being shipped to Europe.

The first observation is exacerbated by the fact that the trained workforce of world-leading laser scientists, engineers, and technicians, who were the engine behind the forty-year progress shown previously, are retiring or relocating to Europe. In fact, key expertise for the design and construction of high energy laser systems is already diminishing in the US, and the construction of HAPLS and the 10-PW L4 for European ELI has only marginally postponed this effect. Without a major high-power laser development program, that workforce will inevitably atrophy.

The second observation, that no US facility is actively planning to directly explore beyond a PW and 10^{22} W/cm^2, will lead to a continued decline of the past dominance of the US in high-field laser physics, and may lead to a precipitous atrophy of the field in academia. Importantly, while current US facilities continue to operate at their once-record levels, their ability to be scientifically productive will inevitably drop. The "low hanging fruit" is rapidly being picked and further refinement and understanding will require higher repetition rates (aka higher utility) with their inherent improved stability and repeatability.

The third observation, that US expertise is delivering frontier laser capabilities for the EU's ELI, on the surface has a strong positive element – it is a notable benefit of applying the decades of fusion laser R&D at our nation's national laboratories to hard global problems. However, with no sustained investment in advancing the state of the art and of ensuring challenges for the next generation of laser designers and builders, we will find capabilities eclipsed by those of the nations currently robustly supporting laser technology advances and invigorating networks among laser experts and end-users. Particularly effective examples of the latter are the successful European and Asian approaches - Extreme Light Infrastructure[7], Laserlab Europe[11], Asian Intense Laser Network[12], the widespread investment in Germany's academic institutions, and China's aggressive laser development program – that have helped make the case for high peak power laser facilities and which help facilitate interactions between facilities and free movement of science and experiments between them.

Needs for a National Solution

To capture some of the drivers for a national solution, Figure 6 overlays the global survey of high-power lasers with some of the key applications areas envisioned for high peak and average power systems. Most importantly, the 1000x increase in average power at fixed 100-TW peak power is shown, pointing towards the applications of collider physics, medical therapy, light source applications, materials development/processing, space debris cleaning, and inertial fusion energy. Specifically, laser driven particle and radiation beams, aka "secondary sources", offer unique properties that are not accessible with conventional radiofrequency accelerators, such as

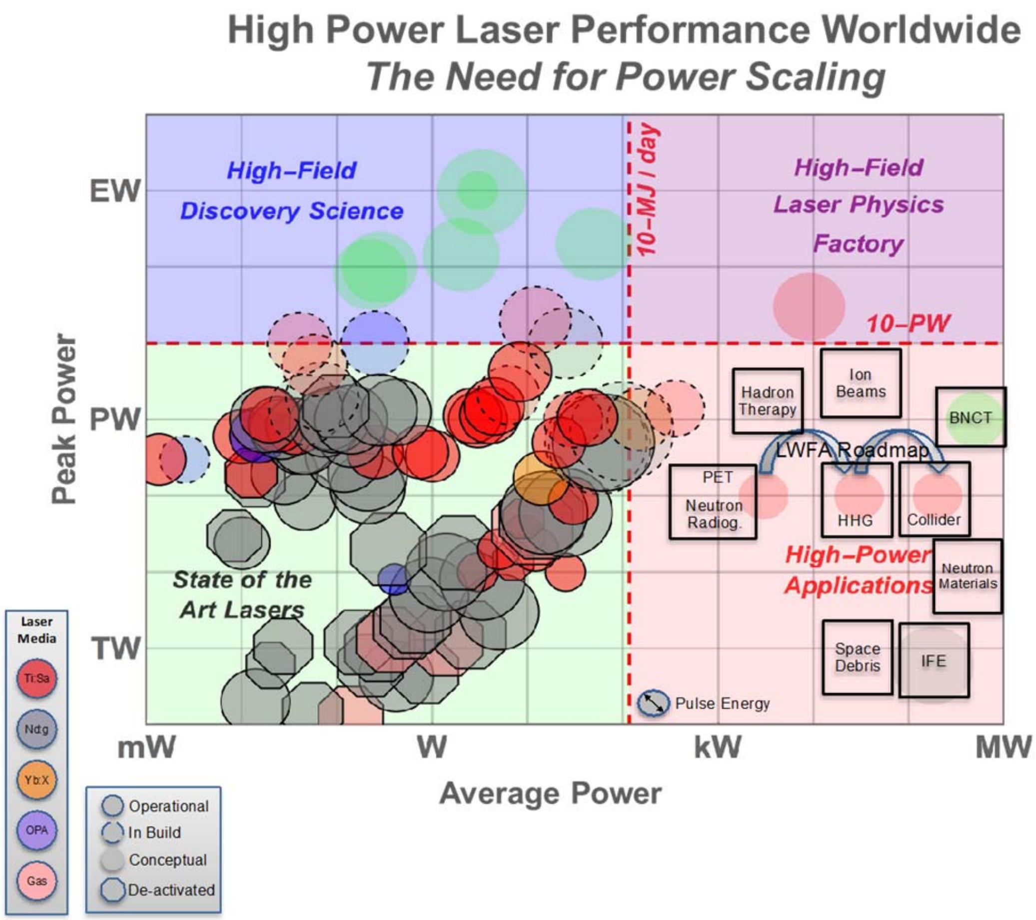

Figure 6: High-power lasers globally as a function of peak power and average power. In addition to operational, de-activated, and in-build systems as showed in the previous figures, this figure includes some recent discovery-science-enabling conceptual design ideas (circles with no border) for 0.1-1 Exawatt peak powers, and 10s to 100s of kilowatt application-enabling average powers. Additionally, key applications are indicated: laser-wakefield accelerator (LWFA) prototypes at 3 and 30-kW and a laser-plasma collider 300-kW unit cell (of which there would be ~200 in a TeV-scale collider); positron emission tomography (PET) radioisotope production, hadron and Boron-neutron capture (BNCT) therapies; ion and neutron beams for radiography, non-destructive inspection and materials processing; high-harmonic generation (HHG) light sources; laser-ablation based space debris clearing; and inertial fusion energy unit-cell (of which an IFE plant would require 100-200). Of particular note in this figure is the cluster of systems following a 45-degree upward path. These systems, predominately fusion laser architectures, scale both peak and average powers by scaling aperture and hence pulse energy at constant fluence. The four decades of sustained programmatic investments in fusion laser technology have brought innovations such as multi-beam operation, robust and aggressive thermal management, and novel materials to maintain scaling along this pathway. Future scaling along this well-traveled pathway will lead into the quadrant for applications at extreme peak powers.

ultrashort pulse duration allowing time-resolution of dynamic processes, small source size for high resolution imaging, directional beams (e.g. neutrons), and high compactness; in fact, the flexibility to quickly change the type of secondary radiation by switching the "converter" target in front of the laser driver may constitute a disruptive technology for the non-destructive imaging industry. The applications shown in Figure 6 constitute the bulk "application pull" driving laser development along the horizontal (average power) axis of the plot. It is clear that a national strategy should place emphasis on scaling these application-enabling 10-TW to multi-PW systems to higher average powers. Exploration beyond the 10-PW threshold is the "discovery science push", driving laser development along the vertical (peak power) axis. Especially with regards to cultivating a strong domestic next-generation scientific community, we must not neglect the 'prestige' value of pursuing peak powers towards the Exawatt. Of note in Figure 6 is the clustered line of systems following the 45-degree diagonal from sub-W average power TW systems to ~100-W average power PW systems. From a laser development perspective, the unique aspect of this family of systems is that it represents scaling of both average and peak powers by single-beam and multiple beam aperture scaling. It is along this pathway that both capability and utility are increased and hence a national strategy of pursuing higher peak powers for discovery science would be best served by following that mainline path.

We posit that the appropriate national solution involves a programmatic approach to maintaining and growing a world-leading community of laser scientists and engineers who push the state of the art of the high-power laser technologies which will underpin the national missions within NNSA and the DOE Office of Science, drive industrial and medical applications and cost-effectively enable discovery science at 100-PW and beyond. This would involve flagship facilities that couple to existing unique diagnostic capability – for example, a HAPLS-like high-utility laser system added to a unique light source like LCLS; that establish critical test-beds for next-generation diode-pumped high-energy fusion beamlines; and that can prototype innovations born of our universities and utilize new architectures for scaling beyond 10-PW. As an example, Figure 6 also illustrates conceptual designs for 10-100 PW systems, most of which utilize directly or indirectly the laser technologies currently under development within the US.

The US needs deeply-networked flagship facilities that attract the best staff and enable international leadership in science and technology. As the establishment, operation, maintenance, and continued improvements/upgrades of high- power lasers and facilities exceed university scale, core competency centers are needed. Historically, laser experiments advanced via step changes in the ability to access even more "extreme" conditions via higher laser power, energy, or intensity. This needs to be tensioned against the need for robust operations, well-diagnosed/well-behaved systems, and a complete facility infrastructure (source, sample, instruments, detectors, analysis, etc), so a critical early action is to define the "facility gap" which must be closed. Importantly, we must strike a balance between broadly-enabling technologies (e.g. high average power), and those with deep, targeted impact (e.g. atto-second science). "Stand alone" high-power facilities are now commercial commodities. Flagships need to significantly advance the state-of-the-art industrial lasers and/or take advantage of the potential for coupling unique capabilities (e.g. laser-based accelerators, Z-pinch, implosion laser, XFEL, etc). There is excellent communication and synergy between LLNL and SLAC, offering a ready platform for rapid development and sustained leadership. For laser-based accelerators, the recent DOE Advanced Accelerator Development Strategy Report underscored the need for advanced high-average power lasers, whose goal of a kHz, 100-TW peak and 300-kW average power “unit cell” for a future TeV-scale laser-plasma accelerator should be vigorously worked towards. Flagships also need to sustain the nation’s world-leading community of laser scientists and engineers, and must maintain expertise in fusion laser technology that will underpin the DOE’s next steps – be they an upgrade to NIF’s power and energy, a follow-on IFE-enabling machine, or a new HEDS/WDM driver that is as-yet not envisioned. Finally, it is crucial to provide and establish enabling mechanisms for industrial engagement – for example the Fraunhofer institutes in Germany – whereby industry can invest in and contribute to academic research and development with direct benefit of the progress made. This is an important part of the broader critical need to establish a robust network which successfully combines an international scientific community, a strong base of domestic universities and colleges, core competency centers (flagship facilities) stewarded by national laboratories, and a consortium of industries who are simultaneously challenged to move forward into new markets, to innovate cutting-edge technologies, and to welcome the freshly-minted new scientists, engineers, and technicians nurtured by the network.

US investment in flagship high-power high-intensity short pulse laser facilities, critically requires synergy between the users’ scientific needs and laser performance parameters from the beginning of the conceptual design process. The user governance model of several U.S. laser facilities (NIF, OMEGA, LCLS) has proven to be very successful, suggesting that the ability to meet this integrated need is well-embedded in the US culture.

Action/Summary

It is imperative that the US enact a national program on High-Power Lasers. We suggest an initial five-year plan with government-integrated $100-500M/yr budget split 80% - 15% - 5% among the flagship facilities, academic programs, and industry consortia. This program should have a principal objective to cultivate the science network of academia, national labs, and industry consortium. It should fund two flagship facilities, for example the development and commissioning of a diode pumped petawatt laser on the LCLS, which presents unique opportunities for making and measuring extreme states of matter, and a High-Power Technologies Testbed which would seek to demonstrate next-generation diode-pumped high-energy laser technologies and routes to ultra-high peak power generation. Importantly, the Testbed must provide opportunity for university and industrial science innovations in addition to engineering technology innovations, as so must have a target facility with which to perform truly frontier Discovery Science experiments beyond 10-PW. Finally, key technology development should be nurtured through industry/lab/university consortia to drive down the cost of semiconductor lasers, develop and prototype advanced optical materials, shepherd standards and best practices, and transform decades-old optical manufacturing with production innovations like advanced and additive manufacturing. This national program would lay the foundations for profoundly impactful applications of high power lasers in medicine, manufacturing, energy, and science and would nurture and mentor the young students of today to become the future leaders in these fields.

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