Petawatt Laser Systems

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Since lasers were first demonstrated,[1] researchers have endeavored to increase their focused intensity (power/unit area). Within a few years, the demonstration of Q-switching[2] and then mode locking[3–7] significantly increased the peak power of lasers. However, the following two decades saw little progress in achieving substantially higher peak powers. Then, in 1985, the first demonstration of chirped-pulse amplification (CPA)[8] paved the way for dramatic increases in the peak power of lasers and their accompanying focused intensity. Today, peak powers as high as 10^{16} W or 10 PW (Ref. 9) and focused intensities of 10^{23} W/cm^2 (Ref. 10) have been demonstrated in the laboratory.

The ability to achieve these intensities in the laboratory creates extreme conditions that make possible, for example, the study of high-density laser–plasma interactions, the generation of beams of particles (electrons, positrons, neutrons, protons) and radiation (x ray, gamma ray), particle acceleration, the study of quantum vacuum interactions, and science on an attosecond time scale.[11] These opportunities have spurred an enormous international effort to build high-intensity laser facilities that support a large variety of scientific endeavors.[12] The authors have written an e-book for the SPIE Spotlight Series that introduces the reader to the laser science and technology underpinning petawatt laser systems, hopefully providing an appreciation of the substantial technological advances required to achieve today's state-of-the-art high-intensity laser system performance. This summary provides an overview of the various topics covered by the Spotlight e-book.

An overview of the building blocks of a petawatt laser system is shown in Fig. 1. CPA-based petawatt laser systems begin with seed pulses that are generated from mode-locked laser cavities employing broadband gain media such as titanium-doped sapphire or neodymium-doped glass. Depending on the performance requirements and the specific architecture of the petawatt laser system, conditioning that improves pulse contrast, shapes the spectrum to overcome gain narrowing, or uses the pulse itself to generate ultra-broadband light via nonlinear processes that serve as the seed for the system are employed prior to amplification. This work reviews broadband materials, common mode-locking methods, and various pulse-conditioning techniques utilized in petawatt laser systems.

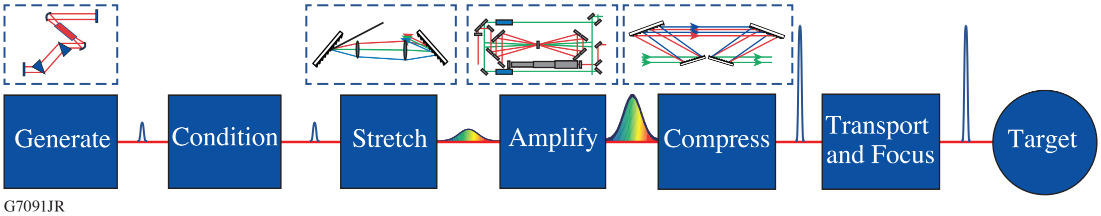

Figure 1
Building blocks of a petawatt laser system incorporating the CPA architecture.

To reach petawatt-level peak powers, these seed pulses require eight to nine orders of magnitude of amplification. Nonlinear optical effects and optical damage, however, significantly limit the ability to directly amplify ultrashort laser pulses. CPA first stretches a broadband pulse in time so that the peak power inside the amplifier is significantly reduced, thus avoiding destructive nonlinear effects. Then after amplification, the pulse is recompressed back to near its original duration, generating a high-energy ultrashort pulse. We introduce the reader to the effects of dispersion on ultrashort pulses and how dispersion is used to stretch and compress the duration of these pulses. Nonlinear effects relevant to high-power laser systems are described along with a discussion of how one determines the minimum stretched pulse width required to safely achieve a particular output energy. Finally, we review the design of pulse stretchers, compressors, and considerations necessary to minimize the final output pulse width.

There are currently two approaches that have been demonstrated for generating petawatt laser pulses. One produces 150- to 1000-J pulses with durations between 150 and 1000 fs (10^{-15} s). The other generates much shorter pulses (~20 to 30 fs) with tens to hundreds of joules of energy. In either case, broadband amplifiers are required to safely generate the required energy while simultaneously maintaining sufficient bandwidth of the pulse. Two basic types of amplifiers have been developed; one uses energy-storage laser media that are optically energized or "pumped," and the other uses nonlinear crystals to mediate the exchange of energy from a high-energy narrowband pump pulse to a weaker broadband seed. We describe the principles of both types, how they can be combined using the relative strengths of each to form "hybrid" systems, and considerations for scaling to higher *average* powers (e.g., increased repetition rates) and future approaches.

Delivering petawatt laser peak powers to a target would not have been possible without large-aperture optics that have both broadband reflectivity (or diffraction efficiency) and high damage thresholds. This necessitated significant technological development to produce compressor diffraction gratings and transport mirrors that met these requirements while maintaining high wavefront quality for tight focusing. Even with high damage thresholds, the highest-energy petawatt laser systems motivated the development of fabrication techniques that could deliver the above qualities at meter-scale apertures. Since they are critical components of these laser systems, gold and broadband multi-dielectric coating development, large-aperture manufacturing, and issues of damage are reviewed.

Equally important is the ability to control and diagnose the performance of the laser system. Optimal recompression of the amplified pulse requires accurate *characterization* of the output pulse and fine *control* of the relative phase of the spectral components based on these measurements. Realizing the maximum intensity on target requires near-diffraction-limited focusing. Achieving this entails accurate focal-spot characterization, preferably at the target location, and the ability to manipulate the wavefront of the on-target beam. We review techniques for phase measurement and control in both the spectral and spatial domains, and introduce the reader to spatiotemporal couplings, which span both domains.

For most of the science enabled by petawatt laser systems, it is the peak *intensity* on target that is the critical parameter, not the peak power. This makes the final focusing of the laser a key consideration in the system design. Although minimizing wavefront aberrations and spatiotemporal couplings in the front end, amplifiers, and pulse compressor is critical to preserve the focusability of the laser beam, ultimately the focal spot size is defined by the parameters and performance of the final focusing optics. We discuss large-aperture, low-*f*-number off-axis parabolas that are used to achieve small focal areas, schema to protect high-value final optics from target debris, methods for improving on-target pulse contrast at the back end of the system, techniques to characterize the *in-situ f*ocal spot size at the target location, and future prospects for increasing on-target intensity.

The journey from the first demonstration of lasing action to the realization of 10-PW laser pulses took 60 years and significant technological development. Today, there are petawatt-class laser facilities all over the world (see ICUIL website[13]) with many more in the design and construction phase. These facilities make possible scientific explorations that were previously unachievable in the laboratory. This work introduces the reader to the laser science, engineering, and technology required to successfully deliver the highest focused intensities on Earth.

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