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Recent Advances

Petawatt Lasers: Science and Applications

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Abstract. With the advent of the chirped-pulse amplification technique (for which the Nobel Prize in Physics in 2018 was awarded), high-power lasers with Terawatt (TW) and Petawatt (PW) peak powers(1TW = 10^{12} W, 1PW = 10^{15} W) have become ubiquitous. Here, we briefly review progress in the development of these lasers and discuss the science and applications they open up.

Keywords: High Power Lasers, Ultrashort pulses, laser-matter interactions

1. A Brief History of High-Power Lasers

Ever since the demonstration of the first laser in 1960,[1] attempts have been made to increase the laser power so that they can be focused down to create extreme conditions in the laboratory. This opened up a new class of lasers - pulsed lasers - where the energy is compressed into short pulses, enabling them to reach high peak powers ($P = E_n/\tau$, where P is the peak power, E_n the energy and τ, the length of the laser pulse). Technologies developed in the past few decades producing shorter and shorter pulses have enabled Terawatt and Petawatt lasers with energies less than that in a cup of tea (100's of Joules). Although they produce peak powers greater than a national power grid in principle, this power is available for a billion-millionth of a second, thus making sure that the energy conservation laws are not violated.

Until 1980, techniques for generating short pulses were confined to mode-locking and Q-switching,[2] which limited the pulse lengths to a few picoseconds (10^{-12} s). This in turn limited the peak powers of these lasers to Gigawatts (10^9 Watts),[3] as shown in Fig. 1. These were large-scale systems, mostly involving Neodymium phosphate glass (Nd:glass) - which can sustain high energy pulses - as the laser medium. Possibility of directly and indirectly compressing matter to high densities and heating them up to hundreds of electron volts ($1eV = 11600K$), thereby generating conditions for fusion, was a major driver;[4] they were concentrated in a handful of countries, with Lawrence Livermore National Labs (LLNL) in the US leading the way. Increasing the laser power was limited due to non-linear optical effects (eg. self-focusing) induced in the medium. These effects were caused by the the modification of refractive index of materials when subjected to high light intensities; the refractive index $n(I)$ becomes a function of intensity - $n(I) = n_0 + n_2 I$ where n_0 is the constant, linear refractive index that we normally consider and n_2 is the nonlinear refractive index.[5]

The invention of Chirped Pulse Amplification by Donna Strickland and Gerrard Mourou

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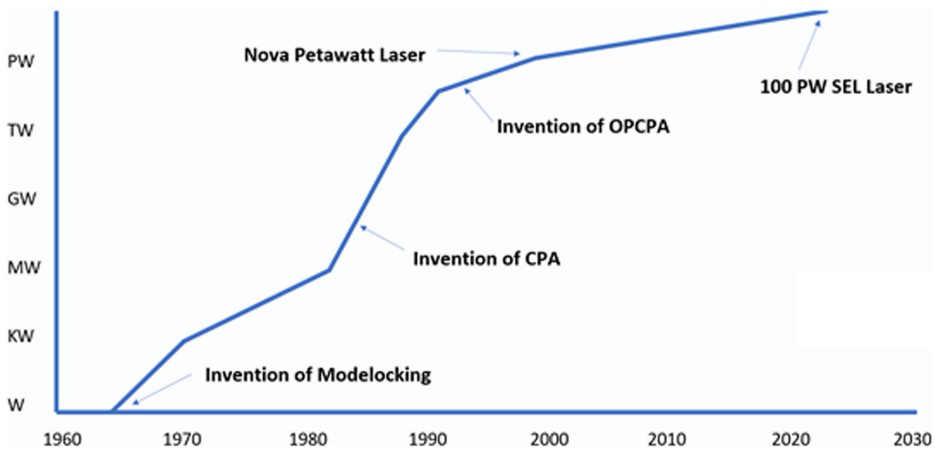

Fig. 1. Laser peak power through years © Cambridge University Press[3]

overcame this limitation in 1980.[6] They adopted a technique from radar technology for compensating for the spectral phase originating from the dispersion of multiple wavelength components in the pulse.[7] This technique enabled laser pulses to be stretched in time using dispersive elements such as prisms and gratings and amplify them to the required energy, before reversing the dispersion in a compressor, thus avoiding the nonlinear effects in the amplifier, as shown in Figure 2. This, along with the transformative development of new laser materials such as Titanium-doped Sapphire (Ti:Sapphire, $Ti : Al_2O_3$) in 1986,[8] paved way for multi-Terawatt and Petawatt lasers.

These developments enabled NOVA, the world's first petawatt laser at LLNL in 1996, which delivered 1.5 PW with energy up to 680 J to target, as part of LLNL's laser-fusion programme.[9] Although NOVA was decommissioned after 3 years, it lead to an explosion of high power lasers around the world. This was assisted by the high bandwidths supported by Ti:Sapphire gain media as well as other nonlinear optical techniques such as Optical Parametric Chirped Pulse Amplification (OPCPA),[10] enabling laser pulses as short as 10's of femtoseconds, consequently reducing the energy (and therefore cost) required to reach multi-Terawatt and Petawatt power levels. Although there were only a handful Petawatt-class lasers around the world in the beginning of the millennium, a myriad of such systems have appeared on the world map in the last two decades, as shown in Figure 3.[11] Today, several systems with multi-Petawatt peak powers are in operation or construction, including the Extreme Light Infrastructures[12] and Apollon[13] with 10PW power laser beams. In the UK, a 20PW laser is currently under design. A 100-PW laser, named The Station of Extreme Light, is currently under design in China and is supposed to be operational by 2025.[14] In India, the Raja Ramanna Centre for Advanced Technology (RRCAT, Indore) has recently upgraded their 150TW system to a PW.[15] The Tata Institute of Fundamental Research (TIFR) in Mumbai has a 150TW laser system and its Hyderabad campus is scheduled to get a PW laser in the next couple of years. BARC also has a high-power laser programme.[15]

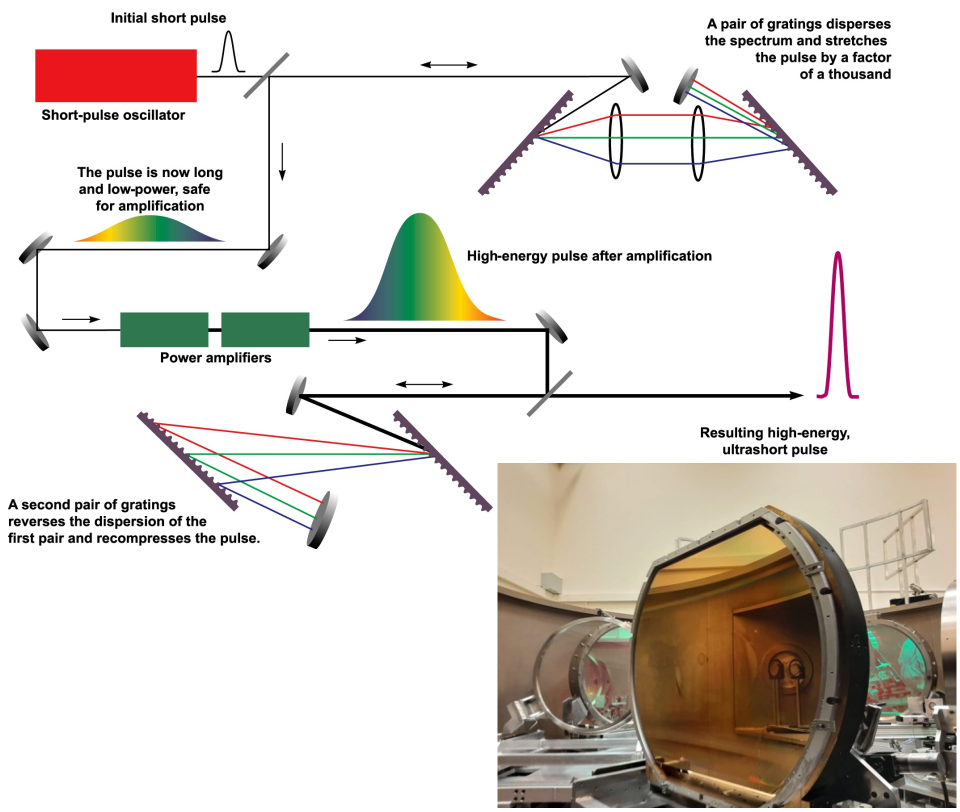

Fig. 2. Schematic of Chirped Pulse Amplification. Inset shows the compressor gratings in the Vulcan laser facility at RAL.

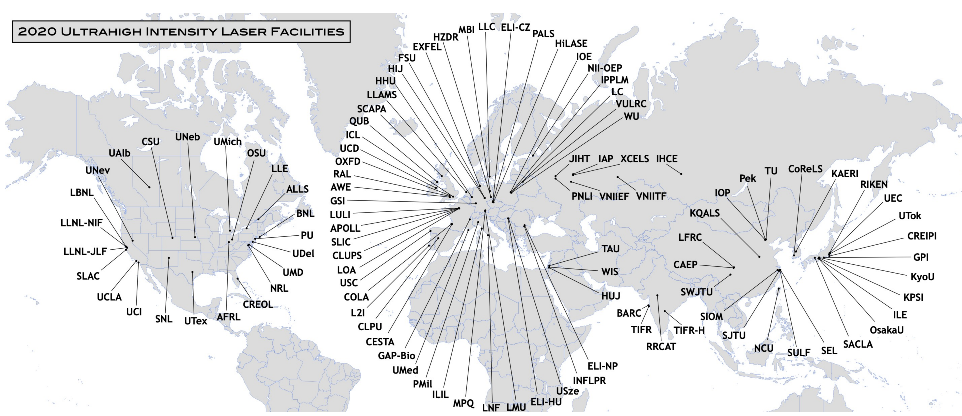

Fig. 3. High Power Laser systems around the world © ICUIL

2. Science of the Extremes

Pulsed lasers can provide electric field intensities transcending linear optics. The intensity-dependent refractive index or polarisability of materials (resulting from the anharmonic motion of electrons in high fields) introduces several nonlinear optical phenomena even at relatively modest intensity levels.[5] The ability to generate femtosecond pulses provides an easier route to reach high electric field intensities ($I = \frac{E_n}{\tau.A} \sim E^2$, where E is the electric field amplitude of the light wave). As the intensity is increased, the resulting electric fields become comparable to the atomic Coulomb field. From a classical picture, the Coulomb field binding the 1s electron in a Hydrogen atom is $\sim 10^9$ V/cm, which means, if exposed to higher fields, the atom will be readily ionised (corresponding to 10^{16} W/cm^2 in light intensity). However, due to ionisation processes involving multi-photon effects, quantum tunnelling and suppression of the Coulombic barrier in strong fields, ionisation happens at much lower intensities, typically at 10^{13} W/cm^2.[16]

Bulk ionisation in the focal volume of such a high power laser pulse quickly results in a hot soup of electrons and ions -plasma - irrespective of the nature of the target medium at the focus (i.e. solid, liquid or gas). Subsequently, the charged particles in the plasma respond to the electric field of the driving laser. For femtosecond pulses, the heavier ions do not have the time to move much so we normally only consider the electron motion. The oscillation of electrons with the velocity ($v_{osc} \sim \sqrt{I\lambda^2}$ where v_{osc} is the quiver velocity, I the electric field intensity and λ the laser wavelength) forms the first step of interaction of laser light with the plasma.[17] This, and the characteristic time in which plasma responds (the plasma period -the inverse of the plasma frequency, which is just a function of the electron density n_e, as given by $\omega_p = \frac{n_e e^2}{\varepsilon_0 m_e}$, determine most of the characteristics of the plasma as energy gets transferred from the laser pulse to the plasma through collisional and non-collisional absorption mechanisms.[18] Thus, depending on the intensity and the plasma (electron density), laser-driven plasmas can be heated up to temperatures ranging from a few electron Volts to hundreds of electron Volts ($1eV = 11600K$). This can create some of the most extreme conditions on earth: mega-ampere currents,[19] giga-bar pressures and mega-gauss magnetic fields,[20] opening up a plethora of opportunities for fundamental science and applications. A few examples are given below.

- High Energy Density Science - The ability of high power lasers to compress materials either directly using light pressure ($\sim I/c$, where I is the electric field intensity given by $I = \frac{E_n}{\tau.A}$, where A is the area of the focal spot and c the velocity of light) or indirectly using the ablation pressure (Newton's third law combined with the outward-going plasma plume at supersonic speeds) led to a new field - High Energy Density (HED) Science.[21] Intersecting multiple fields, including condensed matter physics, astrophysics and plasma physics, HED physics is the science of extreme pressures, above 1 million atmospheres, which, among other things, is also important for the stewardship of safe and reliable stockpile of nuclear weapons.[22] Consequently, this and the prospect of laser fusion remain one of the main drivers for high-energy laser programme (kilo/mega Joule, nanosecond-picosecond laser establishments) in the US, UK, France and China.
- Inertial Confinement Fusion - Inertial Fusion, along with magnetic confinement

fusion, is one of two credible, approaches to obtaining energy from nuclear fusion. While magnetic confinement fusion uses magnetic fields to hold a hot, low-density plasma in place while the plasma burns quasi-continuously, somewhat akin to a conventional fire, inertial fusion uses a driver (typically high-power lasers) to implode a hollow spherical shell containing fusion fuel, compressing it by 1000 times. This creates density and temperature conditions exceeding those in the centre of the Sun, over a very brief duration, meaning the power source is pulsed, like an internal-combustion engine. The fusion fuel's own inertia confines it, holding it in place while it burns.[23] Significant international efforts are ongoing to demonstrate the feasibility of laser-driven inertial fusion and to understand the required driver energy-scale, with global investments in laser fusion facilities totalling $12B.

- Laboratory Astrophysics - Some of the extreme conditions generated by high power lasers mimic stellar conditions and interiors of planets, albeit in a micron-scale in a laboratory. This has led to a new field - laboratory astrophysics - where some of the outstanding questions in cosmology and astrophysics can be tested out in the laboratory, with appropriate scaling. Recent research have been especially promising in investigating Warm Dense Matter that forms planetary cores,[24] identifying mechanisms for primordial magnetic fields (eg. Biermann battery) that play a significant role in stellar structures[25] and understanding complexities in stellar jets formed in newly born stars where magnetic fields around them force matter to shoot at hundreds of miles per second.
- Compact Particle Accelerators - Accelerators are typically large devices - the higher the energy, the longer the accelerator - because of the number of acceleration stages involved. For example, the Large Hadron Collider at CERN is about 25 km long in circumference. In the past decade, high-power lasers have shown the potential for a transformative change in accelerator science by significantly reducing their size.[27] At intensities above 10^{18} W/cm^2, the quiver motion of electrons in the laser field becomes relativistic. Therefore, the magnetic field component in the Lorentz force becomes appreciable, which gives a longitudinal drift to the electrons along the laser propagation direction. In a gaseous plasma, this causes a charge separation between the electron cloud and the massive ion cloud, forming an extremely large electric field potential called a wakefield.[28] As the laser pulse moves through the plasma, this potential moves too and any electron that gets trapped in the potential, gets accelerated continuously, just like a surfer getting accelerated by the waves in the sea. Since the potential is proportional to the electron density and inversely proportional to the charge separation (microns), plasmas can sustain over 10,000 times higher electric fields compared to a conventional accelerator stage. Consequently a km-long conventional accelerator can be replaced by few cm-long plasma accelerator. In the past few years, energies of the electron beams produced by laser-driven wakefield accelerators have reached $\sim$ 8GeV (1GeV = 99.999987$\%$ of c in velocity), making the prospect of plasma-based high-energy particle accelerators and colliders a real possibility.[29]

Along with the fundamental science, the secondary sources produced by laser wakefield accelerators also open up niche applications in industry and medicine.

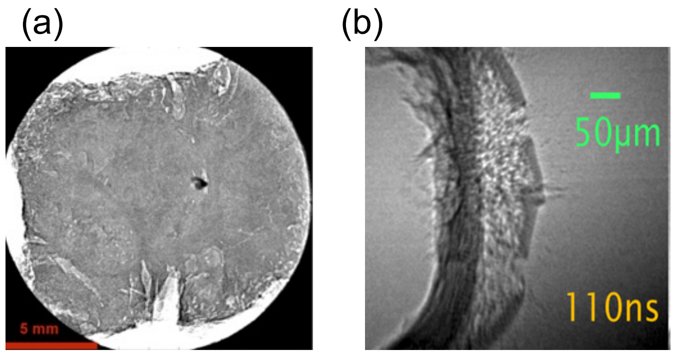

Fig. 4. (a) X-ray Phase contrast image of breast tissue with a calcification site (b) Time-resolved x-ray snapshot of a shock propagating through aluminium ©Nature Publishing Group

As the electrons get accelerated in the wakefield, they undergo micro-undulations because of the ion core at the centre of the wake. This results in a synchrotron-like x-ray beam - betatron emission - which is spatially coherent.[30] This opens up new imaging modalities such as high-resolution x-ray phase contrast imaging, which, unlike the conventional x-ray imaging, is sensitive to even small differences in densities.[31] They have a lot of applications in non-destructive testing in manufacturing as well as in medicine. For example, this can be used for early detection of osteoporosis and cancer where the aberrations start as small density differences in micron-scale, as shown in Figure 4 (a). Further, since the laser driver is pulsed, the electron beams and consequently the x-ray beams from plasma accelerators are also pulsed. These femto-second x-ray beams can freeze-frame extremely fast motions including shocks propagating through materials,[32] as shown in 4(b). Currently, facilities based on laser-driven plasma accelerators are under design; the Extreme Photonics Applications Centre (EPAC) in the UK[33] and the EU facility EuPRAXIA[34] will exploit the applications of plasma accelerators in coming years.

While the relativistic optics offered by intense laser pulses at intensities $\sim 10^{18} Wcm^{-2}$ has a lot of applications, the quest for higher light intensities continue. Current multi-PW laser facilities offer intensities that are several orders of magnitude higher than this; South Korea's Center for Relativistic Laser Science (CoReLS) has recently demonstrated the highest intensity available so far - $10^{23} Wcm^{-2}$.[35] At these intensities, matter is driven extremely far from equilibrium, and this strong-field physics regime provides probes for exploring the quantum nature of the universe.[36] For example, it is possible to explore the quantum nature of vacuum at extreme intensities. At the quantum level, vacuum is not really empty but is filled with "virtual" matter-antimatter pairs that are created and annihilated continuously, existing for an extremely short time ($\sim$ zeptoseconds - 10^{21}s).[37] Given the right conditions (eg. subjecting to an extremely high field), the lifetime of these "virtual" particles can be increased. In fact, this put a theoretical limit to the achievable intensity levels - $\sim 10^{29} Wcm^{-2}$, which is called the Schwinger limit, where the laser could heat the quantum vacuum such that matter-antimatter pairs are spontaneously created at the focus, preventing further increase in electric field intensity.[38] Although this intensity level is not currently achievable, the QED regime may be accessed by interacting an ultra-relativistic (multi-GeV) electron beam with existing multi-PW lasers at intensities greater than $10^{21} W cm^{-2}$. Exploring this rich physics is one of the most exciting new frontiers using high-intensity lasers and experiments in this regard are currently ongoing and/or under design at multiple high intensity laser labs around the world.

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