Analysis of the Principles and Applications of Ultra-intensity and Ultrashort Laser

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Abstract. With the development of laser technology, how to improve the output performance and peak power of lasers has become one of the hot directions of current research. This study analyzes the principles and applications of ultra-intensity and ultrashort pulse laser. It firstly outlines the development history of laser technology and the basic definition of ultra-intensity and ultrashort pulse laser. It also mentions the realization methods for generating ultra-intensity and ultrashort pulse lasers, such as mode-locked femtosecond oscillators and CPA-based femtosecond amplifiers. The paper describes the principles of CPA technique and emphasizes its importance in realizing high power ultrashort pulses. The paper discusses various applications of ultra-intensity and ultrashort pulsed laser and summarizes and discusses the major bottlenecks facing current and future ultra-intensity and ultrashort pulsed lasers and their possible solutions. The technical review in this paper aims to enhance the understanding of ultra-intensity and ultrashort pulsed laser and provide insights into the next phase of research exploration in ultra-intensity and ultrashort pulsed lasers.

Keywords: Laser technology; ultra-intensity ultrashort laser; chirped pulse amplification; facilities; applications.

1. Introduction

Laser is widely regarded as a significant technological advancement of the 20th century, and has been dubbed "the sharpest knife", "the most precise ruler" and "the brightest light". As a potent tool, laser has sped up scientific and technological progress, and has been applied widely in the engineering industry [1]. Reviewing the development of laser, Albert Einstein published a paper "Zur Quantentheorie der Strahlung" in 1917, which laid down the theoretical foundation of laser and microwave exciter from the conceptual point of view [2]. In 1947, Willis Lamb and Robert Retherford discovered and demonstrated for the first time the pronounced stimulated emission in the hydrogen spectrum [3]. Charles Hard Townes and coworkers built the first microwave exciter in 1954, which radiated at a wavelength slightly longer than a centimeter with a power of about ten nanowatts, but the radiation was extremely uniform and consisted of a single wavelength [4]. In 1958, Townes and Arthur Schawlow, of Bell Laboratories, extended microwave excitation technology into the infrared and optical regions by proposing a system that could operate at both infrared and optical wavelengths [5]. In 1955, Nikolay Basov and Aleksandr Prokhorov put forward a fundamental approach to laser pumping. Their proposal involved the utilization of light pumping in a multi-energy system to achieve particle number inversion. The inaugural operational demonstration of a laser occurred on May 12, 1960, when Maiman successfully operated a laser device at the Hughes Research Laboratory. Maiman achieved this feat by employing a flashlamp to stimulate a synthetic ruby crystal, resulting in the emission of a red laser beam with a wavelength of 694 nm. This was a significant milestone as it represented the first instance of human acquisition of a laser beam [1].

After the birth of the laser in 1960, laser technology continued to advance, with peak laser power rapidly increasing to MW (10^6 watts) and then GW (10^9 watts) in the 1960s and 1970s. During this era, prominent technological advancements encompassed laser mode-locking [6] and Q-switching [7] techniques for the creation of brief pulses, alongside the utilization of master oscillator power amplifiers for the amplification of such pulses. However, the peak power of lasers remained virtually constant for the next decade due to amplifier material power damage problems. It was not until 1985, Donna Strickland, and Gerard Mourou proposed the important CPA (Chirped pulse amplification)

technique [8]. This technique solved the problem of high-energy amplification of brief pulses, which led to a significant escalation in the peak power of lasers. The increase in peak power has greatly contributed to the development of laser-related science and industry [9]. Ultra-intensity and ultrashort lasers can create comprehensive extreme physical conditions, which have significant applications in laboratory astrophysics, laser fusion, plasma physics, nuclear physics and nuclear medicine, atomic and molecular physics, high-energy physics and other fields, and are an important scientific and technological frontier and competitive field [10]. Two 10 PW lasers were successfully developed in China and Europe in 2017 and 2019, respectively. These lasers were constructed at the super-intense ultrafast laser facility (SULF) and the extreme light infrastructure-nuclear physics (ELI-NP) facility [11]. The United States is now engaged in the development of advanced multi-petawatt (PW) lasers, including the zettawatt equivalent ultrashort pulse laser system (ZEUS) [12]. The J-KAREN-P petawatt lasers in Japan has steadily increased its laser output performance and temporal quality [13]. Currently, there are multiple organizations in China, Europe, the United States, and Russia that are actively engaged in the investigation and advancement of higher-power lasers. The CPA approach is widely employed in contemporary cutting-edge high-power laser systems [14].

In view of the broad application prospects and important scientific significance of ultra-intensity and ultrashort laser, this paper is intended to provide an overview of their technological development and applications, including basic principles, key technologies, advanced equipment, typical applications and challenges.

2. Basic Descriptions

Ultrashort pulsed lasers typically denote pulsed lasers characterized by pulse durations less than picoseconds (10^{-12} seconds). Ultrashort pulsed lasers in the femtoseconds (10^{-15} seconds) class are the most actively researched. Ultra-intensity and ultrashort pulsed lasers are ultrashort laser pulses whose peak pulse power can reach orders of magnitude above GW (10^{9} watts). The highest peak power in the laboratory currently reaches the order of PW (10^{15} watts). Ultra-intensity and ultrashort pulsed lasers refer to laser pulses that possess a combination of ultra-intensity characteristics, ultrashort pulse durations (often in the femtosecond range), and ultra-high peak pulse energy (reaching the order of petawatts). The progression of ultra-intensity and ultrashort laser pulse technology has gone through many phases. The initial development of the ruby laser, which occurred in 1960 [1], resulted in the creation of a laser system characterized by pulse durations in the millisecond range. Later, using the Q-switching technique, lasers with pulse durations in the nanosecond range were generated [9]. This opened up the field of ultrashort pulsed lasers, and in the 1970s and 1980s, mode-locked lasers were generated. By incorporating an optical modulator into the laser cavity, passive mode-locking of the laser was realized, generating pulses on the order of picoseconds or even femtoseconds [15]. This has become an important means of obtaining ultrashort pulses. The year 1985 witnessed a significant breakthrough in the field of laser technology with the introduction of the chirped pulse amplification (CPA) technique. This breakthrough enabled the initial expansion and subsequent compression of laser pulses, resulting in a substantial rise in peak power. As a result of these advancements, laser pulses were able to achieve peak power levels on the terawatt (TW) scale for the first time [10]. In the 1990s, the use of Ti:Saph as a gain medium to produce femtosecond lasers, obtaining shorter pulses [16].Around the 21st century, OPCPA nonlinear optics technology to achieve higher gain efficiency, hence leading to continuous improvements in the peak power of laser [17]. Ultra-intensity and ultrashort laser have gone through several important stages of progress from Q-switching, mode-locking, CPA to OPCPA, with pulse widths decreasing from ns to fs, and peak powers increasing to the order of PW.

The key parameters of ultra-intensity and ultrashort pulse laser include:

Pulse width: tens of femtoseconds to hundreds of femtoseconds.

Center wavelength: from ultraviolet to near infrared; and

Peak pulse power: more than ten gigawatts; and

Peak pulse intensity: greater than 10^{18} W/cm^2.

Ultra-intensity and ultrashort pulsed lasers require both ultrashort pulse widths on the order of femtoseconds and ultra-high peak power and intensity parameters. This makes it an important tool for today's strong-field and nonlinear optics research. The ultra-intensity and ultrashort pulse lasers have the following implementation methods. Passive mode-locking may be achieved in a laser cavity by including a nonlinear diffractive Q-switching mechanism, thereby enabling the generation of femtosecond short pulses [18]. The typical device is a femtosecond titanium gemstone oscillator.

The femtosecond pulse is first stretched by diffraction grating, then amplified and compressed by compression grating, and the peak power greater than TW can be obtained [7]. The use of nonlinear effects to achieve broadband laser amplification, and then compressed, can achieve PW peak power [19]. The laser pulse is further compressed using a double grating or diamond mirror group, and the pulse can be compressed to a single cycle range [20]. Adaptive optics is utilized to improve the peak intensity and focusing quality of the laser [21]. Currently, the main way to obtain an ultra-intensity and ultrashort pulse laser is to use a combination of mode-locked, CPA, nonlinear effects, phase modulation, and other methods in order to boost the peak power while reducing the pulse width.

3. Principles

The chirped pulse amplification (CPA) technique is currently the main means of obtaining high-power ultrashort pulse lasers [10]. Prior to the implementation of the CPA technique, the peak power of laser pulses was constrained to the gigawatt (GW) or terawatt (TW) range because of the occurrence of nonlinear processes such as self-focusing and other nonlinear processes of ultra-high-intensity (GW class per square centimeter) laser pulses in the gain medium, which severely damaged the gain medium. In this section, the CPA technique, grating compression technique, and focusing technique are discussed, which are the key techniques to realize ultra-intensity and ultrashort laser pulses. The CPA technique is capable of attaining significant amplification and peak power through the process of pulse stretching before amplification, followed by pulse compression after amplification. Specifically, a pulse stretcher (e.g., a grating) is used to stretch a short femtosecond pulse into a long pulse on the order of picoseconds or nanoseconds, reducing its peak power. Then, a laser amplifier is used to amplify the stretched low-power long pulse. Finally, the enhanced pulse undergoes compression through the use of a compressor. In this way, high peak power femtosecond ultrashort pulses of greater than TW magnitude can be obtained [22]. A sketch is shown in Fig. 1

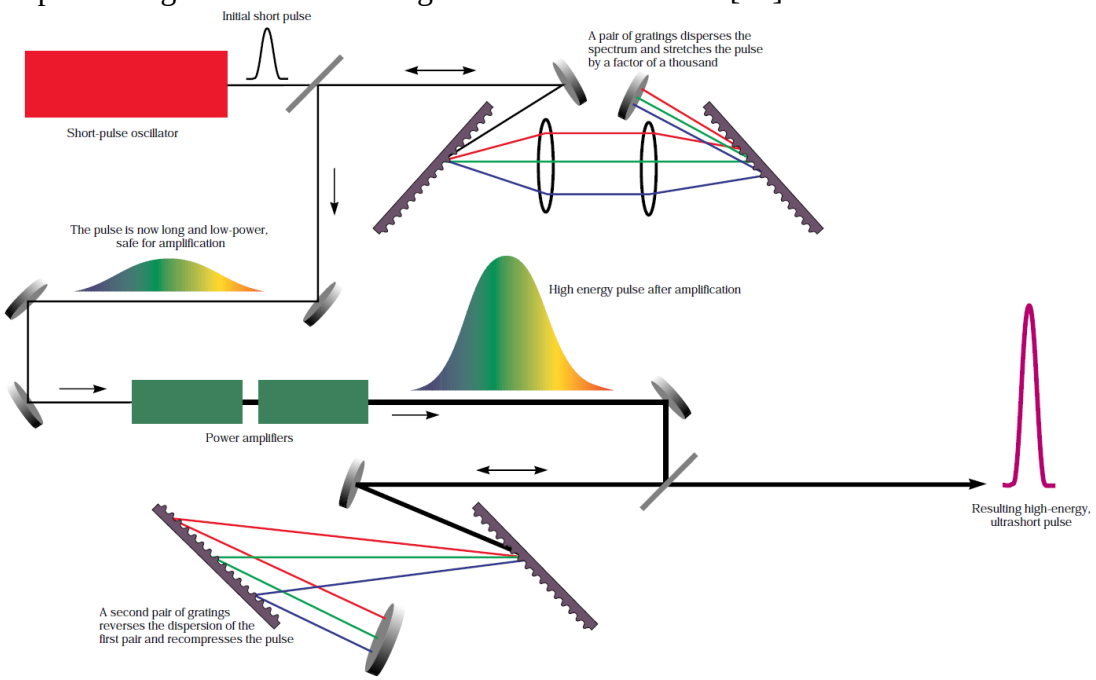


Fig. 1 Schematic of chirped pulse amplification.

This strategy of first stretching, then amplification, and finally compression avoids material damage limitation and significantly contributes to the progress of ultra-intensity and ultrashort pulse laser technology while simultaneously exerting a profound influence on the study of strong-field and extreme physics [23]. In order to compress pulses to shorter time scales, grating compression techniques are used. Linear pulse compression is typically performed using sprayed grating pairs or rhombic mirror sets [24]. Sprayed gratings can be used to compress 40 fs pulses to less than 15 fs in the 800 nm band. The rhombic mirrors can realize more efficient second-order pulse compression on the basis of complex diffractive optical paths and compress the laser into a single cycle-range [25].

Based on CPA, the use of grating pairs or adaptive optics techniques can further compress the laser pulse to the sub-periodic level, resulting in a significant increase in intensity [26]. Using progressive focusing and other methods, it is possible to focus the laser on a sub-wavelength focal point, which can reach up to a very high intensity. Typically, lenses or curved mirrors are employed to achieve two- or three-dimensional laser focusing. However, due to the phase distortion during focusing, the effective light intensity is reduced. In order to achieve higher peak intensities, adaptive optics, such as a wavefront compensation system, are required. This dynamically detects and compensates for wavefront aberrations to achieve ideal focusing of the beam and effectively increase the peak intensity. The implementation of adaptive optics has been found to have a significant effect on enhancing the focusing capabilities and peak intensity of ultra-intensity and ultrashort pulse lasers [27].

4. Facilities

Ultra-intensity and ultrashort pulsed laser facilities are important in scientific research and industrial applications. In scientific research, ultra-intensity and ultrashort pulsed lasers can produce extremely high light intensities, which makes them uniquely suited to the study of high-energy physics, plasma physics, quantum electrodynamics and other fields. In terms of industrial applications, the lasers also have a diverse array of applications within the domains of material processing, medical technology, communication technology, and other related sectors. Therefore, the research and development of ultra-intensity and ultrashort pulsed laser facilities is of great significance in promoting the progress of science and technology. The Lawrence Livermore National Laboratory in the U.S. constructed the world's first PW-class laser, called Nova 2-beam laser facility, in 1996.The J-KAREN PW laser system at the Japan Atomic Energy Agency was the first facility to realize femtosecond PW lasers with titanium gemstones. The zettawatt equivalent ultrashort pulse laser system (ZEUS) in the United States has achieved 3 PW results. The LFEX facility in Japan achieves 3kJ pulse output, corresponding to 2PW peak power, through a Nd:glass laser [28]. The BELLA PW laser system at Lawrence Livermore National Laboratory in the United States can output 40J pulse power, corresponding to 8.3PW peak power, with a pulse width of 30 femtoseconds [29]. The SG-II of China's High Power Laser Science Research Center has also accomplished 1PW output [30].

In the past few years, significant advancements in ultra-intensity and ultrashort pulsed laser technology on the petawatt (PW) scale have been achieved by China, Europe, the United States, and Japan. These laser devices have significantly contributed to the advancement of physics, materials science, engineering technology, and other fields, as well as opening new scientific horizons and technological possibilities. The super-intense ultrafast laser facility (SULF), located in Shanghai, China, has effectively attained a maximum power output of 10 petawatts. The system demonstrates a pulse duration of 30 femtoseconds, a center wavelength of 800 nanometers, and a repetition frequency of 1 hertz [11]. The European extreme light infrastructure-nuclear physics (ELI-NP) facility has also achieved a peak power of 10 PW with a repetition frequency of 1 Hz and a center wavelength of 800 nanometers [12]. These two facilities currently represent the highest level of ultra-intensity and ultrashort pulsed laser technology in the world. Nevertheless, these facilities face several challenges. The maximum power output and concentrated intensity of these facilities remain far lower than the Schwinger limit, indicating that the technology of these facilities still needs to be further improved. In addition, further increasing the power of these facilities would require large-scale engineering

investments and significant economic investments. However, the rapid development of these facilities worldwide demonstrates the potential and promise of PW-class lasers.

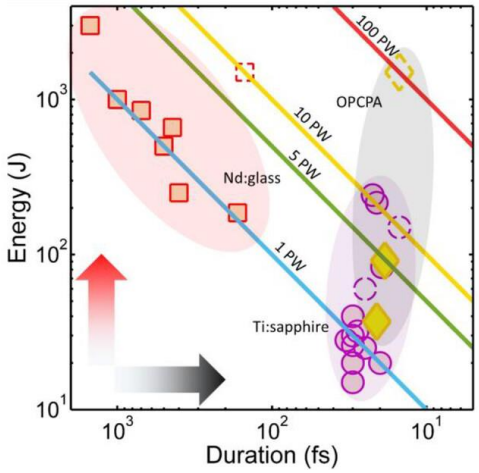


Fig. 2 A few PW lasers and their locations in the duration-energy-peak power diagram.

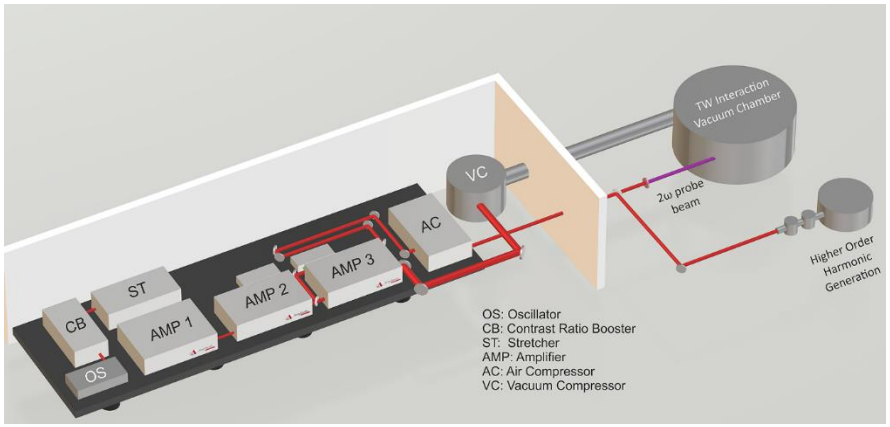


Fig. 3 A three-dimensional schematic layout of the ZEUS 45 TW laser system.

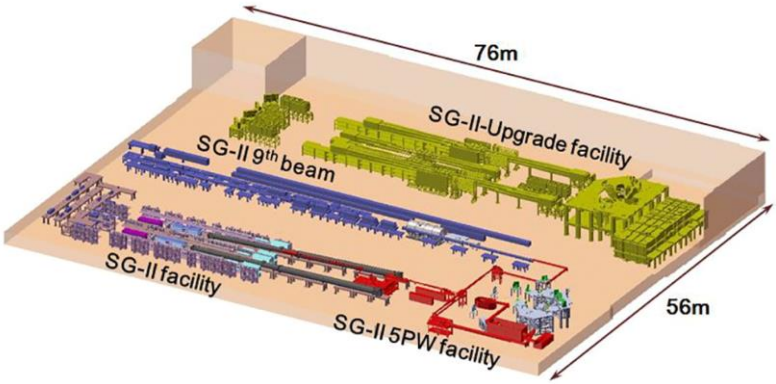


Fig. 4 Layout of the SG series laser facilities.

Seen from Fig. 2 Chinese research teams are constructing 100 PW-class SEL lasers [8], and Europe is actively preparing for the construction of up to 1 EW laser facilities, ELI [31]. At the same time, countries are also exploring to increase the laser repetition frequency to expand the range of experimental parameters. For example, in Europe, ELI-ALPS equipment to achieve 1PW power under 1Hz repetition frequency output; Apollon device aims to achieve 10PW peak power and 1Hz repetition frequency under 15fs pulse width. The expansion of experimental parameters will significantly promote the development of high peak power laser science. In summary, at present, China, Europe, the United States, Japan and other countries have accumulated rich experience in ultra-intensity and ultrashort pulsed laser technology on the PW scale, and have achieved a number of world records. With the continuous development and upgrading of these facilities, they will

continue to push the boundaries of our understanding and technological capabilities in various scientific fields. Some of the laser systems are shown in Fig. 3, Fig. 4 and Fig. 5 [32-34].

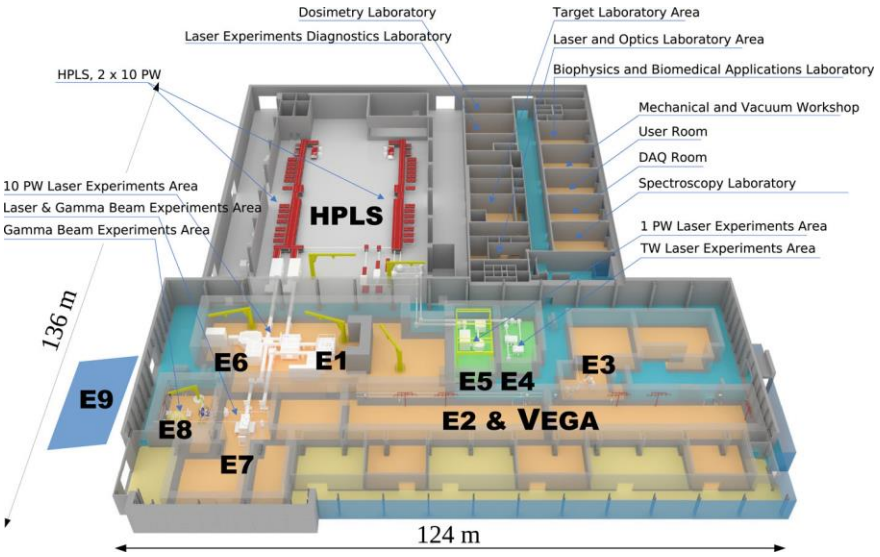


Fig. 5 The configuration of the whole experimental region of the extreme light infrastructure-nuclear physics (ELI-NP) facility.

5. Applications

The advent of ultra-intensity and ultrashort pulsed lasers has given rise to novel advancements in several interdisciplinary domains. Their remarkably high peak power and very brief pulse durations have facilitated a diverse array of applications in both scientific research and industrial settings. In this section, this study will mainly discuss its applications in the fields of particle acceleration, high energy density physics, ultrafast phenomena research and precision materials processing. Ultra-intensity and ultrashort pulsed lasers can generate extremely high electric field strengths, which makes them uniquely valuable for applications in particle acceleration. For example, Leemans et al. successfully accelerated electrons using this laser with an energy of 4.25 GeV [35]. Rehwald et al. used an ultrashort pulsed laser to accelerate protons to 80 MeV (the experiemental setup is shown in Fig. 6) [36].

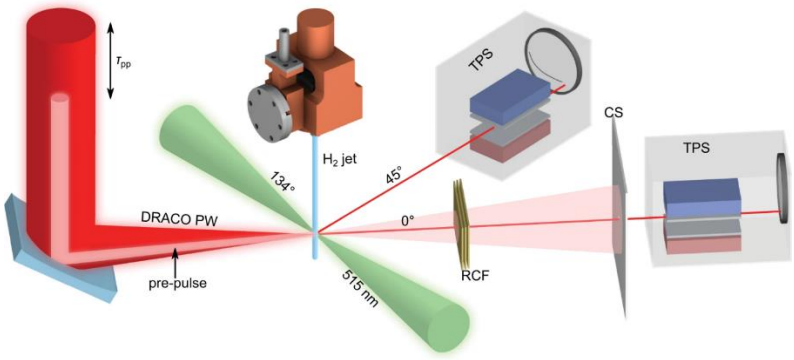


Fig. 6 Proton acceleration experimental setup.

High-energy density physics is a significant field where ultra-intensity and ultrashort pulsed lasers find crucial applications. Ditmire et al. have employed ultra-intensity and ultrashort pulsed lasers within this domain to create and investigate physical processes occurring in dense plasmas under conditions of extreme nature [37, 38], which are scientifically valuable for understanding the physical processes inside stars. Ultra-intensity and ultrashort pulsed laser possess a diverse array of applications within the realm of ultrafast phenomenon study. For example, Krausz and Stockman

used such lasers to observe and study the electronic dynamics of matter on very short time scales [39], providing a new perspective for understanding the microscopic behavior of matter.

Ultra-intensity and ultrashort pulsed lasers provide remarkable accuracy and high peak power, rendering them highly suitable instruments for precision material processing within the industrial sector. The application of laser processing using ultrashort double pulses has experienced substantial growth in popularity since the early 2000s. In recent decades, there has been an emergence of bursts, including numerous pulses with delays of 10 nanoseconds or less, in the field of processing. This development has introduced novel processing modes and led to enhancements in the pace of structuring and the quality of surfaces in processed samples [40].

6. Limitation and Future Outlooks

For ultra-intensity and ultrashort pulse laser, despite being widely utilized in scientific research and industry, its technical and theoretical studies still need to be improved and refined. These existing problems will be discussed in this section, including the problem of laser damage threshold, the difficulty of phase control, and the potential enhancement of repetition frequency and stability. The possible future trends of ultra-intensity and ultrashort pulse lasers will also be analyzed, including the pursuit of higher peak power, enhanced interdisciplinary integration and applications, and advances in advanced phase control techniques.

Although the peak power of ultra-intensity and ultrashort pulsed laser is extremely high, the laser destruction threshold needs to be considered in practical use. Exceeding this threshold may cause structural damage to the target material, which in turn affects the quality of the experiment or product. Therefore, the current imperative lies in resolving the crucial issue of optimizing the laser's peak power to prevent exceeding the damage threshold. In the process of tuning the ultra-intensity and ultrashort pulsed laser, phase control is a central point. However, due to the extremely brief duration of the laser pulse, it is very difficult to realize precise phase control. In addition, the nonlinear effect of the laser may amplify the error of phase control, increasing the difficulty of phase control. Although the existing ultra-intensity and ultrashort pulsed laser technology has been able to realize relatively high repetition frequencies, in certain applications, such as particle acceleration and high-energy density physics, a higher repetition frequency may yield superior experimental outcomes. Therefore, increasing the repetition frequency of lasers while maintaining their stability is a key direction in the current development of the technology. Owing to the progress in technology, the future is anticipated to witness the realization of ultra-intensity and ultrashort pulsed lasers with enhanced peak power. This advancement will yield more robust instruments for high-energy physics, particle acceleration, and related disciplines, potentially inciting novel physical phenomena and expanding the horizons of scientific inquiry. Ultra-intensity and ultrashort pulsed laser have great potential and can find applications in multiple disciplines. It is expected to see more cross-disciplinary research in the future, especially with biology, materials science, and other fields to explore more application possibilities. As new technologies continue to emerge, one has the expectation of realizing more precise phase control. This will offer substantial backing for the modulation of ultra-intensity and ultrashort pulse lasers while also augmenting the laser's overall performance in terms of peak power, repetition frequency, and stability. In summary, ultra-intensity and ultrashort pulsed lasers have made important achievements in scientific research and industry, however, the existing technology still has many areas that need to be improved and optimized, including the laser damage threshold issue, the challenges associated with phase control, and the possibilities for improving both repetition frequency and stability. However, with continued technological advances, there are good reasons to expect the realization of ultra-intensity and ultrashort pulse lasers with higher peak powers in the future, as well as the strengthening of interdisciplinary integration and applications, and the development of advanced phase control techniques. These possible trends will not only advance ultra-intensity and ultrashort pulsed laser technology, but also open up more possibilities for scientific research and industry.

7. Conclusion

In summary, this paper systematically outlines the development history, realization principle, key equipment and its application areas of ultra-intensity and ultrashort pulse laser technology. The ultra-intensity and ultrashort pulse laser generation method, compression and focusing technology, main device platforms, and applications in scientific research and industry are elaborated in detail. Issues of laser damage threshold, phase control, and repetition frequency and stability are also discussed in depth, and possible directions of development are predicted, including the realization of higher peak powers, the strengthening of interdisciplinary integration and applications, and the development of advanced phase control techniques. The challenges facing the field, such as improving laser parameters, controlling phase aberrations, and expanding application areas, are pointed out. It is believed that with further innovations in related core technologies, these problems are expected to be overcome, and the performance and application scope of ultra-intensity and ultrashort pulse laser technology will be further enhanced. These results help deepen the understanding of the field of ultra-intensity and ultrashort lasers, and provides valuable insights for subsequent research exploration.

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