Postprint: Frontier Research on Ultra-intense Lasers and Fusion Physics

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Abstract

The emergence and rapid development of ultra-intense ultra-short lasers have provided humanity with unprecedented extreme physical conditions and novel experimental means. Ultra-intense ultra-short lasers with peak power reaching the petawatt level (i.e., PW, 10^{15} W, quadrillion watts) and pulse duration reaching tens of femtoseconds (i.e., fs, 10^{-15} s, quadrillionths of a second) are regarded as the brightest light sources known to humanity, capable of creating unprecedented comprehensive extreme physical conditions of ultra-high energy density, ultra-strong electromagnetic fields, and ultra-fast time scales in the laboratory, holding significant application value in fields such as atomic and molecular physics, chemistry, materials science, attosecond science, plasma physics, nuclear physics, astrophysics, particle physics, medicine, and life sciences, and constituting one of the major frontier domains in international scientific and technological competition.

Full Text

Preamble

The emergence and rapid development of ultra-intense, ultra-short lasers provide unprecedented extreme physical conditions and novel experimental capabilities. Ultra-intense ultra-short lasers, with peak power reaching the petawatt level (PW, 10^15 W, quadrillion watts) and pulse durations in the tens of femtoseconds (fs, 10^-15 s, quadrillionths of a second), are considered the brightest light sources known to humanity. They can create unprecedented comprehensive extreme physical conditions of ultra-high energy density, ultra-strong electromagnetic fields, and ultra-fast time scales in laboratory settings, holding significant application value in atomic and molecular physics, chemistry, materials science, attosecond science, plasma physics, nuclear physics, astrophysics, particle physics, medicine, and life sciences. This represents a major frontier in international scientific and technological competition.

2 Scientific Problems to be Addressed

The principal investigators of this program are Researcher Li Ruxin and Academician Xu Zhizhan. The host institution is the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, with participating units including the University of Science and Technology of China, Institute of Physics of the Chinese Academy of Sciences, Shanghai Institute of Applied Physics of the Chinese Academy of Sciences, Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, and Shanghai Institute of Ceramics of the Chinese Academy of Sciences. The program comprises three projects.

1 Background and Rationale

Based on the current status and development trends of ultra-intense laser and fusion physics research both domestically and internationally, as well as the existing research foundation (Figure 1 [Figure 1: see original paper]), this program conducts frontier research in ultra-intense lasers and fusion physics, focusing on ultra-intense laser physics and potential new research directions in fusion physics enabled by ultra-intense ultra-short lasers.

(1) Project 1: "Frontier Issues in Ultra-Intense Laser-Plasma Physics"

Principal Investigators: Researcher Liu Jiansheng and Researcher Li Yutong. This project focuses on: fundamental physics of ultra-intense laser-driven phase-space ultra-high-density high-energy electron beams (~10 GeV) and next-generation free-electron lasers (XFEL); quantum electrodynamics (QED) effects in interactions between relativistic (even strongly relativistic) ultra-intense lasers and matter; and generation and application of relativistic vortex lasers. It investigates new physical mechanisms for electron capture in plasmas by ultra-intense lasers ("radiation reaction," etc.), develops ultra-high-brightness gamma-ray sources driven by ultra-intense lasers, and explores their applications in photonuclear physics. Building upon the realization of relativistic vortex lasers and "light fan" driving, the project investigates laboratory astrophysics using relativistic vortex light.

(2) Project 2: "New Fusion Reaction Systems and New Matter Driven by Ultra-Intense Lasers"

Principal Investigators: Researcher Shen Baifei and Professor Zheng Jian. This project focuses on core scientific issues of ultra-intense laser-driven aneutronic proton-boron fusion reactions, such as generating high-current, high-quality proton beams with specific energies through interactions between high-contrast-ratio ultra-intense laser pulses and solids, and achieving the high reaction temperatures required for proton-boron fusion. It explores scientific problems related to fusion reactions far from thermal equilibrium, including innovative research on plasma-state reaction cross-sections and small-cross-section reactions under low cosmic background noise. The project also investigates new matter generation and novel physical properties based on ultra-intense lasers, forming electron-positron pair plasmas to simulate astrophysical environments, and using laser-accelerated high-energy proton beams to explore antiproton production.

(3) Project 3: "Creation and Characteristic Control of Novel Ultra-Intense Laser Fields"

Principal Investigators: Researcher Leng Yuxin and Researcher Su Liangbi. This project investigates control of ultra-high temporal contrast ultra-high intensity laser fields, focusing on key scientific and technological issues such as achieving laser focusing intensity exceeding 10^22 W/cm^2 and ultra-high temporal contrast pulses exceeding 10^11. It conducts research on new principles for generating and manipulating extreme ultra-intense light fields oriented toward exawatt-level peak power, exploring novel principles and methods for amplifying, compressing, and focusing exawatt-level laser pulses, such as parametric fluorescence suppression, optical field coherent synthesis, temporal contrast enhancement based on plasma media, and high-flux amplification. The project also investigates generation and control of ultra-intense light fields in new wavelength bands, including mid-to-far infrared and X-ray, exploring new principles and methods such as GV/cm-level strong THz radiation fields based on ultra-intense laser-plasma interactions and X-ray chirped pulse amplification mechanisms, along with developing corresponding precision control methods and technologies for temporal, spectral, and spatial characteristics.

3 Expected Outcomes

The program' s expected research outcomes include: (1) Generation of 10 GeV-class monoenergetic electron beams based on laser acceleration, providing a technical pathway for future high-performance high-energy electron beams of 100 GeV and beyond; preliminary experimental verification of QED effects; generation of relativistic vortex lasers with intensity greater than 10^18 W/cm^2 and exploration of their applications. (2) Obtaining GeV-class high-energy proton beams through laser acceleration to conduct research on laser-generated antimatter and its interactions. Achieving important results in small-cross-section reactions under low cosmic background noise (such as p+B fusion reaction cross-sections). (3) Generating laser focusing intensity exceeding 10^22 W/cm^2 and ultra-high temporal contrast pulses exceeding 10^11, exploring and developing new principles and methods for exawatt-level extreme ultra-intense light field generation and control, and solving related key scientific and technological problems.

Note: Figure translations are in progress. See original paper for figures.