CONFERENCE PRE-PRINT

DEVELOPMENT OF INNOVATIVE REPEATABLE POWER LASER FOR LASER FUSION

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Abstract

This study reports the development of a high-efficiency, repeatable power laser system aimed at advancing laser fusion research. Significant progress has been made in laser fusion, with recent achievements including a fusion gain exceeding 1. However, the plug efficiency remains below 1%, presenting a significant challenge for practical applications. In this work, a diode-pumped conduction-cooled active mirror amplifier employing Yb:YAG ceramics was developed. By leveraging proprietary bonding technology, challenges such as thermal load and wavefront distortion were successfully addressed, enabling an unprecedented increase in aperture size. This resulted in the world's first demonstration of 10 J, 100 Hz operation, achieving an electrical-to-laser conversion efficiency exceeding 10%, which is ten times higher than that of conventional systems. Consequently, this technological milestone has facilitated the development of a 100 J, 100 Hz laser system, representing a groundbreaking step toward the realisation of inertial fusion energy reactors.

1. INTRODUCTION

The pursuit of clean and sustainable energy has driven extensive research into nuclear fusion. Among the various approaches, laser fusion, a form of inertial fusion energy (IFE), has seen significant progress. Landmark experiments have been conducted at large-scale facilities such as the National Ignition Facility (NIF) and the Omega Facility to explore ignition schemes. The NIF recently achieved a major milestone by demonstrating fusion gain [1], where the energy produced by the fusion reaction exceeded the laser energy delivered to the target. Concurrently, alternative concepts like the fast-ignition scheme are being investigated at institutions such as Osaka University, which aim to achieve ignition with considerably less laser energy. A recent experiment there successfully generated an ultra-high-energy-density plasma at 2.2 Peta pascals, showcasing the potential of this approach [2].

While these achievements are scientifically significant, the transition from single-shot scientific demonstrations to a functional IFE power plant presents immense engineering challenges. A practical reactor requires not only net energy gain but also continuous and stable operation at a high repetition rate, typically several hertz. The current leading facilities, however, are limited to single-shot operation. Furthermore, their overall "wall-plug" efficiency, which is the ratio of fusion energy output to the electrical energy input to the laser system, is exceedingly low at less than 1%. Consequently, the development of a highly efficient and repetitive driver laser is recognized as one of the most critical challenges for the realization of IFE.

The primary bottleneck for high-repetition operation lies in managing the thermal load on the laser's gain medium. During operation, a significant amount of waste heat is deposited in the medium, leading to detrimental thermal effects such as thermal lensing, wavefront distortion, and thermally induced birefringence. These effects degrade the laser beam quality and ultimately limit the system's repetition rate and stability. Traditional flashlamp-pumped glass lasers, which have historically been used, suffer from both low energy conversion efficiency and the poor thermal conductivity of glass, making them unsuitable for high-repetition applications. Therefore, a paradigm shift in laser architecture is imperative to overcome these thermal barriers and pave the way for a viable IFE driver. This paper introduces our development project, which contributes to this new trend, named SENJU (Super-Energetic Joint Unit).

2. DEVELOPMENT TRENDS IN REPEATABLE POWER LASER SYSTEMS

The development of a Repeatable Power Laser hinges on the advancement of diode-pumped solid-state lasers (DPSSLs). In particular, the emergence of transparent ceramics, such as Ytterbium-doped Yttrium Aluminum Garnet (Yb:YAG), has been a key enabler. Yb:YAG is highly favored for its excellent properties, including a low quantum defect that minimizes waste heat generation and a long fluorescence lifetime conducive to efficient energy storage [3]. Furthermore, cryogenic cooling dramatically improves its thermal conductivity, allowing for the effective suppression of heat-induced wavefront distortions, which is essential for maintaining beam quality in high-power systems.

Driven by these material advancements, two primary amplifier architectures have emerged: the gas-cooled multi-slab and the active mirror configurations. The gas-cooled multi-slab architecture, which involves flowing gas between thin, stacked slabs of the gain medium (FIG.1(a)), is well-suited for large energy storage. High-performance examples include the Mercury project at LLNL (61 J, 10 Hz) [4] and the DiPOLE system in the UK and Czech Republic, which has achieved 146 J at 10 Hz [5]. In Japan, Hamamatsu Photonics has also reported a world-class performance of 200 J at 10 Hz [6,7]. While recent studies have demonstrated that cryogenic gas-cooled laser systems can achieve high repetition rates of up to 100 Hz [8], scalability remains a challenge due to constraints on gas flow rate and pressure stability, particularly for expanding to higher energy levels and ensuring long-term continuous operation.

In contrast, the active mirror architecture involves bonding the rear face of a disk-shaped gain medium to a metal heat sink for direct conduction cooling (FIG.1(b)). This method confines heat flow to the axial direction, effectively suppressing the thermal lens effect, and its compact structure provides excellent scalability for high-repetition operation. While systems based on this approach have typically focused on higher repetition rates, such as those at Colorado State University (1.1 J, 1 kHz) [9] and by a DESY/MIT collaboration (1 J, 500 Hz) [10], our research has introduced unique cooling technologies to this method, successfully demonstrating a high-energy, high-repetition-rate operation of 10 J at 100 Hz [11, 12].

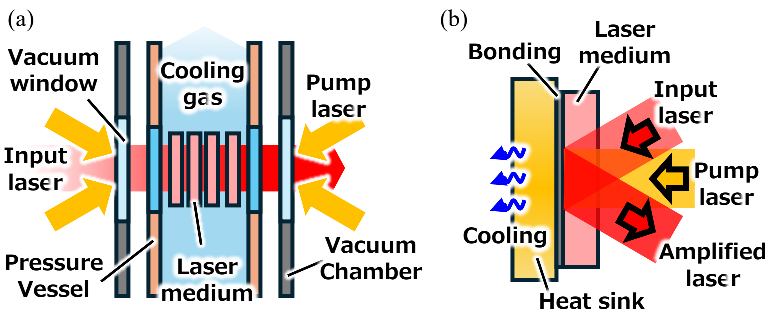

FIG. 1. Schematic of a cryogenically cooled laser amplifier (a) Gas-cooled multi-slab laser, (b) Active mirror laser

3. DEVELOPMENT STATUS OF THE REPEATABLE POWER LASER

3.1. Core technologies for a Repeatable Power Laser

Our research is based on the conduction-cooled active mirror architecture, into which we have integrated several innovative core technologies to achieve both high energy and high-repetition-rate operation. The most significant challenge is the management of heat, which is generated intensively within the gain medium. To ensure stable operation at 100 Hz or higher, it is necessary to simultaneously resolve a complex set of issues, including the management of mechanical stress associated with heating and cooling, and the suppression of parasitic oscillations.

A primary issue is thermal stress. Since Yb:YAG ceramics and metal heat sinks (such as copper) have vastly different coefficients of thermal expansion, significant stress develops at the interface during the cooling process from room temperature to the temperature of liquid nitrogen. This can lead to problems such as wavefront distortion and bond failure. To solve this, we have developed a proprietary multi-layered bonding structure. By inserting molybdenum, which has a thermal expansion coefficient close to that of Yb:YAG, as an intermediate layer and bonding it on both sides with a flexible metal solder, the structure can absorb the differential contraction and mitigate interface stress. This enables stable cooling and minimal wavefront distortion even for large-aperture optics.

Another critical issue is parasitic oscillation, which is caused by amplified spontaneous emission within the gain medium. Conventionally, an edge cladding structure using Cr:YAG is employed for suppression, but the heat generated by absorption can cause a secondary temperature rise. In our work, we devised a method for localized heat removal by installing a copper cooling jacket, through which liquid nitrogen circulates, on top of the Cr:YAG edge cladding. This has been shown to significantly suppress the temperature increase in the Yb:YAG, resulting in a more uniform temperature distribution throughout the medium and contributing to improved output stability.If you need to subdivide the sections of your paper, use the headings shown below. You can use second and third level paper headings. To subdivide further, please use lists numbered (a), (b), and so on, but this is usually not necessary in a paper of normal length.

3.2. 10 J, 100 Hz Conduction-Cooled Cryogenic Yb:YAG Active Mirror Laser: SENJU-Lite

To validate the effectiveness of the core technologies described above, we developed a scale-down model named "SENJU-Lite". This system is a cryogenically cooled Yb:YAG active mirror laser system designed for 10 J, 100 Hz operation, and serves to verify the component technologies for a future 100 J-class power laser (SENJU).

The system, shown schematically in FIG. 2, consists of a front end, a regenerative amplifier, a multi-pass pre-amplifier, and a main amplifier. The front end generates a seed pulse with a width of 10 ns at a repetition rate of 100 Hz using a single-longitudinal-mode fiber oscillator and an electro-optic (EO) pulse slicer. This seed pulse is first amplified to the millijoule level by the regenerative amplifier, and then further amplified to approximately 1 J by the multi-pass pre-amplifier.

The main amplifier is configured with six active mirror heads, the structure of which is shown in FIG. 3. Each head incorporates a 7 mm thick Cr:YAG/Yb:YAG ceramic disk; a 45 mm diameter, 1.0% doped Yb:YAG is used for heads 1-4, while a 50 mm diameter, 0.6% doped Yb:YAG is used for heads 5-6. A Cr^{4+}-doped edge cladding with respective widths of 5 and 7.5 mm is attached to the circumference of each disk to suppress parasitic oscillations and is locally cooled by a copper cooling jacket. A multi-layer bonding structure is introduced between the disk and the copper heat sink, and liquid nitrogen is circulated through each heat sink at a flow rate of 6 L/min. Pumping is performed by 940 nm laser diodes, with a configuration where one laser diode unit simultaneously pumps two disks. The input laser pulse is amplified through a total of 12 passes: it passes sequentially through the six active mirrors, is reflected by a $\lambda/4$ waveplate and an end mirror, and passes through the six active mirrors again in the reverse direction.

The performance of the SENJU-Lite system is shown in FIG. 4. The system successfully produced an output of 10.2 J (average power 1.02 kW) with an optical-to-optical efficiency of 23.6%, for a total pump energy of 41.6 J, as shown in FIG. 4(a). Furthermore, the output energy fluctuation was suppressed to 0.7% (rms) during 10 J, 100 Hz operation, demonstrating stable operation under high-power, high-repetition-rate conditions (FIG. 4(b)).

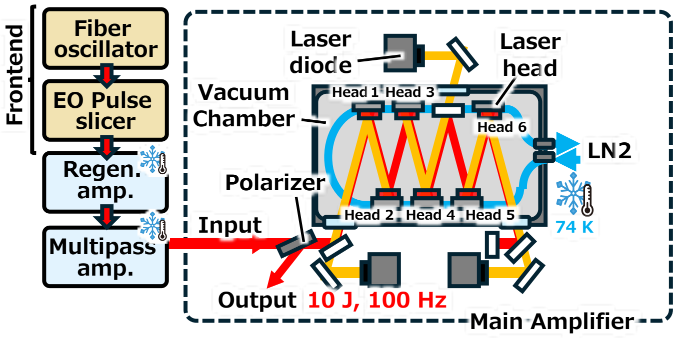

FIG. 2. Schematic of the 10 J, 100 Hz active mirror laser system, SENJU-Lite.

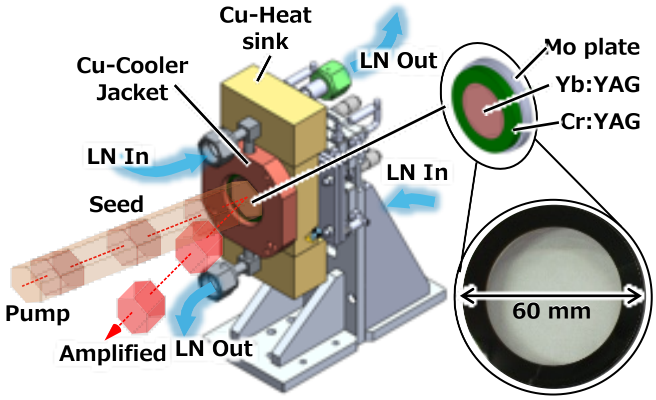

FIG. 3. Schematic of the conduction-cooled active mirror laser head.

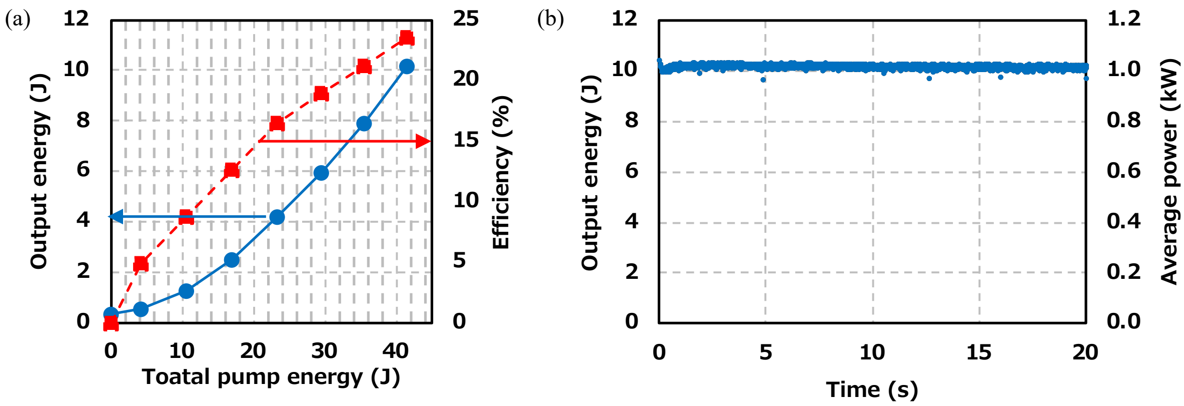

FIG. 4. (a) Output energy and optical-to-optical efficiency as a function of pump energy. (b) Output stability during 10 J, 100 Hz operation.

3.3. 100 J, 100 Hz Conduction-Cooled Cryogenic Yb:YAG Active Mirror Laser: SENJU

Based on the technologies established with SENJU-Lite, development has begun on "SENJU," a module designed to scale the output energy tenfold. The design philosophy is to increase the total energy while maintaining the thermal flux on the gain medium at a level equivalent to that of SENJU-Lite. To achieve this, the gain medium has been scaled up from a 60 mm diameter disk to a 120 mm square, and the amplifier is designed with 10 active mirror heads.

The SENJU system, whose layout is shown in FIG. 5 (a), will use a 20-pass amplification configuration, where the laser pulse passes through the 10 heads, is reflected, and passes through them again in reverse. Each active mirror head is cooled to 78 K by a liquid nitrogen circulation system and is individually pumped by a 50-kW peak power laser diode. The total anticipated pump energy is approximately 300 J, with the goal of achieving a 100 J output at 100 Hz with an optical-to-optical efficiency of over 30%. The main system components were delivered in March 2023, and the system is currently under construction (FIG. 5(b)).

A critical milestone, the bonding of the large-aperture 120 mm square Yb:YAG ceramic laser head (FIG. 5(c)), has been successfully completed. A performance evaluation of a single head has confirmed that it achieves the designed small-signal gain. Furthermore, it was verified that the change in wavefront due to thermal stress during cooling to liquid nitrogen temperatures is extremely small, and depolarization loss can be sufficiently suppressed. These results provide a clear path toward achieving the final project goals.

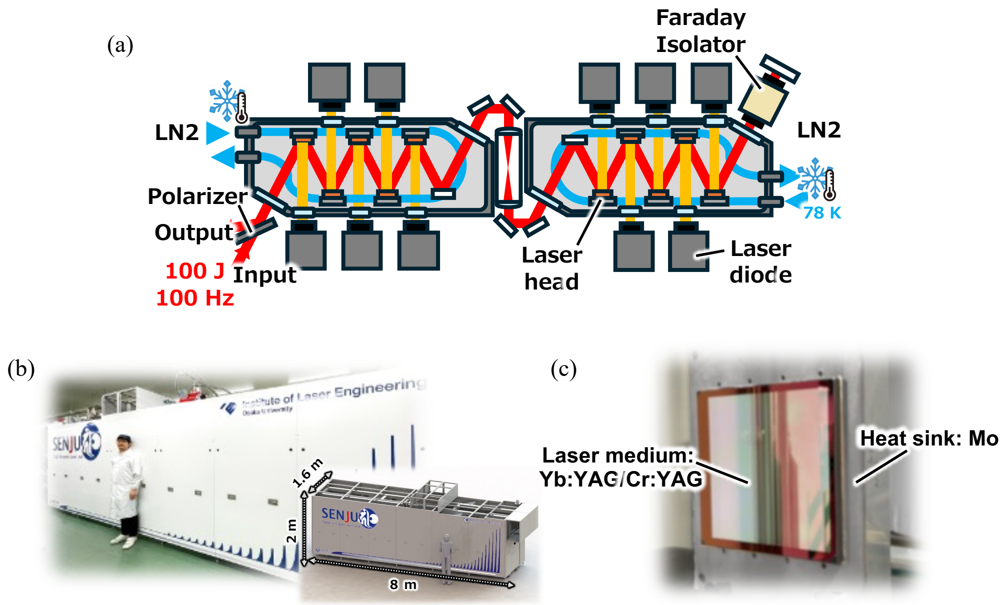

FIG. 5. (a) Schematic diagram of the SENJU system. (b) Photograph and 3D model of the SENJU system. (c) Photograph of the SENJU laser head.

4. CONCLUSION

This paper addresses the critical challenge of developing a viable driver for an inertial fusion energy (IFE) reactor, which requires a paradigm shift in laser architecture to enable highly efficient, high-repetition-rate operation. To address this challenge, we have developed a conduction-cooled, cryogenic Yb:YAG active mirror laser and demonstrated it as an effective solution. The validity of this approach has been clearly shown by the SENJU-Lite system, which established world-class performance at 10 J and 100 Hz by integrating core technologies, including a proprietary bonding structure for thermal stress mitigation and a localized cooling mechanism for parasitic oscillation suppression.

Based on these proven technologies, the 100 J-class module, SENJU, is now under development, with the successful fabrication of its unprecedentedly large-aperture active mirror head marking a significant milestone. The completion of the SENJU module is not the final objective, but rather a starting point for creating a new paradigm in science and technology, based on this robust technological foundation. The modularity at the core of its design philosophy enables a flexible and scalable vision for the future that goes beyond simple system enlargement. At the Institute of Laser Engineering, Osaka University, we are advocating for the "J-EPoCH (Japan Establishment for a Power-laser Community Harvest)" concept [13], a future plan that maximizes this feature. his is a plan to construct an ultra-high-average-power laser system, unparalleled in the world. The goal is to reach the

1-kJ and eventually 10-kJ, megawatt-class level by combining multiple completed SENJU modules (100 J, 100 Hz). This concept has been selected for the "Roadmap 2023," a guideline for science and technology policy, and expectations for its realization are high.

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