DiPOLE - An Efficient and Scalable High Pulse Energy and High Average Power Cryogenic Gas Cooled Multi-Slab Amplifier Concept*)

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We present preliminary amplification results for DiPOLE, a prototype diode-pumped cryogenic gas cooled Yb:YAG amplifier. Amplification of ns-pulses at 1030 nm has demonstrated output energies of 10.1 J at 1 Hz in a 4-pass extraction geometry and 6.4 J at 10 Hz in a 3-pass setup, corresponding to optical-to-optical conversion efficiencies of 21% and 16%, respectively. Measured performance compares favourably to existing systems and confirms the viability of the concept for efficient generation of high energy pulses at multi-Hz repetition rate. Work is now underway to confirm the scalability of the concept with the design of a 100 J amplifier system. This along with advances in Ti:Sapphire amplifier technology opens the way to the development of a multi-Hz, PW-class laser facility at the Central Laser Facility. Knowledge gained from these developments will de-risk the technology necessary to build a sub-aperture beamlet for a laser driver suitable for fusion energy generation.

Keywords: solid-state laser, laser amplifier, pulsed laser, ytterbium laser, cryogenic laser

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1. Introduction

The next generation of ultra-intense laser facilities, currently being established in Europe, require the development of laser amplifier technology capable of producing kJ-level pulses with nanosecond duration at multi-Hz repetition rate and with high wall-plug efficiency. These lasers will either be used directly for generating plasmas, e.g. in the context of inertial fusion energy (IFE) production, in projects such as HiPER [1], or for pumping short-pulse amplifiers such as OPCPA or Ti:Sapphire systems to generate ultra-short, intense pulses to study light-matter interactions and generate compact ultra-bright sources of radiation and particles, in projects such as ELI [2]. For the IFE application a reactor will require a laser driver capable of delivering megajoules of energy in multiple beams onto a target, with the pulse energy of a single beam expected to be of order 10 kJ. Each beam is planned to be made up of an array of sub-aperture beamlets delivering kJ-level pulses [3].

Current kJ-class laser facilities like the National Ignition Facility (NIF) rely on flashlamp pumped Nd:Glass technology, which exhibits very poor electrical-to-optical efficiency and can only be operated at very low repetition rates (few shots per day). Therefore, a new approach in the form of diode pumped solid state laser (DPSSL) systems, using advanced gain media and cooling schemes, is required to overcome these limitations. To achieve this we recently presented a scalable concept for a DPSSL amplifier based on cryogenic gas cooled multi slab ytterbium (Yb) doped ceramic YAG technology, capable of generating kJ-class pulse energies [4, 5]. Figure 1 shows an illustration of our kJ-class amplifier concept. Ceramic Yb:YAG has been chosen as the gain medium as it offers

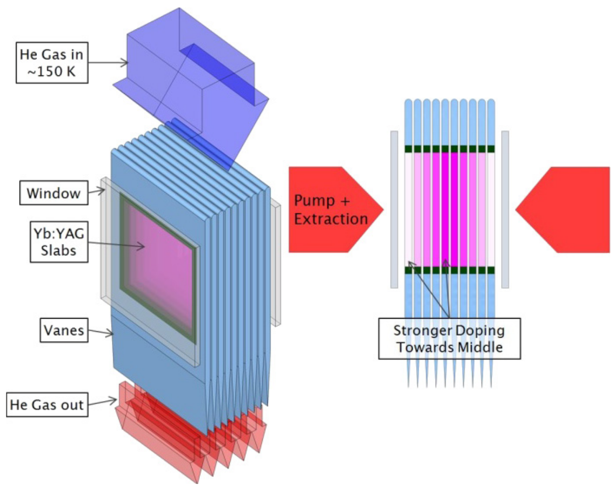

Fig. 1 Illustration of kJ-class amplifier concept: isometric (left) and side view (right).

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relatively long fluorescence lifetimes, a low quantum defect, reasonable gain cross section, and very good thermo-mechanical and thermo-optical properties, factors that are essential for achieving efficient operation of high-energy, high-repetition rate DPSSLs.

In order to demonstrate the viability of this concept, a scaled-down prototype, DiPOLE (Diode Pumped Optical Laser Experiment), is currently under development in the Centre for Advanced Laser Technology & Applications (CALTA) at the Central Laser Facility. The DiPOLE amplifier system is designed to deliver 10 J pulses at 10 Hz repetition rate with an optical-to-optical efficiency of 25% at an operating temperature of 175 K. In this paper, we present recent pulse amplification results obtained over a temperature range from 88 K to 175 K, demonstrating efficient performance at high pulse energy and high average power.

2. Experimental Setup and Results

Figure 2 shows a schematic diagram of the DiPOLE system. A Yb:CaF_2 cavity-dumped oscillator, tuneable from 1025 nm to 1040 nm with a spectral bandwidth of 0.2 nm, was used as the seed source, delivering around 200 µJ at 1030 nm and 10 Hz in a 10 ns (FWHM) pulse duration. The oscillator output was expanded to a 2 mm diameter beam and further amplified by a thin-disk Yb:YAG multi-pass pre-amplifier. This consisted of a 2 mm thick, 2.5 at.% doped Yb:YAG crystal arranged in an active mirror configuration, which was pulse pumped by a 940 nm, 2 kW peak power, diode stack for 1 ms duration. An image-relaying multi-pass architecture [6] was used to double-pass the gain medium 7 times. The pre-amplifier delivered 107 mJ at 10 Hz with an M^2 value of 1.3.

The DiPOLE main amplifier head contained four ceramic YAG discs (Konoshima) each with a diameter of 55 mm and a thickness of 5 mm. The discs consisted of a 35 mm diameter Yb-doped inner region that is surrounded by a 10 mm wide Cr^{4+}-doped cladding to minimise ASE loss and prevent parasitic oscillations at high gain. The cladding provides an attenuation coefficient of 6 cm^{-1} measured at 1030 nm and room temperature. The inner two discs had a higher Yb doping of 2.0 at.% than the outer two discs at 1.1 at.%. Thickness and doping levels were chosen to maximise optical efficiency whilst maintaining an acceptable level of ASE loss at the amplifier's design temperature of 175 K [8]. The discs were held in aerodynamically shaped vanes and arranged in a stack with 1.5 mm gaps in-between discs. Helium gas at cryogenic temperature was forced through the gaps at a typical volume flow rate of 35 m^3/h and pressure of 10 bar. The helium gas was cooled by passing it through a liquid nitrogen heat exchanger and circulated by a cryogenic fan (Cryozone). The amplifier was pumped from both sides by two 940 nm diode laser sources (Ingeneric, Jenoptik and Amtron) each delivering 20 kW peak power with variable pulse duration up to 1.2 ms and repetition rate up to 10 Hz. The emission spectrum of the diode sources was less than 6 nm (FWHM) wide. The pump sources produced a $20 \times 20\,mm^2$ square, flat-top beam profile at their image plane, which was arranged to lie at the centre of the amplifier head [5].

For ns-pulse amplification studies, the main amplifier was seeded by the pulsed output from the pre-amplifier. The circular beam was expanded to overfill the $20{\times}20\,mm^2$ square pumped region within the amplifier, the energy after beam expansion was approximately 60 mJ. A simple bow-tie arrangement was then installed to pass the seed beam through the amplifier up to 4 times, as shown in Fig. 2.

Figure 3 shows the measured output energy for different operating temperatures as a function of pump pulse duration for a 3-pass configuration. The operating temperature quoted corresponds to the helium gas temperature measured at the input to the amplifier. The saturation fluence for the amplifier is between 2.4 J/cm^2 and 3.7 J/cm^2 for temperatures between 100 K and 175 K, respectively, based on reported emission cross-section data of Dong

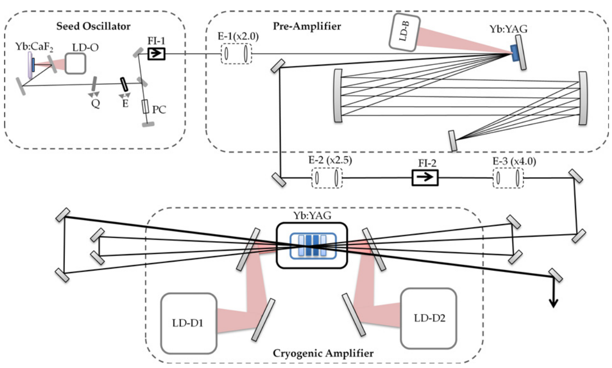

Fig. 2 Schematic diagram of the DiPOLE system.

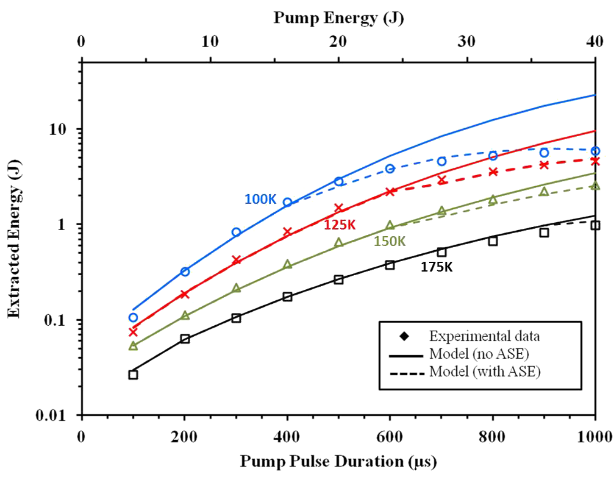

Fig. 3 Extracted energy as a function of pump pulse duration measured at different temperatures for 1 Hz operation in a 3-pass configuration.

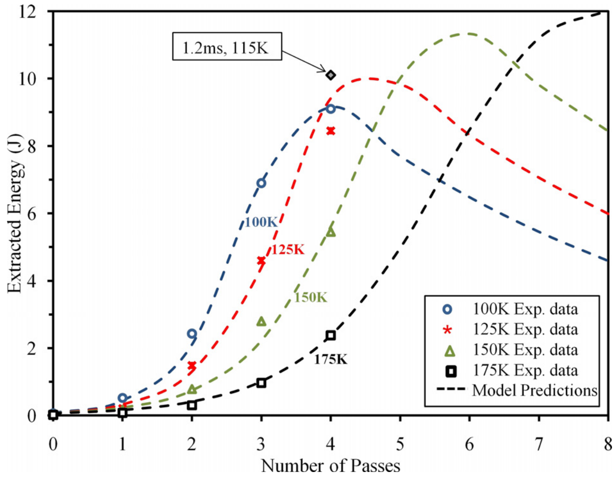

Fig. 4 Predicted output energy of the DiPOLE amplifier for 8 passes along with the experimental values measured for up to 4 passes at different temperatures for 1 Hz operation and 1 ms pump pulse duration.

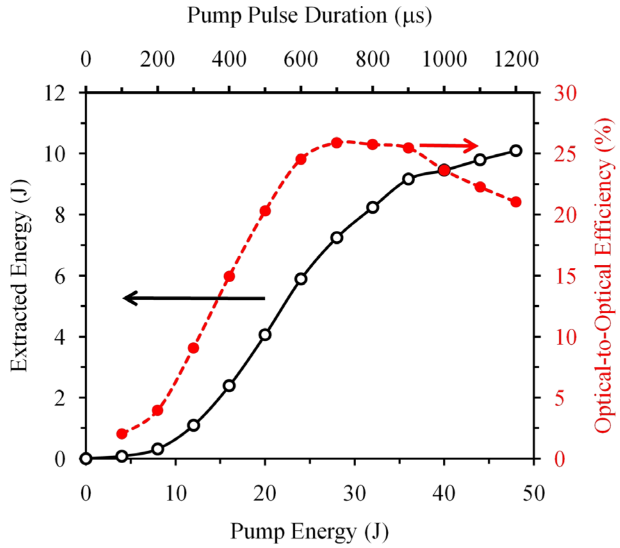

Fig. 5 Extracted pulse energy (solid line) and ηo-o (dotted line) of the DiPOLE amplifier for up to 1.2 ms pump pulse duration at 1 Hz, 4-passes and 115 K coolant temperature.

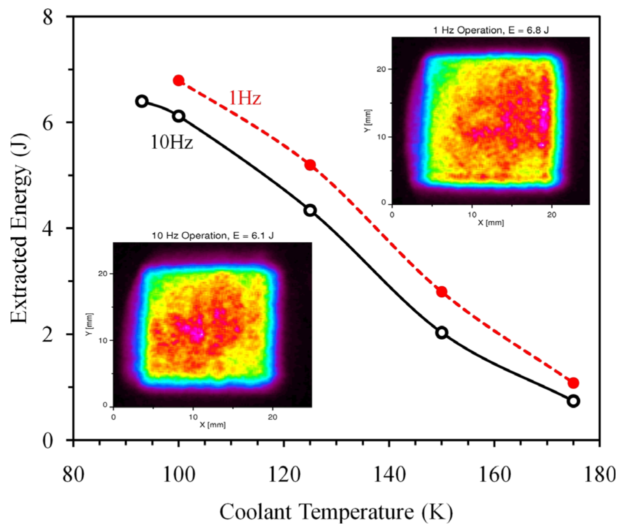

Fig. 6 Extracted energy from the main amplifier at 1 Hz and 10 Hz pulse repetition rates for a 3-pass extraction setup at different temperatures and for fixed pump pulse duration of 1 ms. Inserted are the typical beam profiles for 1 Hz and 10 Hz after the main amplification stage.

et al. [7]. Numerical model predictions with and without the inclusion of ASE losses are also shown in Fig. 3. The performance of the system was modelled as described in [8] along with empirically derived ASE loss values. At temperatures significantly below the design temperature the gain becomes high enough that ASE loss limits the energy stored within the amplifier. This is seen in the curves of Fig. 3 where the extractable energy begins to saturate earlier with increasing pump pulse duration as temperature is reduced.

Figure 4 shows the predicted output energy as a function of the number of extraction passes for a pump duration of 1 ms. Experimental values for extracted energy measured for up to 4 passes, at different temperatures and at 1 Hz repetition rate, are also included in the graph. At 100 K, the maximum energy predicted and observed was clamped at 9.1 J in a 4-pass configuration owing to increased ASE losses. However, at the higher design temperature of 175 K, pulse energy as high as 12 J is expected for 8 passes.

In a separate experiment with the pump pulse duration increased to 1.2 ms, the amplifier delivered 10.1 J at 115 K with a repetition rate of 1 Hz, which corresponds to an optical-to-optical efficiency ($\eta_{\text{o-o}}$) of 21%. Figure 5 shows extracted pulse energy and $\eta_{\text{o-o}}$ as a function of pump energy. Here the amplifier was operated in a 4-pass configuration and the pump energy was varied by changing the pump pulse duration at constant total pump power of 40 kW. The fall in efficiency at pump energies greater than 30 J reflects the onset of ASE at this low operating temperature, limiting the stored energy available for extraction.

Figure 6 compares the output energy from the amplifier at 1 Hz and 10 Hz pulse repetition rates for a 3-pass extraction setup over a range of operating temperatures and for a fixed pump pulse duration of 1 ms. The dependence of extracted energy on coolant temperature is similar for both 10 Hz and 1 Hz operation, with an offset of approximately 8 K. This offset is believed to be caused by an increase in gain medium temperature due to the additional heat load at 10 Hz operation. This can be compensated by reducing the inlet temperature of the coolant, thus restoring performance to a level similar to that at 1 Hz operation. For 10 Hz operation, the highest pulse energy recorded was 6.4 J, in 3-pass configuration, at a coolant temperature of 93 K. This corresponds to an average power of 64 W and an $\eta_{\text{o-o}}$ of 16%. At this operating temperature, approximately 80 K below the design temperature, output energy and efficiency were limited by ASE loss.

To minimise the impact of ASE loss a relay-imaging multi-pass extraction architecture is currently being installed in the laboratory. This uses angular multiplexing to maintain a compact geometry and is capable of supporting up to 9 passes. The addition of extra passes will enable operation at higher coolant temperatures, reducing both gain and ASE loss. Furthermore, relay-imaging after each pass will ensure better overlap between pump and extraction beams is maintained allowing more efficient extraction at high energy.

3. Conclusion

We have demonstrated that the DiPOLE cryogenic gas-cooled amplifier system has already come very close to its target performance of 10 J output energy at 10 Hz repetition rate, which would equate to an average power of 100 W and an $\eta_{\text{o-o}}$ of 25%. Even in its current state, the measured maximum average power of 64 W and corresponding $\eta_{\text{o-o}}$ of 16% compare very favourably to other ongoing high-energy DPSSL projects. The respective values for average power and efficiency are 550 W and 7.6% for Mercury [9], 20 W and 5.7% for LUCIA [10], 213 W and 11.7% for HALNA [11], and 1.2 W and 6% for Polaris [12]. Once the new extraction scheme is in place, we expect to demonstrate $\eta_{\text{o-o}}$ greater than 25% at much higher coolant temperature, which will further improve the overall efficiency of the system.

Given the success of the current DiPOLE prototype amplifier, detailed designs and plans for a scaled-up system delivering 100 J pulses at 10 Hz are near completion. This pump laser system, coupled with advanced Ti:Sapphire amplifier technology similar to that developed on the Astra-Gemini laser [13], opens the way to the development of a multi-Hz, PW-class laser facility at the Central Laser Facility. To further support this goal several theoretical and experimental studies are underway within CALTA. These include the evaluation of large-aperture LBO or highly deuterated KDP crystals for efficient frequency doubling of 100 J-level pulses, development of a fibre based frontend laser with an arbitrary temporal pulse shaping capability, and thermal management and ASE suppression on PW-class Ti:Sapphire amplifiers operating at 10 Hz repetition rate.

The knowledge gained from the current DiPOLE system, and development of a 100 J amplifier, will allow optimisation of the design of a kJ-class laser, which will derisk the technology necessary for development of a subaperture beamlet in a laser driver suitable for fusion energy generation.

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