DiPOLE100 - World's first diode pumped kilowatt average power 100J-level Laser

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Abstract

We report efficient and stable operation of world's first multi-joule DPSSL delivering 1 kW average power in 105 J at 10 Hz, confirming the energy scalability of multi-slab cryogenic gas-cooled amplifier technology. We also report on the commissioning of DiPOLE100 at the HiLASE Centre at Dolní Břežany in the Czech Republic. The laser system, built at the Central Laser Facility (CLF), was dismantled, packaged, shipped and reassembled at HiLASE over a 12-month period by a collaborative team from the CLF and HiLASE.

Introduction

For more than a decade, development of high-energy diode pumped solid state lasers (DPSSLs) has focused on scaling energy and increasing pulse repetition rate to unlock their potential for practical applications. These include new sources for industrial materials processing applications[1] and as pump sources for higher repetition rate PW-class laser[2], which can themselves generate high-brightness secondary radiation and ion sources leading to new remote radiography[3] and medical applications[4].

Over recent years, the DiPOLE team within the Centre for Advanced Laser Technology and Applications (CALTA), part of the Central Laser Facility (CLF), has been developing a 100J-class nanosecond pulsed DPSSL based on scalable cryogenic gas cooled, multi-slab ceramic Yb:YAG amplifier technology[5] capable of operating at 10 Hz repetition rates. This followed on from the successful demonstration of a scaled-down prototype amplifier system that amplified nanosecond duration pulses to energies in excess of 10 J at 10 Hz[6]. Design and build of the first 100J-class system in the UK, DiPOLE100[7], was funded by the HiLASE project[8] in the Czech Republic to demonstrate the potential of high-energy DPSSL technology for industrial applications.

Construction of DiPOLE100 at the CLF began in April 2013 and was completed by October 2015. The potential of the system was confirmed during preliminary testing where 10 ns duration pulses at 1029.5 nm were amplified to over 100 J at 1 Hz[9]. Over the following 12 months, the system was dismantled, packaged, shipped, reassembled, and the system recommissioned at the HiLASE Centre by a collaborative team from the CLF and HiLASE. In this paper we describe the commissioning process for DiPOLE100, and present performance results from the various phases, which culminated in the successful demonstration of the world's first kW average power, high-energy, nanosecond pulsed DPSSL at the end of 2016.

100 J Amplifier Design

Figure 1(a) shows a schematic of the architecture of DiPOLE100, where design details for each amplification stage have been reported previously[9]. A 3D model showing the main system components is given in Figure 1(b). An output energy of 105 J at 10 Hz (1.05 kW average power) was obtained when the final cryo-amplifier (MA2) was seeded with 6 J pulses of 10 ns duration from the cryo pre-amplifier (MA1). This was achieved with a pump energy of 465 J, corresponding to a final-stage optical-to-optical conversion efficiency of 22.5%, as shown in Figure 2(a). Both cryo-amplifiers were operated at a helium gas temperature of 150 K. This is the world's first demonstration of a kW-level HE-DPSSL.

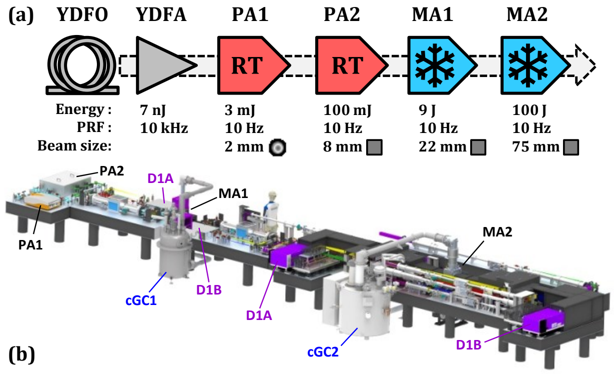

Figure 1: a) Schematic of DiPOLE100 amplifier chain showing typical output performance after each amplifier stage, including free-space beam size and shape: YDFO = Yb-silica fibre oscillator; YDFA = Yb-silica fibre amplifier (inc. temporal pulse shaping); PA = room-temperature pre-amplifier (1=Yb:CaF_2 regenerative, 2=Yb:YAG multi-pass); MA = main cryogenic amplifier (ceramic Yb:YAG multi-slab). (b) 3D model of DiPOLE100 system: D = Diode pumps; cGC = cryogenic gas coolers.

Typical output temporal and far-field profiles measured at maximum energy are shown in Figure 2(b) and (c), respectively. The FWHM angular spread of the central maximum in the far-field image was 28 µrad (x-axis) x 20 µrad (y-axis), corresponding to 2.3 and 1.7 times the diffraction limit for a square top-hat beam, respectively. Further improvement in output beam quality is expected when adaptive wave front correction is fully implemented.

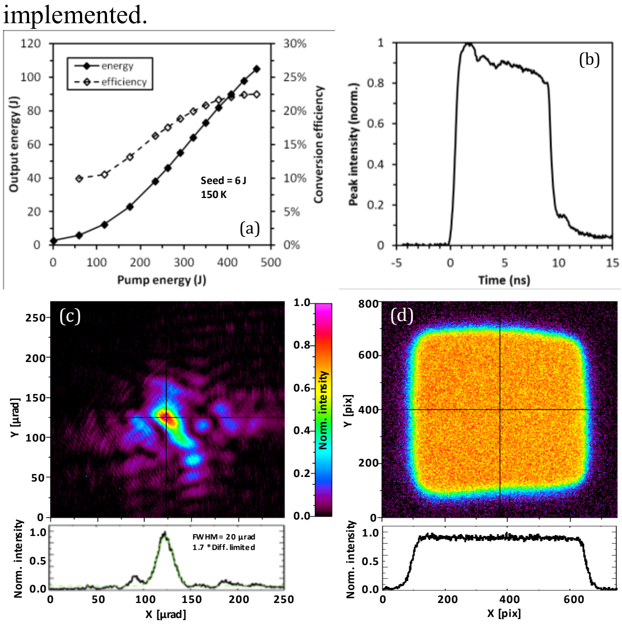

Figure 2: (a) Energy conversion; (b) temporal profile measured with 4 GHz bandwidth limit; (c) far-field intensity image and (d) spatial uniformity profile of output beam with cross-section profiles from DiPOLE100 operating at 10 Hz.

The intensity uniformity of the output (measured away from MA2 amplifier image plane) was confirmed by imaging a portion of the output beam scattered from a ceramic plate. The corresponding spatial profile measured at maximum energy is shown in Fig. 2(d). A total of 4.3 x 10^4 shots at energies in excess of 100 J have been completed over a series of runs, with long term energy stability of 1% RMS recorded over a continuous 1 hour period as seen in Figure 3.

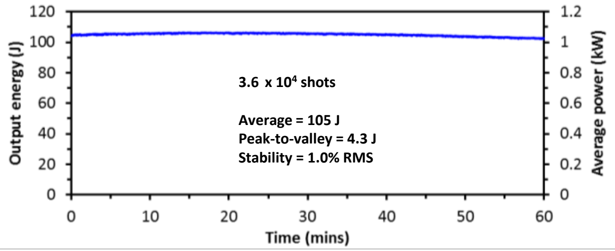

Figure 3: Long term energy stability over 1 hour at 10 Hz.

Disassembly and Delivery to HiLASE

After preliminary testing for 100J at 1Hz[9]was completed at the CLF, DiPOLE100 was dismantled and packaged for shipment to HiLASE. In December 2015, after removal of the pump diode sources, large aperture optics, front end preamplifiers and sensitive optical components, the seven optical tables that make up the DiPOLE100 system (totalling 18 m in length and 2.5 m wide) were dismantled and vacuum-packed ready for shipment. A photograph of one of the dismantled 10 J cryo-preamplifier tables prior to packaging is shown in Figure 4(a). Two heavy goods vehicles (HGVs) and three smaller specialist vehicles were then used to transport the system by road to the HiLASE facility in Dolní Břežany, just outside Prague. Figure 4(b) shows a photograph of one of the HGVs being unloaded at HiLASE. Overall, a total of approximately 20 tonnes of equipment were successfully shipped, including spares.

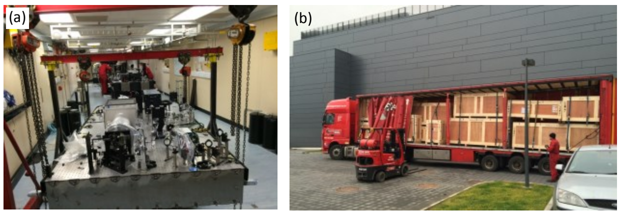

Figure 4: Photographs: (a) disassembly of 10J cryo-preamplifier at the CLF and (b) HGV delivery to the HiLASE Centre.

Rebuild at HiLASE

Over the first six months of 2016 the DiPOLE100 system was rebuilt by a multi-disciplinary team, including: surveyors, electricians, mechanical, vacuum and control system engineers, and laser scientists. Photographs of the HiLASE laboratory before and after re-assembly of the optical tables are shown in Figure 5(a) and (b), respectively. Here the output distribution table; support framework and vacuum piping for the HiLASE 100J beam delivery system; system control and chiller racks; and all the components that remained on the optical tables during transport can be seen.

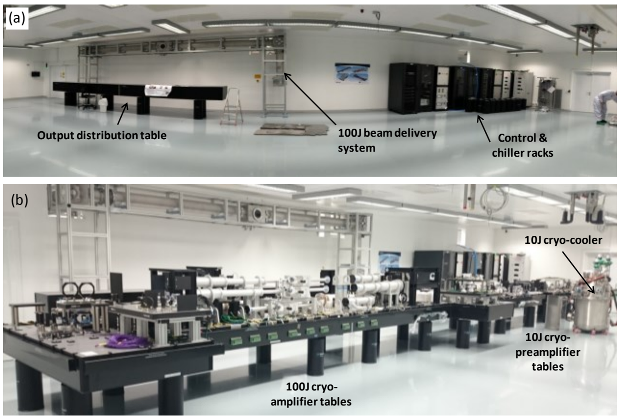

Figure 5: Photographs of the HiLASE laboratory (a) before and (b) after optical table assembly.

After table assembly a purpose-built enclosure was installed that fully surrounds the DiPOLE100 system. Because of space constraints the enclosure was not installed in the UK. The enclosure serves a number of functions, including: user access control, localised environment and cleanliness control, routing for services (electrical, data, gas, vacuum, control etc.), and an integrated support structure for cryogenic transfer lines. A 3D model of the DiPOLE100 enclosure, showing its location within the HiLASE facility, and photograph taken from the 100J cryo-amplifier end of the system are shown in Figure 6 (a) and (b), respectively.

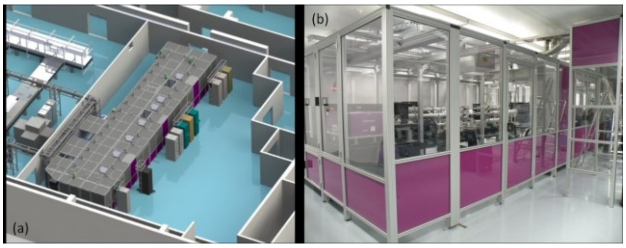

Figure 6: (a) 3D model of DiPOLE100 enclosure and (b) photograph taken from the 100J cryo-amplifier end of system at HiLASE.

After reinstallation of the main system components, removed from the optical tables before shipping, and reconnection of all services the front end was recommissioned. This was completed in May 2016 and the measured performance was similar to that achieved at the CLF[10].

Cryo-Amplifier commissioning at HiLASE

The following sections describe results obtained during commissioning of the 10J and 100J cryo-amplifiers within the DiPOLE100 system at HiLASE.

10 J cryo-amplifier results

Realignment and commissioning of the 10J cryo-preamplifier commenced in June 2016 and was completed within one month. Figure 7 shows photographs of the 10J cryo-amplifier stage prior to disassembly at the CLF and after rebuild at HiLASE. The extruded aluminium support framework and Perspex side panels of the enclosure can clearly been seen in the HiLASE photograph, along with components of the recommissioned front end in the foreground.

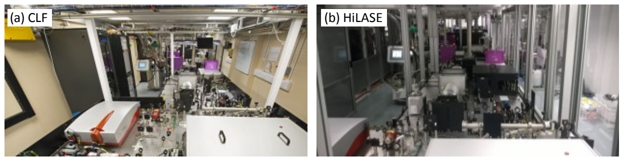

Figure 7: Photographs of 10J cryo-preamplifier stage (a) prior to disassembly at the CLF and (b) after rebuild at HiLASE.

Figure 8(a) compares the output energy and conversion efficiency obtained from the 10J cryo-preamplifier at the CLF and HiLASE, measured at 10 Hz pulse rate under similar cooling conditions (inlet helium temperature 150 K, mass flow rate (MFR) 16 g/s). Performance results taken at the two locations are in very good agreement, confirming the reproducibility of the system and the stability of the design. Short-term energy stability was confirmed at an energy of 7 J over an operating period of 10 minutes, see Figure 8 (b), with a peak-to-valley (PV) and RMS stability of 0.1 J and 0.25%, respectively.

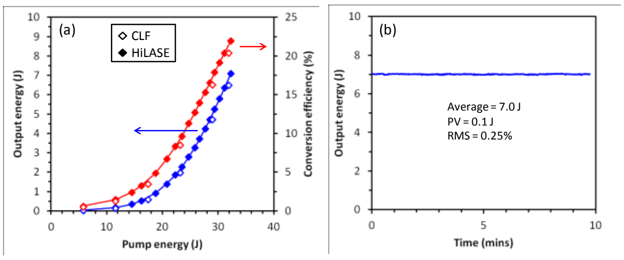

Figure 8: (a) Output energy and conversion efficiency (hollow and solid diamonds represent data measured at the CLF and HiLASE, respectively), and (b) short-term energy stability of the 10J cryo-preamplifier output at 10 Hz.

100 J cryo-amplifier results

Shipment of the 100J cryo-amplifier and its cooling system to HiLASE was delayed in order to correct a mechanical issue at the interface between vacuum-insulated pressurised transfer lines and the amplifier head. This limited the available cooling capacity (MFR of 40 g/s at 2 bar(a) helium pressure) and minimum operating temperature (175 K) of the final cryo-amplifier stage at the CLF, which in turn restricted pre-delivery testing to pulse rates of 1 Hz**Error! Reference source not found.**. A 3D model of the 100J cryo-amplifier head is shown in Figure 9(a), where the interface between the inlet vacuum insulated transfer line and the amplifier head is indicated.

After repair, the system was tested at the CLF before shipping, installation and re-testing at HiLASE, which was completed at the end of October 2016. Figure 9(b) shows the results of helium leak rate (LR) testing of the cryo-amplifier when it was cooled from near-room temperature to its designed operating temperature of 150 K. At 150 K, the helium pressure was increased to approximately 9 bar(a) and the dependence of LR measured at three different MFRs, over a period of approximately 7 hours. Although the plot shows an increase in LR with MFR, it remains stable at less than 5×10^{-8} mbar.l/s for a given MFR. This now provides sufficient cooling capacity to operate safely at the specified system pulse rate of 10 Hz and kW average power level. The temperature stability achieved was within ± 0.1 K of the target temperature, providing the ideal conditions to achieve stable amplification from the final cryo-amplifier.

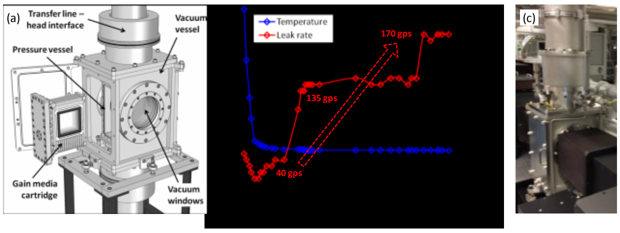

Figure 9: (a) 3D model, (b) helium leak rate dependence on MFR at 150 K, and (c) photograph of installed 100J cryo-amplifier head at HiLASE.

Figure 10 shows photographs of the 100J amplifier stage prior to disassembly at the CLF and after reinstallation at HiLASE, with one of the 100J pump diode units in the foreground (purple box).

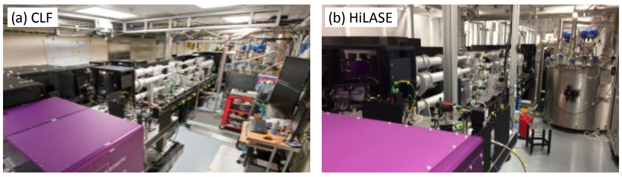

Figure 10: Photographs of 100J cryo-amplifier stage (a) prior to disassembly at the CLF and (b) after rebuild at HiLASE.

A three-stage approach was taken to commission the final cryo-amplifier, which began at the end of November 2016 and took four weeks to complete, finishing on the 16th December 2016. Firstly, the system was tested with both the seed from the cryo-preamplifier and the final cryo-amplifier pumps run at 1 Hz pulse rate, to confirm system alignment and safe operation at the design temperature of 150 K. Figure 11(a) shows the output energy and conversion efficiency obtained for a seed energy of 5 J and 10 ns pulse duration (inlet helium gas temperature of 150 K, pressure 9 bar(a) and MFR of 120 g/s). A conversion efficiency of over 25% was achieved for an output energy of 103 J at 1029.5 nm.

An indication of the output beam size and shape was obtained by taking a burn pattern of a single pulse from the output train at 1 Hz on light sensitive paper placed directly in the beam, after propagating through an OD 1 neutral density filter. A photograph of the burn pattern captured at 103 J is given in Figure 11(b) showing a uniform spatial energy distribution with measured beam size of 77 mm and 75 mm FWHM in x and y axes, respectively. The measured profile shows a super-Gaussian shape with order n_{SG} of 10. The shape and size of the beam are comparable to those recorded at the CLF prior to disassembly and reported previously[9], albeit under different operating conditions, giving confidence that the system was ready for higher pulse rate and average power operation at HiLASE.

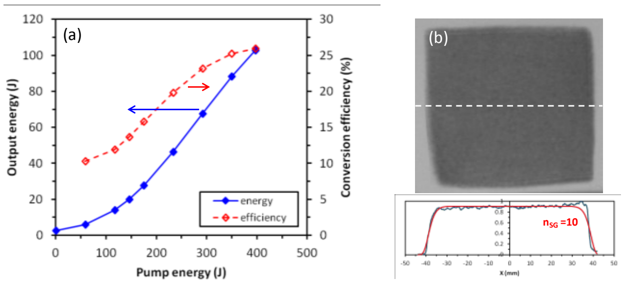

Figure 11: (a) Output energy and conversion efficiency, and (b) burn pattern captured at 103 J with cross-section when final cryo-amplifier operated at 1 Hz at HiLASE.

The second stage of commissioning involved optimising alignment and pumping conditions for operation at 10 Hz. Here input lens positions for the relay-imaging telescopes on each pass were adjusted to compensate for thermally induced defocus in the amplifier, and to optimise the shape of the deformable mirror (positioned on pass 1) to minimise the remaining aberrations in the output beam. This was done with the amplifier seeded at 1 Hz, but pumped at 10 Hz at an appropriate power level (75% of available pump energy and a pulse duration of 800 µs). This was chosen to replicate the expected thermal load in the amplifier, taking into account predicted energy extraction when operating at a 100 J-level. The amplifier was operated at an inlet helium gas temperature of 150 K, pressure of 9 bar(a) and an increased MFR of 180 g/s.

For the final stage of commissioning at 10 Hz the system was operated remotely from the HiLASE control room. The seed energy was increased to 6 J and the output energy was ramped up gradually to 100 J to anneal optical components until the design operating power level of 1 kW was achieved. Figure 12(a) shows performance data from the first operating run over 5 minutes at 105 J, 10 Hz clearly showing the energy ramping process. This output energy was achieved at a pump energy of 465 J and operating temperature of 150 K, corresponding to an optical-to-optical conversion efficiency of 22.5%, as seen in Figure 12(b).

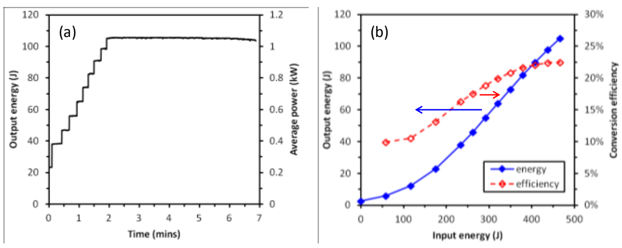

Figure 12: (a) Output energy ramp to 105 J and (b) energy and conversion efficiency when final cryo-amplifier operated to 1 kW average power level at 10 Hz at HiLASE.

Since the initial performance demonstration, DiPOLE100 has been operated for a combined total of over 2.5 hrs corresponding to almost 100,000 shots at energies in excess of 100 J at 10 Hz, as shown in Figure 11. The longest single run lasted 1 hour with an average output energy of 105 J and RMS energy stability of approximately 1% recorded over 36,000 shots. An indication of the long-term energy stability of the system is given in the inset of Figure 13 where the output energy over a 30 minute period (18,000 shots) is shown.

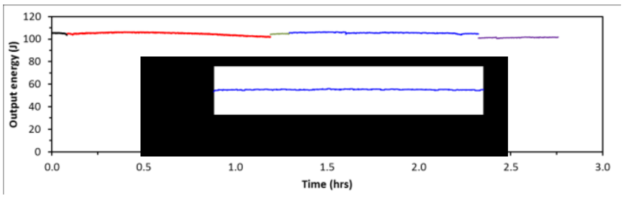

Figure 13: Record of DiPOLE100 operation at energies over 100 J at 10 Hz. Inset shows long-term energy stability over 30 minute period (18,000 shots).

Figure 14 (a) shows an output beam profile measured on a diagnostic camera at 102 J and 10 Hz along with a horizontal cross-section taken through the centre of the beam. The red curve is a 10th order super-Gaussian fit to the cross-section data. The circular shaped fringes are artefacts caused by diffraction within the diagnostic channel. An image of the focal spot of the beam captured at maximum output energy is shown in Figure 14(b). The FWHM angular spread of the central maximum was 19 µrad (x-axis) and 20 µrad (y-axis), corresponding to 1.5 and 1.6 times the diffraction limit for a square super-Gaussian beam, respectively. The shape of the deformable mirror was not changed from that determined during 1 Hz seed tests so optimisation may yield further improvement in beam quality.

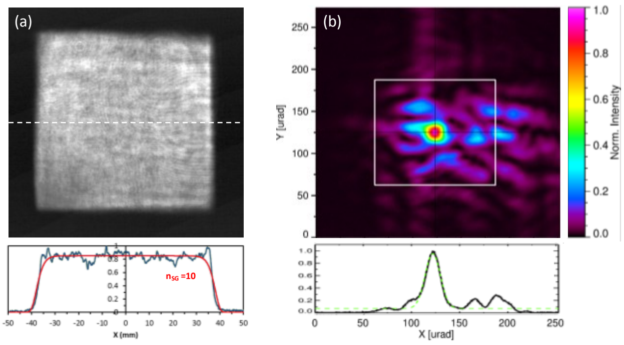

Figure 14: (a) Near-field and (b) far-field profiles of DiPOLE100 output beam measured at 102 J and 10 Hz.

Summary

After shipment from the CLF, the DiPOLE100 laser system was rebuilt and recommissioned at the HiLASE Centre over a 12-month period by a collaborative team from the CLF and HiLASE. This involved 17 separate visits to HiLASE by 15 team members from the CLF (a total of ~140 working days). The laser has been operated at its design specification of 100 J and 10 Hz and is the world's first kW average power, high-energy, nanosecond pulsed DPSSL, confirming the power scalability of DiPOLE multi-slab cryogenic gas-cooled amplifier technology. DiPOLE100 is now operational at HiLASE facility where it is being used to drive applications in advanced materials processing, laser shock treatment of high value mechanical components, and laser induced damage testing.

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