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# Extreme Photonics Applications Centre: High Energy DPSSL Pump for a 10 Hz PW-level Laser

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## ABSTRACT

The Extreme Photonics Applications Centre is an upcoming state-of-the-art research facility under construction at the Rutherford Appleton Laboratory in the United Kingdom. It will deliver petawatt pulses at an unprecedented rate of 10 Hz, made possible by pumping titanium-doped sapphire gain medium with a diode-pumped solid state laser (DPSSL) based on the Central Laser Facility's cryogenic DiPOLE technology. We will briefly present the DPSSL pump design and its incorporation into the wider PW system, reporting on the most up-to-date commissioning status and results of the DPSSL pump laser, which is on target to be fully commissioned by summer 2023.

**Keywords:** DPSSL, multi-slab amplifier, high energy, high average power

## 1. INTRODUCTION

The Central Laser Facility (CLF) is currently constructing the Extreme Photonics Applications Centre (EPAC): an upcoming state-of-the-art research facility for academia and industry. The petawatt-level facility utilises a diode-pumped solid state laser (DPSSL) as the pump for its main amplifier. The DPSSL pump is capable of delivering 120 J per pulse with a 10 Hz repetition rate. However, the pump output has a wavelength of 1030 nm and must be converted to 515 nm, as the main amplifier is a titanium-doped sapphire (Ti:Sa) laser. This will allow it to deliver 30 fs pulses of 30 J at an unprecedented repetition rate of 10 Hz to radiologically shielded experimental areas.

## 2. THE PUMP LASER DESIGN

The pump laser comprises of three major sections: a front-end (FE), a 10 J-class amplifier and a 100 J-class amplifier, as can be seen in figure 1. The amplifier design is based on the DiPOLE architecture,[1] utilising Ytterbium-doped Yttrium Aluminium Garnet (Yb:YAG) gain media slabs. The slabs are contained within an amplifier head, using gas at cryogenic temperatures to cool the slabs, enabling the amplifier to operate at 10 Hz. All of the sections and components within the DPSSL are synchronised using signals from a single delay generator to select a repetition rate up to 10 Hz. The 1030 nm output of the DPSSL system will be converted using second harmonic generation with an efficiency of approximately 70%[2] to frequency double to 515 nm for the main amplifier in a subsequent section of the system not described here.

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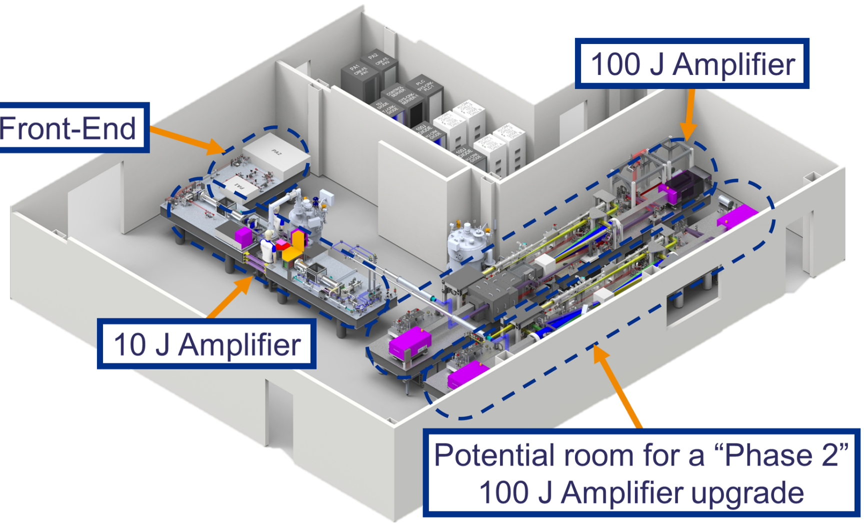



Figure 1. The layout of the DPSSL pump laser for EPAC's main PW amplifier, outlining the major sections.

### 2.1 The Front-End

The front end begins with a fibre seed source (Modbox, iXblue), which uses an acousto-optic modulator to convert the CW seed into 100 ns pulses. These are then shaped temporally into the desired pulse shape using an electro-optic modulator that is controlled by a signal from the device's arbitrary waveform generator. This will be used to define the pulse length and pre-compensate for changes in pulse shape due to amplification in the laser's amplifiers. The target output pulse is a 15 ns square pulse.

The fibre seed source outputs energy of 10 nJ per pulse, which is coupled directly into the first pre-amplifier (PA1), a customised Magma 5 regenerative amplifier provided by Amplitude, capable of amplifying pulses of length from 1 ns to 15 ns. PA1 is designed to amplify pulses to 3.5 mJ, with a Gaussian beam profile of 2 mm $1/e^2$ diameter. After PA1 the beam is propagated through a beam expander (Jenoptik) and $\pi$-shaper (AdlOptica), which results in a 6 mm diameter circular super-Gaussian beam that is propagated into the second pre-amplifier (PA2, Lastronics).

PA2 is a custom-made multi-pass booster amplifier that amplifies the pulses up to 150 mJ energy. As a result of the square beam shape of the pump laser within PA2, only a square section of the beam profile is amplified, which pre-shapes the beam to an 8 mm x 8 mm square. After PA2 a Pockels cell has been deployed to allow operating the system at a lower repetition rate than 10 Hz, as well as cleaning up any pre- or post-pulses that might appear. The beam is then expanded to 22 mm by 22 mm and imaged onto a square serrated aperture – the pre-shaping of the beam inside PA2 therefore reduces losses at the aperture. As the beam propagates to the 10 J amplification stage, it is then spatially filtered using a pinhole at the centre of a vacuum spatial filter (VSF).

### 2.2 The 10 J Amplifier

The 10J amplifier is a multipass system with an amplifier head connected to a cryostat at the centre, a scheme which is based on the CLF DiPOLE architecture. The square super-gaussian pulses from the FE are relay imaged onto the centre of the 10 J amplifier head through VSF's. The scheme is shown in figure 2. Four Yb:YAG ceramic gain media slabs (Crystal Laser/Baikowski) with varied $Yb^{3+}$ concentrations are pumped simultaneously from both sides with 30 kW pump diodes (Leonardo) at 939.5 nm centre wavelength. The slabs are held in an amplifier head with pressurised helium gas flowing along the faces of the slabs. The helium gas is cooled to 120 K using liquid nitrogen.

The beam passes through the amplifier seven times. Each pass through the amplifier is image relayed onto the centre of the amplifier head using 4F telescopes with a VSF to remove high spatial frequencies and keep

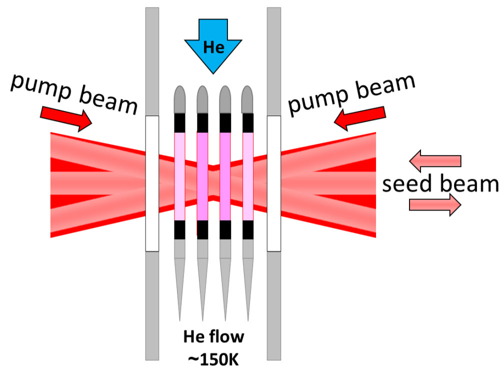



Figure 2. A diagram showing the basic principle of operation of the DiPOLE architecture. Yb:YAG gain media slabs are held in vanes inside the amplifier head. Cryogenically-cooled helium gas flows between the vanes, cooling the gain media to a temperature of approximately 150K. The slabs are pumped from both sides with 940 nm lasers, which overlap entirely with several passes of the seed beam through the gain media.

a smooth beam profile. On the third pass, there is an in-house adaptive optic (AO) mirror that corrects any wavefront distortions; the wavefront sensor associated with the AO is placed in a diagnostic line after the final pass of the 10 J amplifier. The critical components inside the amplifier head are monitored in situ using a dark field diagnostic line, which is used to detect damage early and prevent it propagating through the system.

At the output of the 10 J amplifier stage, the amplified beam can contain up to 14 J of energy in a 22 mm square beam. During normal operations, the amplifier will only need to deliver 7 J to seed a single 100 J amplifier. However, there is also scope to add a second 100 J amplifier to increase available pump energy to the Ti:Sa system. Therefore the beam transport between the 10 J and 100 J has the capability to control the proportion of the beam transferred to seed each 100 J arm.

### 2.3 The 100 J Amplifier

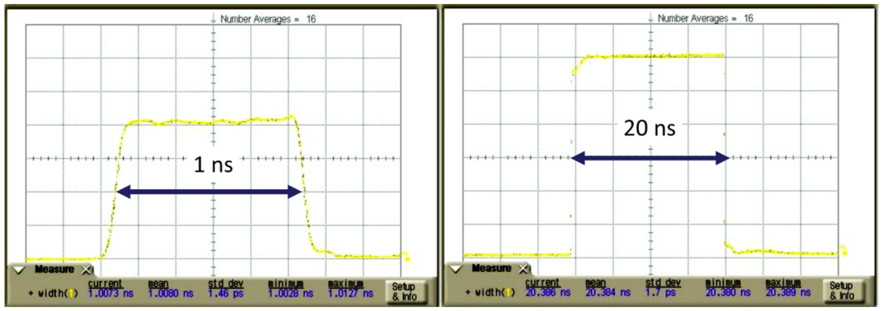
The 100 J amplifier operates on a similar principle to the 10 J amplifier. The amplifier head contains six Yb:YAG slabs (Baikowski) kept at 150 K using the same principle as the 10 J amplifier head. The slabs will be pumped from both sides by 350 kW diode lasers (Lastronics/Coherent). The beam in this amplifier is larger, a 75 mm square and the seed beam will only pass through the amplifier head four times. The beam is image relayed on each pass using VSFs in the same manner as it was in the 10 J amplifier system. There is an AO mirror (Imagine Optic) deployed within this amplifier on the first pass with the associated wavefront sensor again deployed at the output of the amplifier to enable pre-compensation of any wavefront distortions through the amplifier.

The output from the 100 J amplifier is delivered into the next room, which houses the Ti:Sa amplifier, where the pump beam will be frequency doubled to a wavelength of 515 nm, to match the absorption line of the Ti:Sa gain medium.

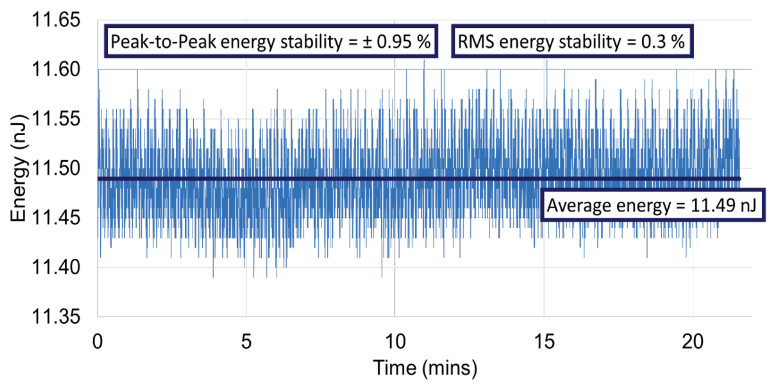
## 3. CURRENT STATUS

The EPAC pump laser is currently under construction at STFC's Rutherford Appleton Laboratory in the United Kingdom. The building was completed in April 2022 and installation of equipment has begun.

The FE system described in section 2.1 was pre-built and commissioned in a temporary location, but has now been moved to its final location and is currently being recommissioned. Figure 3 shows the temporal pulse shaping capabilities and energy output of the fibre seed source. The temporal traces show square pulses of 1 ns and 20 ns length but the fibre seed source can output any arbitrary shape up to a length of 100 ns with a step size of 125 ps. For a 10 ns square pulse, the average energy output is 11.5 nJ with a root mean square (RMS) and peak-to-peak (PtP) stability of 0.3% and ±0.95% respectively, measured over 20 minutes. PA1 is capable of amplifying this to energies above the required 3.5 mJ and outputs a Gaussian beam profile with a $1/e^2$ radius

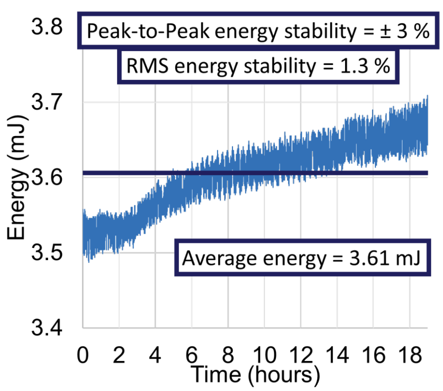



(a)

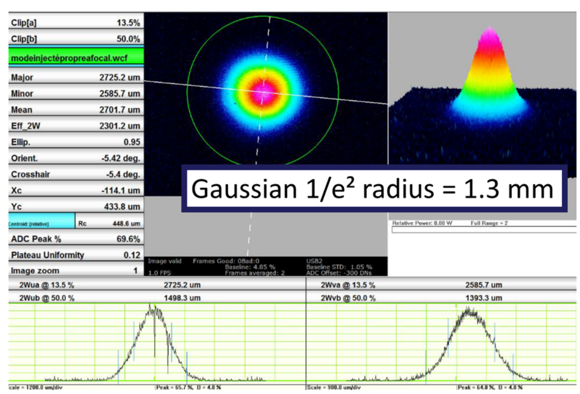



(b)

Figure 3. The the temporal pulse shaping capabilities (a) and energy output for a 10 ns square pulse (b) of the fibre seed source (iXblue).




(a)




(b)

Figure 4. The pulse energy (a) and the beam profile (b) of the output from the first pre-amplifier (Amplitude) for 10 ns square pulses.

of 1.3 mm (figure 4). The energy demonstrates a drift on the order of hours (which is suspected to be due to temperature changes in the lab), but this variation remains within ±3% PtP and the RMS stability at 1.3%.

Figure 5 shows the energy output from PA2 during an 8 hour operation overnight. The amplifier can comfortably reach 100 mJ of energy, without using its maximum pump power and with an input energy of approximately 2 mJ. The energy drop overnight was caused by a drift in pointing of the seed beam, as the energy increased back up to 100 mJ with a slight adjustment in alignment. This issue will be mitigated with an automated beam-steering system that will be installed at the input to PA2 prior to final commissioning.

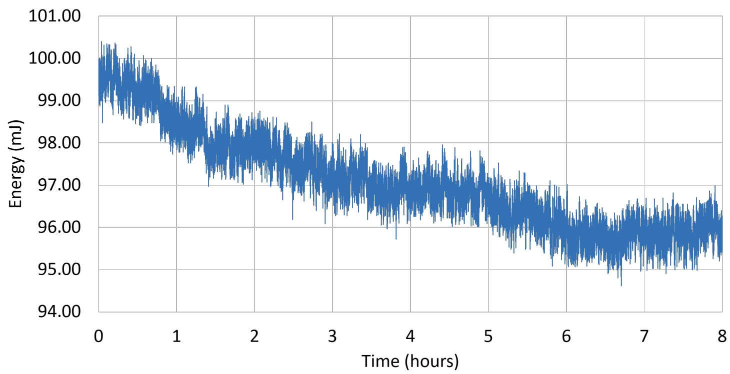
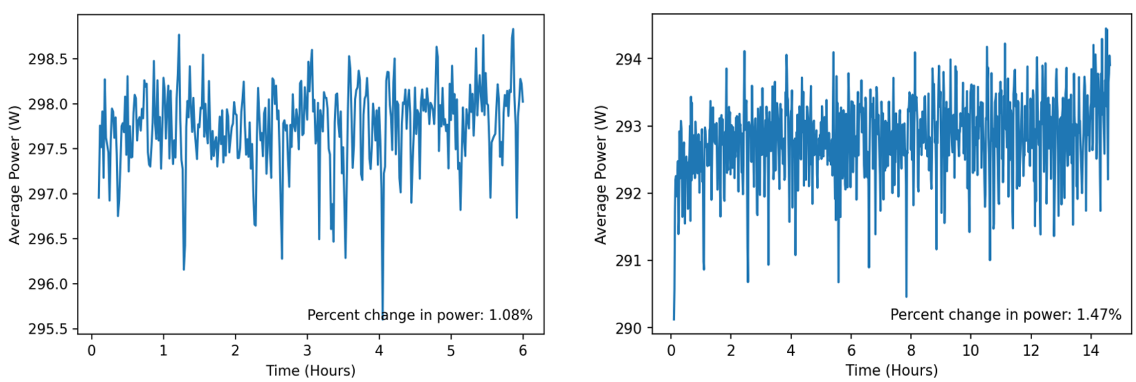



Figure 5. The long term pulse energy output from the second pre-amplifier (Lastronics) for an input energy of approximately 2 mJ.

The 10 J pump diodes have been installed and commissioned. Figure 6 shows the power output of the 10 J pump diodes for 1 ms pulses at a 10 Hz repetition rate. Both operate at over 29 kW peak power (290 W average power), with PtP stabilities of 0.73% (Pump A) and 1.47% (Pump B).




(a) (b)

Figure 6. The long term average power output for both 10 J pump diodes (Leonardo).

The majority of mechanical and opto-mechanical components for all pump laser sections have been installed and the laser is due to be fully commissioned by summer 2023.

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