

# Current status of the DiPOLE project

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## Introduction

DiPOLE stands for Diode Pumped Optical Laser Experiment. It is a project at the CLF to develop the foundations of novel high energy, high average power laser systems based on diode pumped solid state laser (DPSSL) technology. Compared to conventional systems, this approach promises dramatically increased repetition rates (and hence average powers) at significantly higher electrical-to-optical conversion efficiency. DiPOLE has been included as an emerging opportunity in the Research Councils UK Large Facilities Roadmap [1].

Laser amplifiers capable of producing energetic ns-pulses are one of the main tools for laser plasma research and high-energy applications. Laser chains containing such amplifiers can produce ns-pulses or ps-pulses if the chirped pulse amplification (CPA) technique is used. Depending on the application, these pulses are either applied directly or are used to pump other amplifiers (e.g. Ti:Sapphire or OPCPA) in order to obtain even shorter pulses in the fs-regime. Currently, ns-amplifiers are based on flashlamp-pumped Nd:glass technology and their repetition rate is limited to a few shots per minute for amplifiers delivering tens of joules of pulse energy to a few shots per day for lasers delivering kJ-level pulse energies. Increasing the repetition rate of such laser systems to the multi-Hz level (typically 10 Hz) is pivotal for the following applications:

- Opening up new horizons in fundamental laser plasma interaction research by enabling higher throughput and the exploration of larger parameter spaces.
- So-called secondary sources which use laser-generated plasmas to produce ultra-short pulses of energetic particles (electrons or ions) or electromagnetic radiation (ranging from THz to hard X-ray). High repetition rate drive lasers are required to generate sufficiently high particle and photon numbers. Much of the pan-European ELI project focuses on the development and exploitation of secondary sources [2].
- Inertial confinement fusion (ICF), which is expected to be demonstrated for the first time within the next two years. Whereas current low-repetition rate facilities like NIF and LMJ are suitable for proof of principle experiments, high-efficiency, high repetition rate DPSSL based laser drivers open up the possibility to develop ICF into a reasonably clean, practically inexhaustible source of energy. This is the focus of the pan-European HiPER project [3].

## Amplifier concept

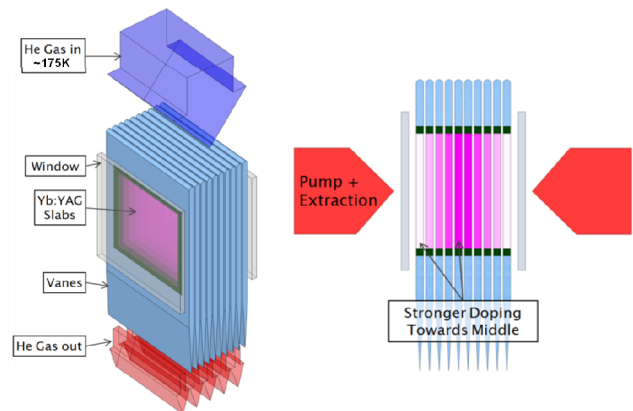
The main activity within DiPOLE is the development of a DPSSL amplifier concept that is capable of delivering kJ-level pulses at 10 Hz repetition rate. The amplifier design chosen is based on a gas-cooled multi-slab concept. This architecture was first demonstrated in the Mercury system [4] and consists of multiple thin slabs of gain medium each separated by a small gap and arranged sequentially in a stack formation. Each slab is face cooled from both sides by a transverse stream of gas and, in our case, this gas is cooled to cryogenic temperatures. The high surface area of the slab faces ensures efficient heat removal and the low overall aspect ratio ensures ASE loss is

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kept to a minimum. A  $\text{Cr}^{4+}$  absorptive cladding around the edge of each slab is also included to further suppress ASE and prevent unwanted parasitic oscillations. Furthermore, because the aspect ratio of the gain medium can be chosen freely without compromising cooling, this concept represents a flexible architecture that can easily be scaled for lower (10s J) or higher (up to kJ) energy output from a single (or several) amplifier head(s).

The basic structure of a cryogenic gas-cooled ceramic Yb:YAG slab amplifier is shown in Fig. 1. Cold helium gas is forced through the gaps between the slabs for cooling and the amplifier is end or face-pumped from both sides. The Yb-doping level in the slabs is increased towards the centre of the amplifier to ensure a uniform heat load in each slab. The stepped doping profile has the additional benefit of reducing the overall thickness of the amplifier for a given maximum gain coefficient. The reduction in amplifier thickness is particularly important for high intensity applications, especially when using YAG (as it has a high nonlinear refractive index), to ensure the overall B-integral for the system is kept at a manageable level, minimising the impact of nonlinear effects.



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

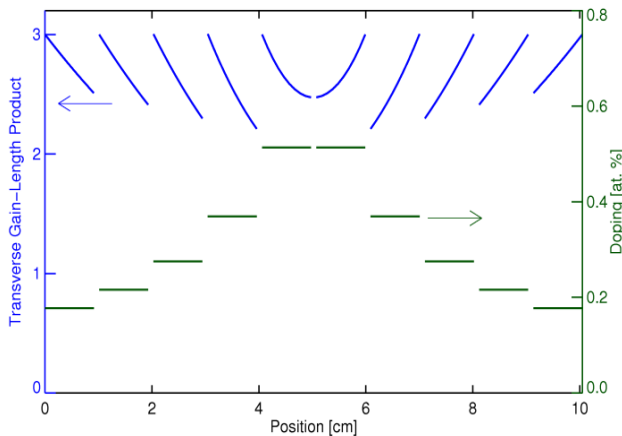
## Baseline Amplifier design

The details for a baseline cryogenic gas-cooled Yb:YAG amplifier design capable of handling kJ-class pulses have been presented previously [5] and are summarised in Table 1. These have been calculated based on performance predictions from a 1D numerical model including spectral dependence of pump absorption and taking into account appropriate pump parameters (fluence, pulse duration, spectral width etc.) and assume an operating temperature of 175 K. The design is based on a target output fluence of  $5 \text{ J/cm}^2$  at 1030 nm, which represents a safe operating level for generating nanosecond pulses in YAG. To handle 1 kJ output pulses the amplifier aperture then needs to be  $200 \text{ cm}^2$  ( $14 \text{ cm} \times 14 \text{ cm}$ ) assuming a square aperture beam is used. The baseline modelling predicts a pump storage efficiency (pump energy / extractable energy) of 50% and a small signal gain of 3.8.

Target output fluence	5 J/cm <sup>2</sup>
Aperture	14 cm x 14 cm
No. of slabs	10 (5 doping levels)
Slab thickness	10 mm
Total pump intensity	10 kW/cm <sup>2</sup>
Pump duration	1 ms
Pump wavelength	939 nm
Laser wavelength	1030 nm
Temperature	175 K
Saturation fluence	3.7 J/cm <sup>2</sup>
Storage efficiency	50% (5 J/cm <sup>2</sup> stored)
Small signal gain	3.8

**Table 1:** Baseline parameters for a 1 kJ amplifier.

The baseline amplifier design consists of 10 slabs with five different doping levels. The doping levels have been calculated to ensure that the product of the small signal gain coefficient ( $g_0$ ) and the diagonal transverse dimension of the square slabs ( $D$ ) is always less than or equal to 3. This criterion has been chosen to ensure that the impact of ASE loss in the amplifier is kept to a minimum [6]. Model predictions also indicate there is an optimum optical depth (product of Yb doping concentration and gain medium thickness) of 3.3 % cm that maximises energy storage potential. The calculated doping levels for each slab and variation of the transverse gain-length ( $g_0D$ ) product through the amplifier are shown in Fig. 2.



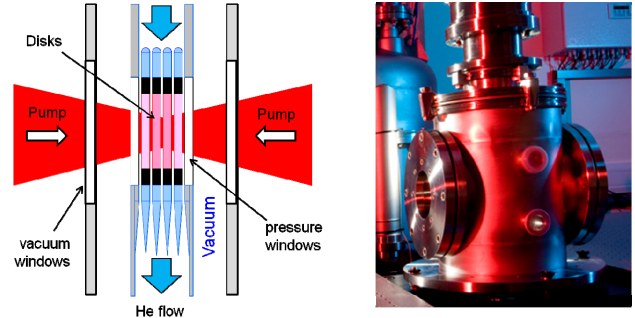
**Fig. 2:** Optimum doping profile where  $g_0D \leq 3$ .

### DiPOLE Prototype Amplifier

To test the proposed cryogenic gas-cooled multi-slab amplifier concept in the laboratory, a lower-energy prototype system, DiPOLE, is under development at the CLF [7]. This is a scaled down version of the 1 kJ design, sized to deliver 10 J at 10 Hz, which will provide a test bed for the technology. The main aims of the DiPOLE project are to validate and calibrate model predictions, quantify ASE losses, test cryogenic gas-cooling technology, test Yb:YAG ceramics and other potential gain media, and, most importantly, demonstrate the viability of the concept for efficient and cost effective generation of high-energy nanosecond pulses suitable for IFE applications. A summary of the status of the various sub-systems that make up the DiPOLE amplifier system is given in the following sections.

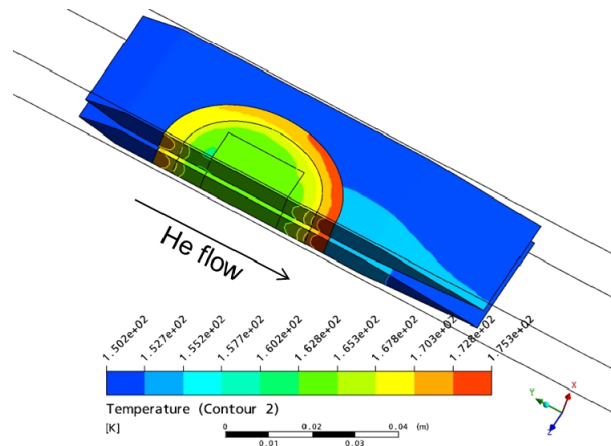
### Amplifier head design

The amplifier head design is based on four co-sintered ceramic YAG discs (55 mm in diameter x 5 mm thick) where the Yb-doped region (35 mm diameter) is surrounded by a 10 mm thick Cr<sup>4+</sup> cladding to absorb unwanted transverse fluorescence. Given the 2 cm total gain medium thickness, two different Yb doping levels of 1.1 and 2.0 atomic% have been chosen to maximise storage efficiency and to equalise heat loading. The discs are mounted in aerodynamic vanes within a vacuum insulated pressure vessel through which cryogenically cooled He gas is flown at  $\sim 25$  ms<sup>-1</sup>. The amplifier is end-pumped from both sides through vacuum and pressure windows by two diode laser systems operating near 940 nm. A schematic and photograph of the amplifier head is shown in Fig. 3.



**Fig. 3:** Schematic and photograph of prototype amplifier head.

The predicted temperature distribution for a DiPOLE amplifier disk is shown in Fig. 4. This indicates that a uniform temperature distribution should be achievable over the square pumped region with a small temperature gradient of only  $\sim 3$  K.



**Fig. 4:** Predicted temperature distribution for DiPOLE amplifier (half) disks.

### Ceramic Yb:YAG disks

The ceramic Yb:YAG disks for DiPOLE were produced by Konoshima [8] in Japan and a photograph of one of these is shown in Fig. 5, clearly showing the Yb and Cr-doped regions. The optical quality of the polished ceramic disks has also been assessed in a Zygo interferometer with transmitted wavefront errors (TWE) of less than  $\lambda/8$  measured at 633 nm. A sample interferogram of a ceramic disk with a measured peak-to-valley TWE of 0.12 waves at 633 nm is shown in Fig. 6. The measured spectral transmission at room temperature of the Yb and Cr-doped regions is compared in Fig. 7.

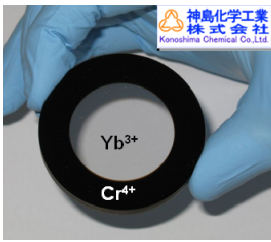


Fig. 5: Ceramic Yb:YAG.

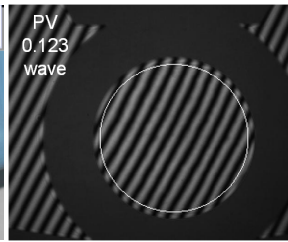


Fig. 6: Interferogram of ceramic Yb:YAG.

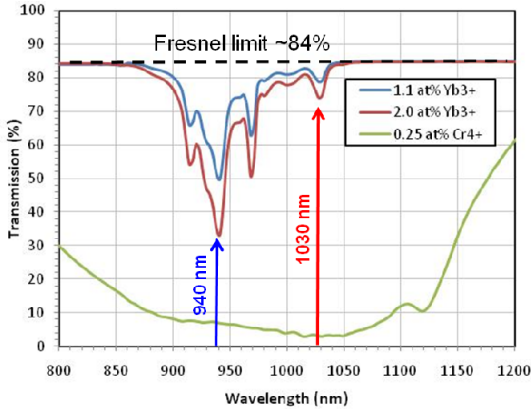


Fig. 7: Transmission spectra of Yb and Cr doped regions of uncoated ceramic YAG disks.

These transmission spectra clearly show the increase in 940 nm pump absorption with Yb-doping level and the presence of room temperature re-absorption loss at 1030 nm, which illustrates the benefit of actively cooling the disks to achieve efficient operation. The transmission spectra for the Cr-doped region confirms this should act as an effective absorptive cladding in the near-infrared to minimise ASE.

### Cryogenic gas-cooling system

A schematic of the cryogenic gas-cooling system developed for DiPOLE is shown in Fig. 8. The system consists of a cryostat, containing a liquid nitrogen heat exchanger to cool the helium gas, a circulating fan and a pair of vacuum insulated cryogenic transfer lines to transport the cooled gas to and from the amplifier head. The system operates at helium pressures up to 20 bar with volume flow rates up to 50 m<sup>3</sup>/hr and stable operation has been tested to below 100 K. The cooling rate can be controlled to minimise thermal shock stresses on the amplifier disks. A screen shot of the monitoring and control interface for the cryogenic cooling system is shown in Fig. 9.

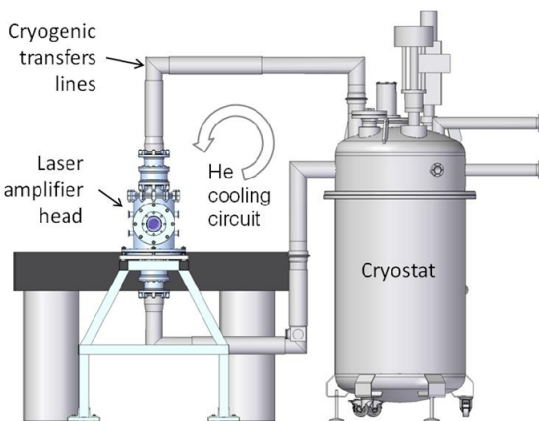


Fig. 8: Schematic of DiPOLE cryogenic gas-cooling system.

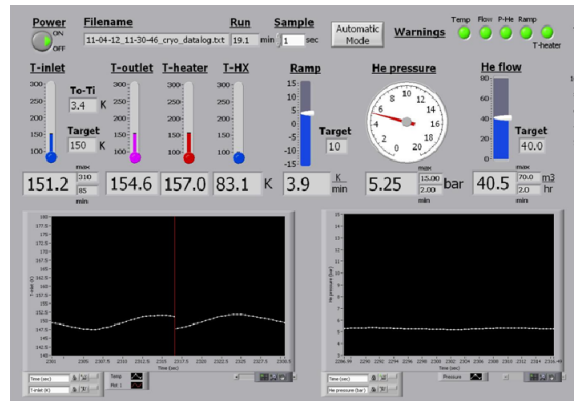


Fig. 9: Control and monitoring interface for cooling system.

### Diode pump laser

DiPOLE has two diode pump lasers each delivering 20 kW peak power in pulses of between 0.2 and 1.2 ms duration in a uniform square beam (2 x 2 cm<sup>2</sup>), with a corresponding pump intensity of 5 kW/cm<sup>2</sup> and at a repetition rate of between 0.1 and 10 Hz. The uniformity of the pump intensity distribution is shown in Fig. 10 and the steep well defined edges can be seen in both vertical and horizontal intensity profiles.

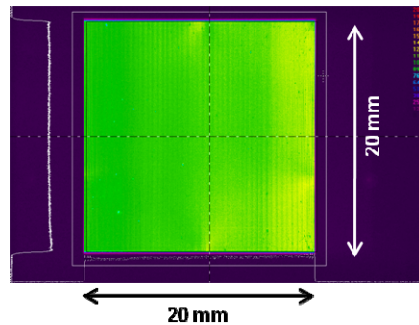


Fig. 10: Measured pump intensity distribution.

The centre wavelength of the sources was specified to be 939 nm with ~80% of the measured energy contained within  $\pm 3$  nm of this wavelength. The wavelength of the diode modules within each source can be tuned by appropriate control of their temperature and individual bias current. A measured output spectrum from the diode source is shown in Fig. 11, along with the absorption cross-section spectrum of Yb:YAG at 175 K reported by Brown et al 9. The good match between the two spectra should ensure efficient pump absorption.

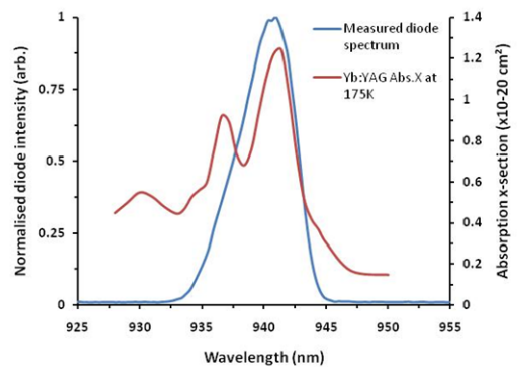
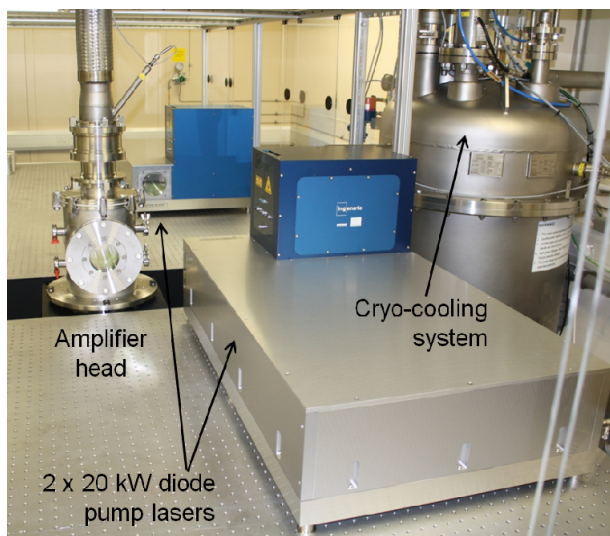


Fig. 3: Comparison of pump output spectrum and reported Yb:YAG absorption cross-section at 175 K 9.

Pump radiation from both sources is coupled into the amplifier head by means of a pair of dichroic mirrors designed for high reflectivity of pump light at 940 nm (s-polarised) and high transmission of the 1030 nm beam (p-polarised) to be amplified. An angular offset is introduced between the two pump beams to

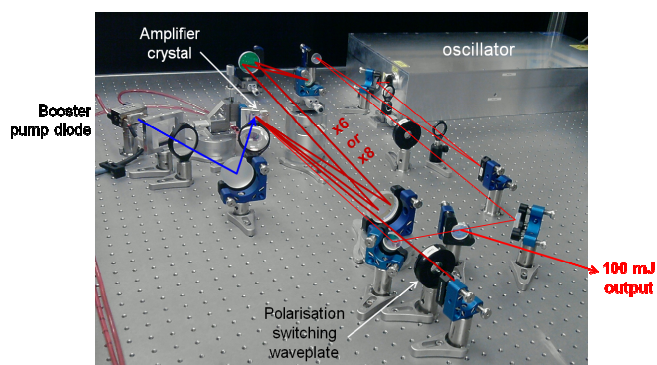
prevent re-injection into the opposing source. A photograph showing the two pump lasers, the cryogenic cooling system and the amplifier head installed in the DiPOLE laboratory is given in Fig. 12.



**Fig. 12:** Photograph of DiPOLE laboratory.

### Front-end

The front-end seed source for the DiPOLE amplifier is based on a master oscillator power amplifier (MOPA) design and has been built by Siebold et al at HZDR, Dresden, Germany [10]. The free-space oscillator is a diode-pumped cavity-dumped Yb:glass laser providing narrow linewidth  $\sim 0.2$  nm pulses tunable between 1020 and 1040 nm. The temporal pulse shape is fixed with duration between 5 and 10 ns and the system is optimised to deliver  $\sim 300$   $\mu$ J pulses at a repetition rate up to 10 Hz. The oscillator output is then amplified in a separate diode-pumped multi-pass Yb:YAG booster amplifier using an active mirror configuration. This has demonstrated over 100 mJ output energy at repetition rates up to 10 Hz. A photograph showing the oscillator and booster amplifier layout is shown in Fig. 13. The oscillator beam is coupled into the amplifier through a polariser and the relay-imaging multi-pass is configured for either 6 or 8 passes. On exit the polarisation of the amplified beam is rotated by 90 degrees before being returned for a further 6 or 8 passes and finally being coupled out from the initial polariser.



**Fig. 13:** Photograph of front-end oscillator and booster layout.

### Conclusions

In summary, we have presented a conceptual design for a cryogenic Yb:YAG amplifier that can be scaled to kJ energy levels and beyond, owing to its geometry and unique cooling technique. Considerable enhancement in optical-to-optical conversion efficiency is predicted with the reduction of pump fluence at cryogenic temperatures owing to a reduction in reabsorption loss, increased pump adsorption and higher gain cross sections. A prototype, scaled-down version of the amplifier, DiPOLE, is currently under development at the CLF to confirm the viability of this approach. To date the main system components (amplifier head, cooling system, pump lasers and front-end source) have been designed, built and commissioned in the DiPOLE laboratory, and the design of the multi-pass extraction architecture is currently being finalised. It is anticipated that high energy operation should be demonstrated by the end of 2011.

### References

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