# Concept for Cryogenic kJ-Class Yb:YAG Amplifier

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**Abstract:** More and more projects and applications require the development of ns, kJ-class DPSSL systems with multi-Hz repetition rate. We present an amplifier concept based on cryogenically cooled Yb:YAG, promising high optical-to-optical efficiency and high gain.

**OCIS codes:** (140.3280) Laser amplifiers; (140.3480) Lasers, diode-pumped, (140.3615) Lasers, ytterbium, (140.5560) Pumping

## 1. Introduction

Currently, most lasers for producing multi-J to multi-kJ ns pulses are based on flashlamp pumped Nd:glass technology. These lasers show very poor electrical-to-optical (e-o) efficiency and can only be operated at very low repetition rates (few shots per minute to few shots per day, depending on size). A new approach is required to overcome these limitations in order to advance fundamental laser-plasma research and to enable envisioned real world applications such as laser driven particle accelerators and inertial fusion energy (IFE) production.

Two multi-national laser research projects have been started in Europe. The first is ELI [1], focussed on ultra-short pulse laser research and applications, and the second is HiPER [2], focussed on IFE research. Both projects require the development of kJ-class ns-lasers operating at high e-o efficiency and at repetition rates around 10 Hz. Several concepts for high-energy laser amplifiers have been proposed by the partners participating in these projects. All concepts are based on Yb-doped, laser diode pumped gain media as it is thought that only this approach can deliver the required performance at an affordable price. The amplifier concept that has been developed at the Central Laser Facility will be described in the following sections. The motivation for the choices made and initial numerical modelling results will be presented.

## 2. Choice of gain medium

The gain material of the amplifier needs to provide a long fluorescence lifetime, to minimise the number of pump diodes required, good thermo-mechanical properties, to handle the high average power, it must be available in large sizes and good optical quality, to handle the high pulse energy and it should provide a reasonably high gain cross section to enable simple and efficient energy extraction.

Yb as an active laser ion offers very long fluorescence lifetimes, a low quantum defect (pump wavelength 940 nm, laser wavelength 1030 nm), reasonable gain cross sections and efficient high power laser diodes are readily available at its pump wavelength. Two host materials have been identified that offer good thermo-mechanical properties and can be manufactured in large sizes: crystalline calcium fluoride (CAF) and ceramic YAG. Yb:CAF has a very long fluorescence lifetime of 2.4 ms and a large gain bandwidth (> 50 nm) [3] and is therefore a promising candidate for directly diode pumped chirped pulse amplification (CPA) systems for producing sub-ps pulses [4]. However, since it exhibits a very small gain cross section, very large fluence levels are required for both pumping and extraction in order to achieve good optical-to-optical (o-o) efficiency. On the other hand, Yb:YAG has an order of magnitude higher gain cross section with a reasonable fluorescence lifetime of 1 ms. Since the main application of our envisioned kJ-class laser is the production of ns-pulses, either for pumping amplifiers for fs-pulse generation (Ti:sapphire or OPCPA) or for driving inertial fusion targets, we think that ceramic Yb:YAG is the best choice for the gain medium.

## 3. Amplifier design and modelling

In order to determine amplifier design parameters, some numerical modelling was carried out. In this model, the storage efficiency $\eta_{stor}$ was calculated for various parameters like pump fluence, pump pulse duration and pump spectral width. $\eta_{stor}$ is defined as extractable fluence divided by pump fluence. Loss mechanisms and associated efficiency factors that influence $\eta_{stor}$ are $\eta_{fluo}$ for the fluorescence decay, $\eta_{QD}$ for the quantum defect, $\eta_{abs}$ for pump light that passes through the gain medium without being absorbed and finally $\eta_{reabs}$ for the minimum upper state population that needs to be established in order to overcome reabsorption that exists due to the quasi-3-level nature of Yb:YAG. If a pump pulse duration of 1 ms is chosen, $\eta_{QD}$ and $\eta_{fluo}$ limit $\eta_{stor}$ to 58 %. It turns out that $\eta_{abs}$ and $\eta_{reabs}$ need to be balanced off against each other and that for a given set of pump-related parameters, there is one optimum gain medium optical depth (OD = thickness times doping concentration) that yields the maximum $\eta_{stor}$. If

OD is chosen too low, too little pump light is absorbed, if OD is too high, reabsorption losses become dominant.

The following results are calculated, unless stated otherwise, for an amplifier that is end-pumped from both sides with a pump pulse duration of 1 ms, a 5 nm FWHM pump spectral width, centred at the optimum wavelength in the 940 nm absorption band. Spectrally resolved pump absorption cross sections were taken from [5]. Quantities calculated were $\eta_{stor}$ and the small signal gain G, defined as $G = \exp(\eta_{stor} F_{pump}/F_{sat})$ where $\eta_{stor} F_{pump}$ is the extractable fluence and $F_{sat}$ the gain saturation fluence. First, calculations were carried out for room temperature operation. The results are shown in Fig. 1. It becomes apparent that very strong pumping is required, firstly to overcome the high reabsorption losses and to achieve good efficiency and secondly to overcome the still rather low gain cross section and achieve reasonable gain. The required high pump and extraction fluences are difficult to achieve because of limited pump source brightness and limited laser damage threshold.

Cooling the gain medium to 175 K drastically changes the situation, as illustrated in Fig. 2. Reabsorption is reduced and the gain cross section increased, leading to greatly improved efficiency and gain, especially at moderate fluences. A pump fluence that is realistically achievable with today's laser diodes is 10 J/cm$^2$ (5 J/cm$^2$ from each side), yielding a storage efficiency of just over 50 % (resulting in an extractable fluence of 5 J/cm$^2$) and a small signal gain of 3.8. This fluence is therefore chosen as the preliminary operating point for our amplifier.

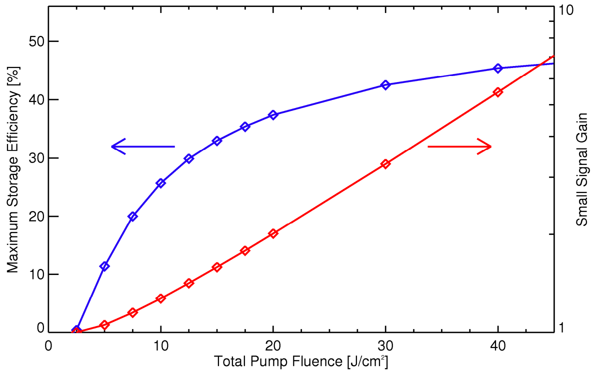

Fig. 1. Maximum storage efficiency (blue) and small signal gain (red) for amplifier operated at room temperature.

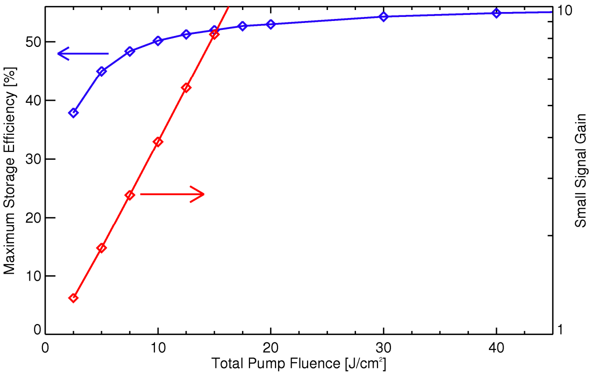

Fig. 2. Maximum storage efficiency (blue) and small signal gain (red) for amplifier operated at 175 K.

Operating at cryogenic temperatures yields the added benefit of improved thermo-mechanical and thermo-optical properties like increased thermal conductivity and reduced temperature dependence of the refractive index. Another effect is the narrowing of spectral features both in the emission and the absorption spectrum. The absorption spectra measured at room temperature and at 175 K are shown in Fig. 3, together with a 5 nm FWHM Gaussian spectrum for comparison, which is assumed to be the spectral shape of our pump source. If these pump and absorption spectra are used to calculate storage efficiency for two different scenarios, results as shown in Fig. 4 are obtained. Even though the pump fluence in the low temperature scenario is only half that of the room temperature case, a significantly higher storage efficiency is predicted, which also shows a much weaker dependence on pump centre wavelength. So despite narrower absorption features, the requirements with respect to spectral performance of the pump diodes are less critical for low temperature operation.

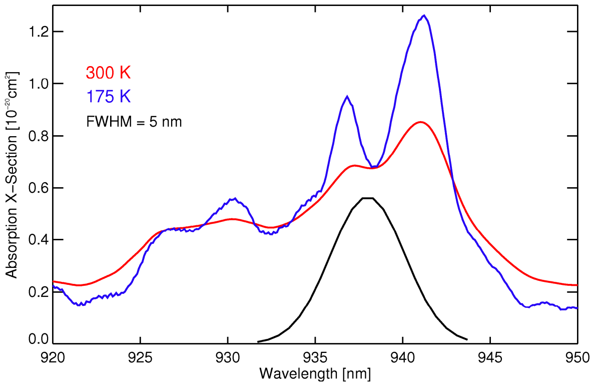

Fig. 3. Absorption spectra of Yb:YAG at different temperatures and 5 nm wide pump diode spectrum for comparison.

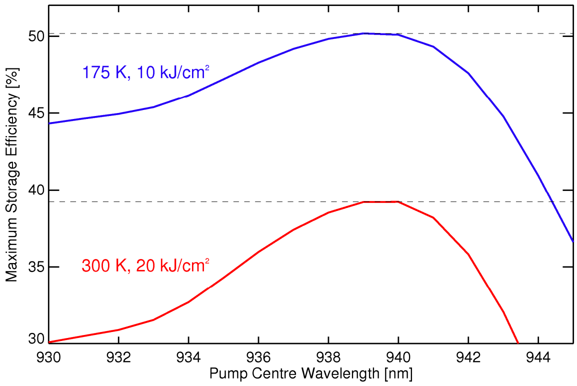

Fig. 4. Storage efficiency as function of pump centre wavelength for two different scenarios.

After determining operating temperature and pump fluence for our envisioned amplifier, the actual geometry needs to be defined. If the laser system is to yield an output energy of 1 kJ and the amplifier is to be operated at an output fluence of 5 J/cm$^2$, the aperture needs to be 200 cm$^2$ or 14 x 14 cm$^2$ if a square beam shape is adopted. The optimum OD = $N$x$l$ obtained from the numerical calculations is 3.15 % cm, where $N$ is the Yb-doping concentration in atomic % and $l$ the geometrical thickness of the amplifier. The choice of $N$ and consequently $l$ is governed by ASE management considerations. If the gain-length product along the diagonal across the (square) surface of the amplifier is to be kept below 3, we require $N < 0.18$ % and hence $l > 18$ cm. Such a thick amplifier requires distributed cooling as demonstrated on the Mercury laser [6]. There, the gain medium is divided into a stack of thin slabs with He gas flowing through the gaps between the slabs. The concept is illustrated in Fig. 5, where an amplifier consisting of 10 slabs is shown. If the criterion that the transverse gain-length product must not exceed a certain value is applied to each individual slab, one realises that the doping concentration can be increased towards the centre of the amplifier. The advantage is twofold: firstly, since the required overall OD remains the same, the amplifier as a whole becomes thinner, saving material and reducing the impact of nonlinear effects, and secondly the optical power absorbed in the individual slabs and hence the heat load is equalised. An optimised doping profile for a 10-slab amplifier is shown in Fig. 6, together with the transverse gain as a function of position. The overall thickness of the gain medium is reduced from 18 cm to 10 cm in this configuration.

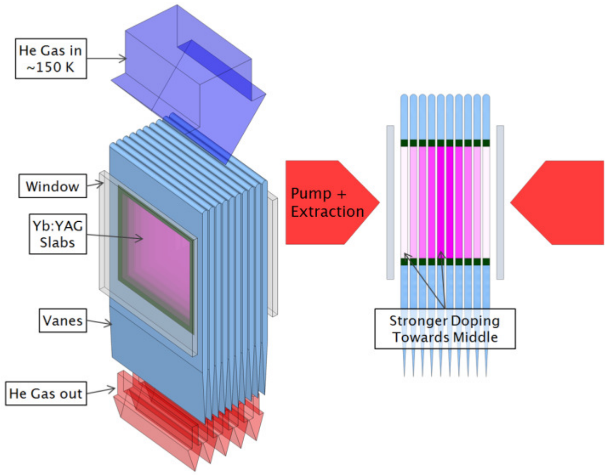

Fig. 5. Illustration of amplifier geometry: isometric (left) and side view (right).

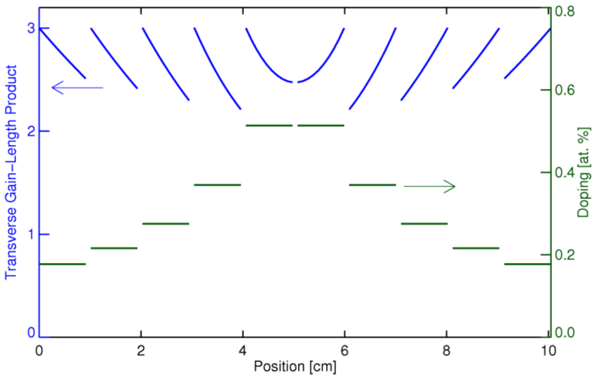

Fig. 6. Transverse gain-length product and doping levels along optical axis in 10-slab amplifier.

## 4. References

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