Low Pressure Helium Cooled Active Mirror Amplifiers for HiPER KiloJoule Beamlines[*]

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The European laser driven fusion project HiPER relies on kilojoule, nanosecond pulse trains with repetition rates close to 10 hertz and high wall-plug efficiency. We propose a scheme based on diode-pumped amplifiers using Yb^{3+}:YAG ceramics as gain medium. An active mirror architecture where the high reflection coated side is cooled using a low pressure static Helium gas cell, is proposed.

Keywords: diode pumped solid state laser, inertial fusion energy, thermal management, helium cooling, YAG

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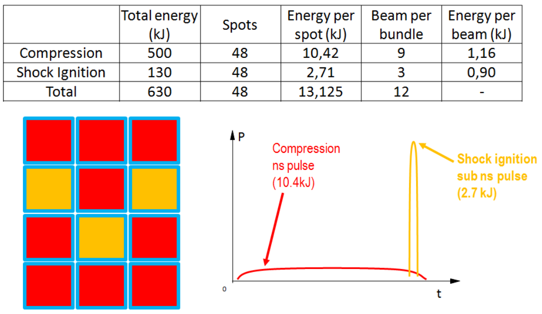
1. Introduction

HiPER (High Power laser Energy Research) [1–3] in Europe, LIFE (Laser Inertial Fusion Engine) [4] in the United States of America and GENBU (Generation of ENergetic Beam Ultimate) [5] in Japan are scientific programs dedicated to demonstrate the feasibility of laser driven fusion [1] as a future energy source. Several groups within HiPER are actively pursuing research in Europe in the field of high average-power Diode-Pumped Solid-State Lasers (DPSSL) [6]. The Laboratoire pour l'Utilisation des Lasers Intenses (LULI) at the Ecole Polytechnique, France, is working on a HiPER scheme relying on cryogenically cooled active mirror amplifiers using Yb^{3+}:YAG ceramics. Six amplifiers in a double pass configuration will be required to reach the 1 kJ unit beam (called "Beamlet") requirement for HiPER (see Fig. 1).



	Total energy (kJ)	Spots	Energy per spot (kJ)	Beam per bundle	Energy per beam (kJ)
Compression	500	48	10,42	9	1,16
Shock Ignition	130	48	2,71	3	0,90
Total	630	48	13,125	12	-

Fig. 1 HiPER shock ignition scheme relies on 48 spots on the target. The ~500 kJ total energy amount will therefore have to be delivered through 48 bundles of twelve ~1 kJ beams.

Considering the state of the art coating design for high Laser Induced Damage Threshold (~30 to 40 J/cm^2, 10 ns, 1 μm) as well as the component lifetime requirement (10^9 shots) and a reasonable damage safety factor, it seems safe to target a maximum extraction fluence of 10 J/cm^2. Consequently, about 100 cm^2 of beam aperture are needed for a ~1 kJ laser beamlet. A single beamline (see arrangement of 12 beamlets in Fig. 2) will be based on 9 incoherently combined beamlets for the compression pulses whereas, considering the requirements in terms of spot size, the 3 remaining beamlets will be coherently combined for shock ignition pulses.

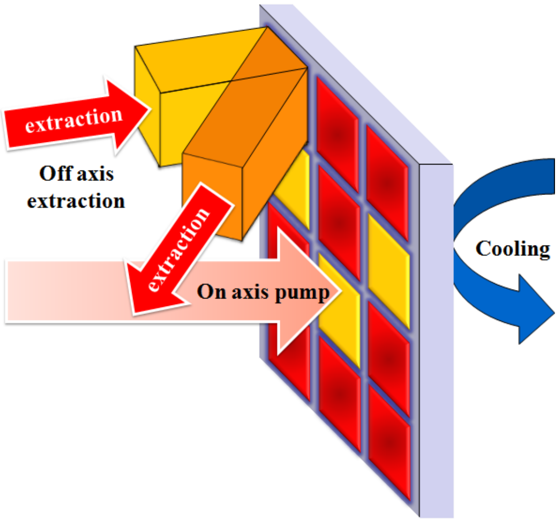


Fig. 2 Pumping, extraction and cooling axis with LULI active mirror architecture.

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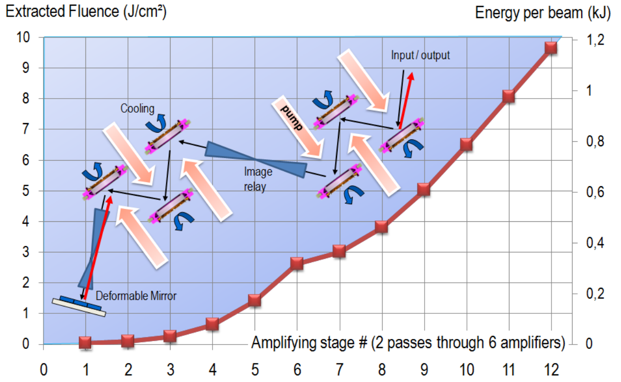

Fig. 3 Energy (right scale) and fluence (left scale) build-up through the LULI proposed beamline for HiPER. The six disk arrangement for an Yb^{3+}:YAG amplifying chain is displayed, where the laser beam passes through the amplifier system twice and through each disk four times in total.

2. Optical Layout

Figure 3 displays a schematic of the proposed 2-pass amplifying chain for HiPER. The laser beam passes through the amplifier system twice after reflection on a deformable mirror (left): it therefore travels through each disk four times. Six of these amplifiers will be used in series in order to reach the requested energy level. The ~100 cm^2 amplifier disks will be slightly rectangular to accommodate for an extraction angle of 20 degrees. Such large surface Yb^{3+}:YAG gain medium are available as ceramics. Required doping levels will be quite low, around 0.1 at%, while the thickness will be close to 2 cm. Requested pump intensity is in the order of 6 kW/cm^2. Optical to optical efficiency above 30% can be reached when operating the laser at reduced temperature (in the 100 K to 200 K region), where emission and absorption cross sections are considerably higher for Yb^{3+}:YAG than at room temperature. In the same time the dominant ground level absorption of Yb^{3+}:YAG is less important compared to room temperature operation case.

3. Amplifier Thermal Management with He Cell

Working at lower temperatures than 300 K reduces the ground state absorption at the emission wavelength [7] and increases significantly the emission cross section value at the nominal working wavelength. Consequently this makes it more difficult to efficiently manage ASE issues [8]. At such temperatures, one cannot rely on classic index matching approaches, using e.g. liquids. It is therefore required to rely on co-sintered Cr^{4+}:YAG ceramics to suppress parasitic oscillations (see Fig. 4).

Within the Lucia program [9], we are currently developing a new kind of thermal management approach [10], where static Helium gas contained in a low pressure (< 1 bar), sub-millimetre thin cell located at the High Reflectivity coated side of the active mirror, is used to transfer, with a fine control, the heat from the gain medium to a copper heat sink at 77 K (Fig. 5).

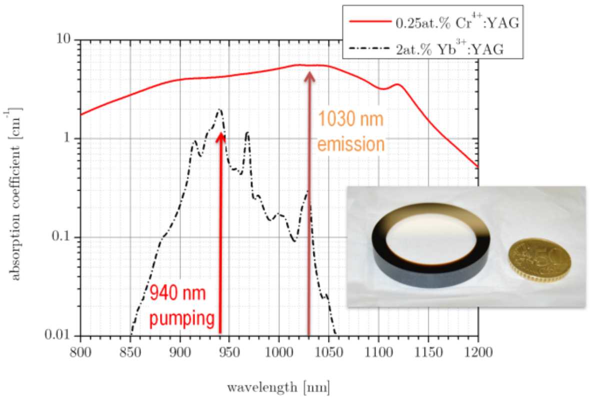

Fig. 4 Absorption coefficient of 2 at.% doped Yb^{3+}:YAG ceramic and 0.25 at.% doped Cr^{4+}:YAG ceramic at room temperature.

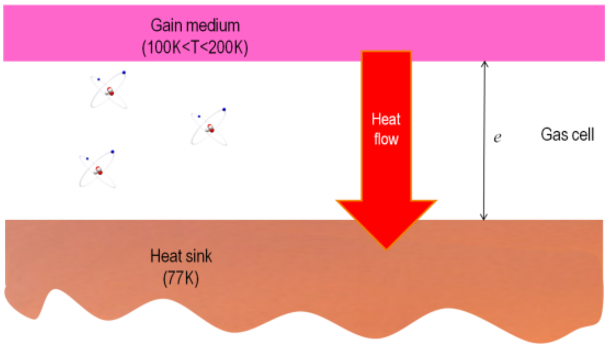

Fig. 5 Static Helium filled cell allowing to control the heat flow by adjusting the gas pressure and gas cell thickness.

For a fixed gas cell thickness, the gain medium temperature can be tuned by adjusting the Helium cell pressure in the 500 Pa to 5000 Pa range (Fig. 6). Helium thermal conductivity dependence with Temperature (T), pressure (p) and thickness (e) is given by the following equation:

$$k(T) = k_{\mathrm{bulk}}(T) \cdot \left(1 + \frac{8}{3} \cdot \frac{k_{\mathrm{bulk}}(T) \cdot T}{e \cdot p \cdot \sqrt{3 \cdot R \cdot T}} \cdot \left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} - 1\right)\right)^{-1},$$

where R is the specific gas constant for Helium whereas α_1 and α_2 are the thermal accommodation factors for Cu and YAG surfaces which roughness are respectively 0.8 µm (Ra) and 5 Angströms (rms). The heat sink is thermalized at 77 K since it is immersed into a LN_2 bath.

For practical reasons, we propose to design a two steps level copper plate accommodating a single He pressure (for instance 4.10^3 Pa with 50 µm in front of the cladding and ~200 µm in front of the gain medium as illustrated on Fig. 7). Such structure would be required if the same tem-

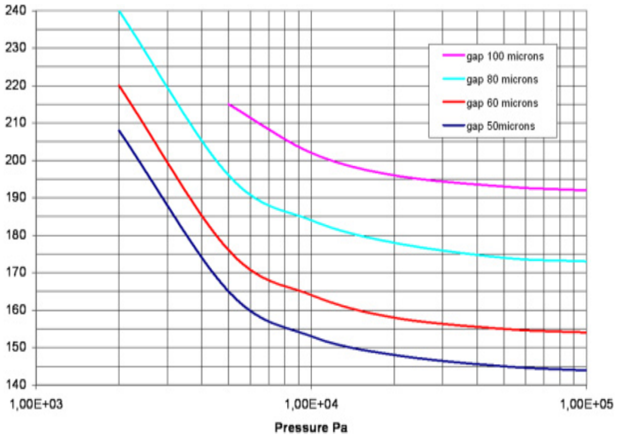

Fig. 6 Gain medium temperature (vertical) as a function of helium gas pressure for gaps of variable thicknesses.

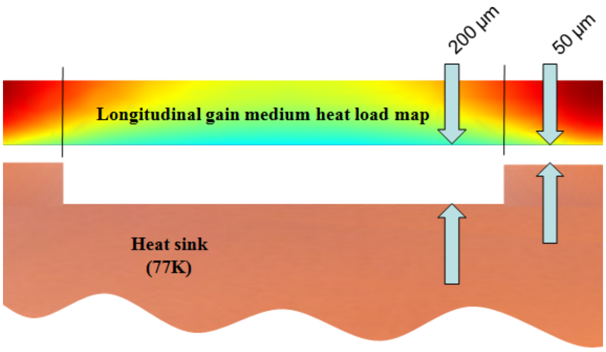

Fig. 7 Two steps copper heat sink structure for adjustable Helium thermal conductivity. The YAG gain medium is displayed with its temperature distribution map illustrating the higher thermal load in the edge at the cladding material location.

perature for both cladding and gain medium is needed.

Experimental validation within the Lucia test bed is under preparation (Fig. 8). A first cryogenic amplifier head prototype is currently being manufacture allowing us to prove the performance of this particular cooling approach. Since this proposed HiPER kJ beamline design is based on the active mirror scheme with a similar heat flux, i.e. in the range of 10 W/cm^2, we are confident in the ability of such approach to fulfil HiPER beam line demands.

Fig. 8 Picture of the cryogenic prototype laser head to be operated with a 77 mm diameter Yb^{3+}/Cr^{4+}:YAG gain medium. The top right insert displays the copper side of the Helium cell.

Acknowledgments

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