Cryogenic Cooling For High Power Laser Amplifiers

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Abstract

The Extreme Light Infrastructure (ELI) will be a new scientific European infrastructure devoted to scientific research in lasers field, dedicated to the investigation and applications of laser-matter interaction at the highest intensity level (more than 6 orders of magnitude higher than today's laser intensity). The ELI project, a collaboration of 13 European countries, will comprise three branches: Ultra High Field Science that will explore laser-matter interaction, attosecond Laser Science designed to conduct temporal investigation of electron dynamics in atoms, molecules, plasmas and solids at attosecond scale, High Energy Beam Science devoted to the development and usage of dedicated beam lines with ultra short pulses of high energy radiation. Using DPSSL (Diode Pumped Solid State Lasers) as pumping technology, PW-class lasers with enhanced repetition rates are developed. Each of the Yb YaG amplifiers will be diode-pumped at a wavelength of 940 nm. This is a prerequisite for achieving high repetition rates (light amplification duration 1 millisecond and repetition rate 10 Hz). The efficiency of DPSSL is inversely proportional to the temperature, for this reason the slab amplifier have to be cooled at a temperature in the range of 100K-170K with a heat flux of 1 $MW*m^{-2}$. This paper describes the thermo-mechanical analysis for the design of the amplification laser head, presents a preliminary proposal for the required cryogenic cooling system and finally outlines the gain of cryogenic operation for the efficiency of high pulsed laser.

1. Introduction

The efficiency of a laser is strongly connected with the thermo mechanical deformations of amplification media. A great part of the amplification energy is transformed in heat inside the laser amplification media. This heat flux introduces mechanical deformation which is called “thermal lensing”. This phenomenon is due to the non uniform heat deposition and non uniform cooling. This “thermal lensing” destroys the quality of the laser beam (power density and wave front). For these both reasons, lot of simulations and experimental analyses are engaged to improve the design of the amplifier and its cooling system. When a material is cooled down its thermal properties are changing, the heat conductivity increases and the heat capacity decreases. So an increase of the thermal diffusivity is observed for operation at low temperature (< 200 K) compare to room temperature. As a consequence, the thermal gradient inside the amplification material can be reduced and the heat flux can be removed easily. In addition, experiments and simulations [1]-[4] have shown that laser materials have better amplifier performance when cooled. All these enhanced properties drive the development of high pulsed lasers at low temperatures with the objective of improving beam parameters. However, the cooling of amplifying sections at low temperatures (150-170 K) will require a more complex and more expensive infrastructure especially for the production of refrigeration capacity.

2. Material and Design of Amplifiers

2.1. Amplification Section Design

To avoid a very large thermal gradient in the ceramic medium, the amplification medium has to be actively cooled. For this purpose, the outer surface of the ceramic is cooled by a forced convection with forced flow circulation. To increase the heat exchange surface, the amplifier is divided into several slabs separated by cooling channels as shown in figure 1.

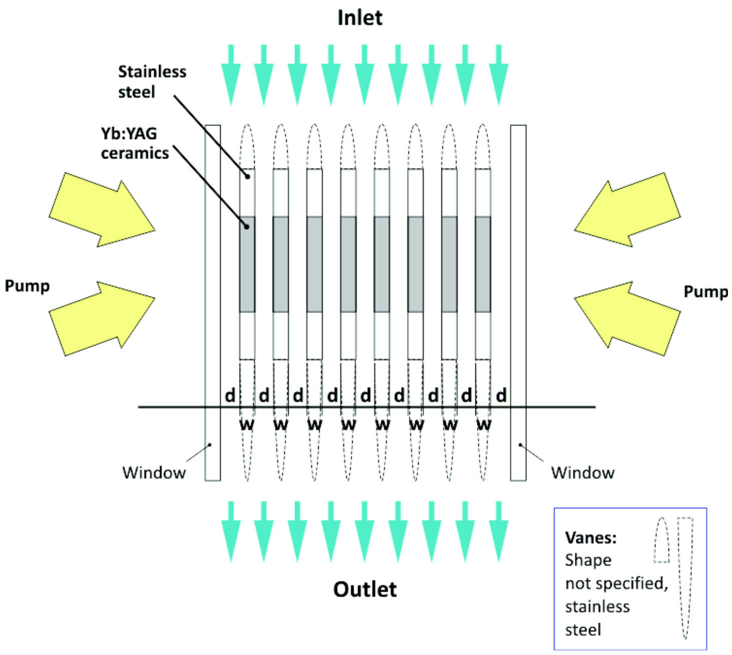

Figure 1 - Schematic cross section of the cryogenic amplifier head.

Helium gas has been chosen as a coolant gas for two major reasons. The first one is optical consideration [5]. The Helium refractive index is the lowest index for gases (10 times less than Nitrogen). The second one is thermal consideration. Helium gas has a high heat capacity (5.2 J/g/K) and the temperature increase during a laser shot will be low. The combination of these two properties shows that helium gas is a good candidate as a cooling gas.

2.2. Material Properties

Generally, the active medium of a solid-state laser consists of a glass or crystalline host material to which is added a dopant such as neodymium, chromium, erbium, ytterbium or other ions. YaG (yttrium aluminium garnet;Y3Al5O12) with Yb doping is a promising crystal [3] that is used as a lasing medium for solid-state lasers.

The reference values at room temperature are given below:

Young modulus	E = 300 GPa at 300 K
Poisson ratio	ν = 0.23 at 300 K
Yield tensile strength	σ = 280 MPa at 300 K
Volume mass	ρ = 4560 kg*m^{-3}

The non linear behavior of materials at low temperatures requires experimental measurements in particular for the thermo mechanical properties. For our purpose the main values are the thermal expansion, the thermal conductivity and the thermal capacity which govern the temperature map during transient phenomena. The thermo-mechanical properties of YaG ceramics are described in table 1.

TABLE 1. PHYSICAL PROPERTIES OF YAG CERAMICS

T	k	Cp	D thermal diffusivity	α	∫α*dT
K	Wm^{-1} K^{-1}	Jkg^{-1} K^{-1}	m2s	$m*m^{-1}K^{-1}$	$m*m^{-1}$
100	3,27E+01	1,60E+02	4,47E-05	2,77E-06	1,650E-04
120	2,42E+01	2,20E+02	2,42E-05	3,13E-06	2,240E-04
140	1,94E+01	2,75E+02	1,54E-05	3,48E-06	2,901E-04
160	1,64E+01	3,28E+02	1,10E-05	3,81E-06	3,629E-04
180	1,46E+01	3,78E+02	8,45E-06	4,12E-06	4,422E-04
200	1,32E+01	4,24E+02	6,84E-06	4,43E-06	5,277E-04
220	1,22E+01	4,67E+02	5,71E-06	4,72E-06	6,192E-04
240	1,12E+01	5,06E+02	4,85E-06	5,01E-06	7,165E-04
260	1,02E+01	5,42E+02	4,13E-06	5,29E-06	8,195E-04
300	8,07E+00	6,05E+02	2,92E-06	5,83E-06	1,042E-03

The properties observed at low temperature give lower dilatation coefficient and higher thermal diffusivity than at room temperature and would therefore facilitate the amplifier design.

2.3. Laser efficiency

Many experiments [1]-[4] show that the efficiency of the amplification with YaG lasers doped Yb increase when the temperature of the amplification media is decreasing. This efficiency, which is 15% at room temperature, can reach 40% at a temperature in the range of 80-120 K as shown in table 2.

TABLE 2. AMPLIFICATION EFFICIENCY VERSUS TEMPERATURE FOR DPSSL LASER

Temperature K	80	120	170	220	295
Laser output/diode output ηS	0.39	0.37	0.28	0.2	0.15

3. Thermomechanical Analysis

3.1. Buckling stress

The amplification medium is surrounded by a non active frame (undoped) which is here for fabrication and assembling reasons. In this case during the laser shots only the inner part is heated and compressive forces appear in the inner media. Ceramics are very brittle and the stresses developed in the media have to stay lower than the stability stresses. This criterion is determined by coupling the cooling parameters and the mechanical properties of the ceramics. The stability criterion minimizes the media deformation and "thermal lensing" effect. The following figure shows the scheme of the cooling.

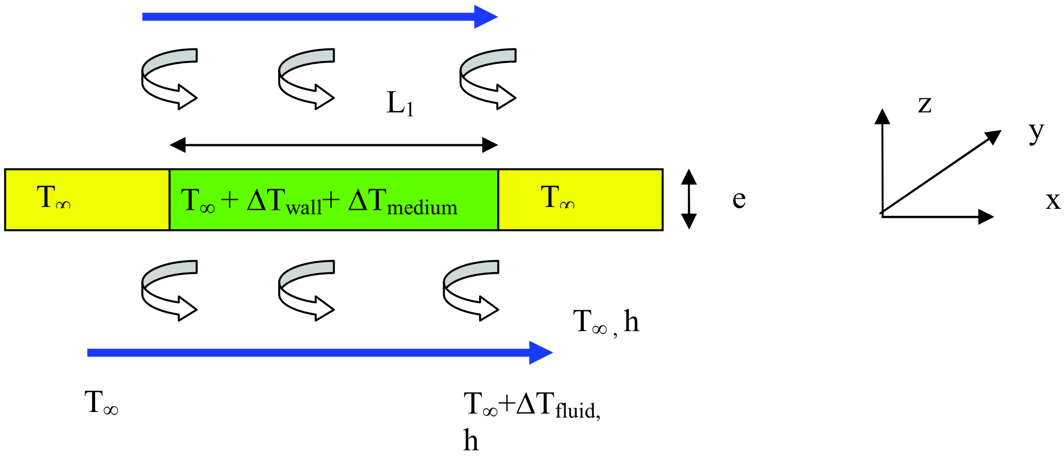

Figure 2 - Scheme of an amplification plate for the thermo mechanical analysis

The gas has a temperature T∞ at the upstream and a heat exchange coefficient h at the interface surfaces. For uniform cooling all along the cooling channels, the temperature difference ΔT_{fluid} in cooling gas is taken < 1K. To remove the heat power generated in the ceramics, a second ΔT2 appears between the gas and the solid medium. Finally, a third ΔT_{medium} appears in the ceramics. We suppose that ΔT_{wall} and ΔT_{medium} exist only in the active medium and the temperature of the surrounded non active medium stays at T∞ as shown in the figure 2. In this situation, compressive forces appear in the inner medium and buckling stresses could be developed. The compressive forces [6] depend on ΔT inside the ceramics as expressed in equation (1). Compressive forces can introduce bucking phenomena if they are greater than a limit value called “stability value” [6] expressed in equation (2).

$$\sigma_y = \sigma_x = -\frac{\alpha * E * \Delta T}{1-\nu} \text{ for a square plate} \qquad (1)$$

$$\sigma_m = 2 * \frac{\pi^2}{L_1^2} * \frac{E * e^2}{12 * (1-\nu^2)} \qquad (2)$$

Where E is the Young modulus, ν is the Poisson coefficient, α the thermal linear expansion coefficient and σx and σy are the stresses along x and y axes, e the slab thickness.

3.2. Thermal heating and deformations

The thermal heating from the pumping process is a volume deposition (q $W*m^{-3}$). With such a scheme the temperature profile inside the crystal will be parabolic.We consider that the configuration is symmetric. The temperature through the thickness is given by equation (3).

$$T = \frac{q}{2*k}\left(\frac{e^2}{4} - z^2\right) + \frac{q*e}{2*h} + T_\infty \qquad (3)$$

$$Bi = \frac{h * Lc}{k} \qquad (4)$$

Where q is the volume deposition ($W*m^{-3}$), e the slab thickness, k YaG material conductivity, h heat exchange coefficient, T∞ fluid temperature, Bi Biot number, Lc characteristic length of plate (Volume / Section).

The hypothesis that no axial flux occurs is verified if Bi >> 1 which could be obtained in present amplifier design with thickness 8 mm, length 100 mm and heat exchange coefficient h~3000 W.m^{-2}K-.1

Using the superposition principle and the different origins (axial/transverse) of thermal gradients, the maximum of stresses is reached at the center of the slab for x = e/2 and y = L1/2 and it can be given by equation (5)

$$\sigma_y = \sigma_x = -\frac{\alpha * E * q * e}{2*(1-\nu)} * \left(\frac{e}{6*k} + \frac{1}{h}\right) \quad (5)$$

The buckling stress for YaG plates has to be limited at a value around 28 MPa and the temperature difference between the amplification plates is chosen in the range of 20 K. Figure 3 presents the stress evolution according cooling temperature, slab thickness and heat exchange coefficients at wall interfaces. This analysis shows that many couple of parameters can be found with the respect of the highest mechanical stresses (< 28 MPa). The final choice has to take into account also hydraulic analyses.

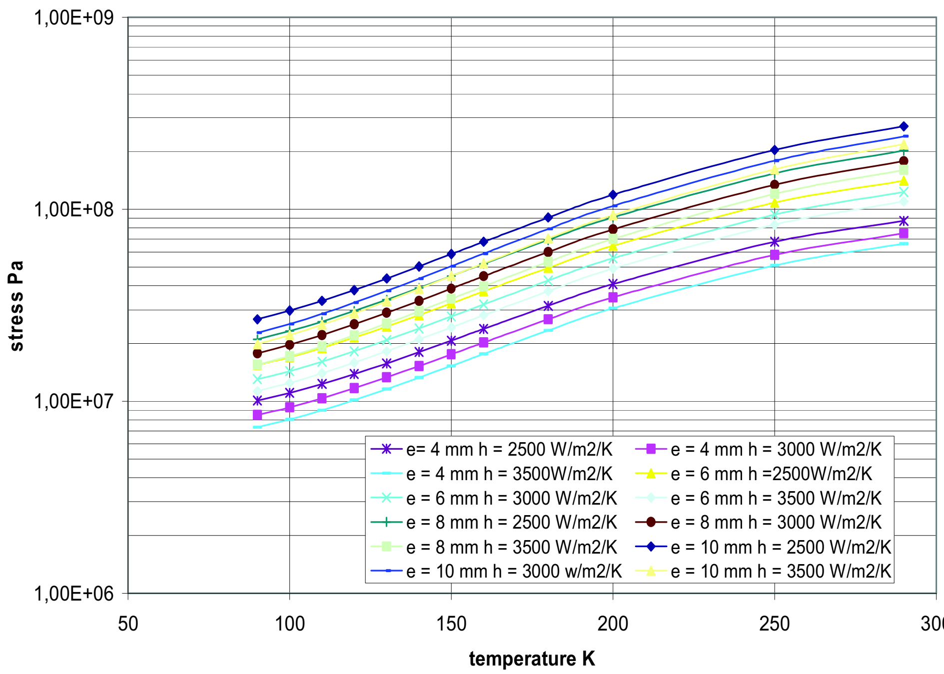

Figure 3. Thermo-mechanical stress analysis for different slab thickness and cooling properties

4. cooling System

4.1. General Consideration

Such lasers are pulsed laser and have a typical duty cycle with the duration of the pumping phase (light amplification) of 1 millisecond and a repetition rate of 10 Hz. In these conditions the heat deposition will be considered as adiabatic, and for the calculation of the cooling system, an averaged power is considered.

4.2. Axial temperature gradient

Thermo mechanical analysis is performed assuming as low as possible temperature difference around slab. As a consequence, a minimal cooling flow has to circulate in the cooling channels to minimise the fluid ΔT. The maximum axial gradient in the ceramics fixes the lowest helium mass flow as presented in equation (6).

$$\dot{m} = \frac{q * e * L_1^{\ 2}}{2 * C_{pfluid} * \Delta T_{axial}} \tag{6}$$

Where $\dot{m}$ is the mass flow, q is the volume deposition ($W*m^{-3}$), e the slab thickness, L1 the slab length, Cp the heat capacity, ΔT axial the thermal gradient in gas.

4.3. Velocity profile

The flow condition for the thermal gradient is not sufficient for efficient cooling and the velocity profile close to the heating surface has to be as flat as possible. To reach a flat profile, the edge channel effects have to be reduced. This condition can be obtained by having a very narrow channel with a very large width-height ratio as shown in figure 4.

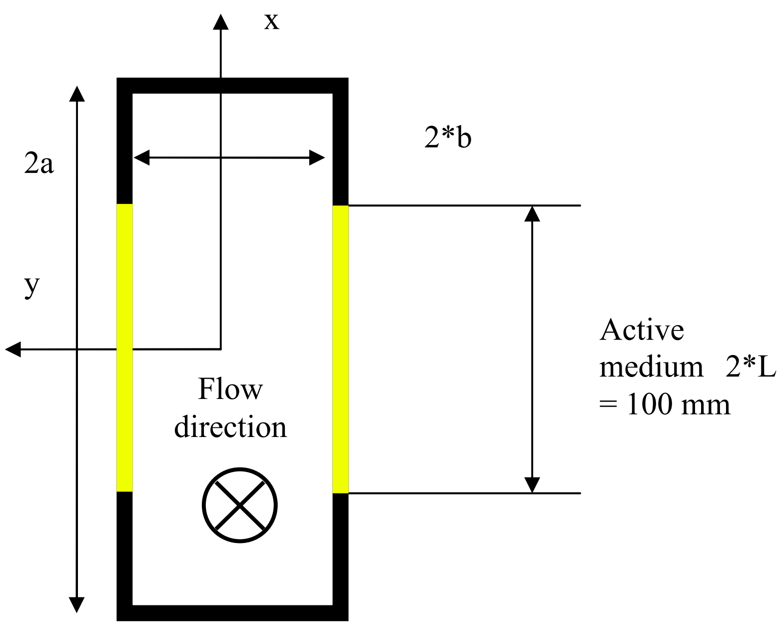

Figure 4. Section of a cooling channel.

To be sure that the velocity variation would be less than 1 % between the centre and the edge of the heated surface, the ratio width-height must be higher than 15 as shown in figure 5. In ELI design case, a channel with a height of 160 mm and a width in the range of 4 to 6 mm has been chosen.

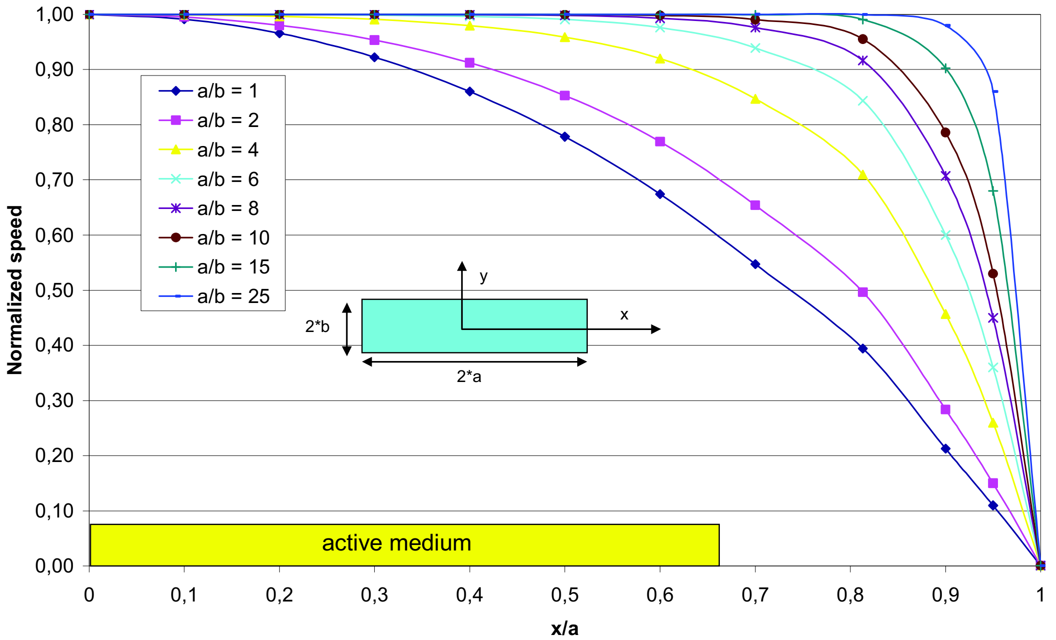

Figure 5. Velocity profile near the heated surface for different channel sizes

4.4. FEM analysis

At this level FEM simulations are engaged with a predefined geometry. The goal of these calculations are to optimize the hydraulic parameters and also to evaluate the turbulence level in the cooling channel which can lead change in the refractive index of Helium and lead change in the front wave of the laser beam. The gas flow, when it is turbulent, shows detachment of the boundary layer. This phenomenon affects the heat exchange coefficient. For this reason some profile of the plate is required for the upper stream and the downstream flow. In our case an elliptic profile has been chosen as shown in the figure 6.

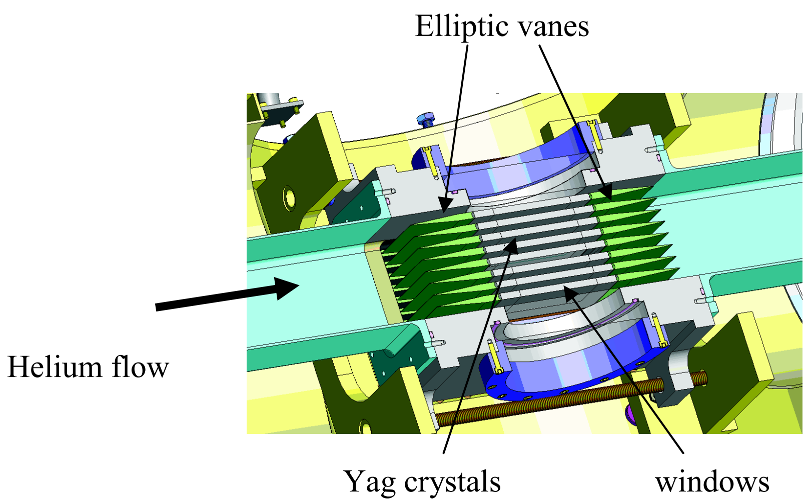

Figure 6. Section of a cooled amplifier

4.5. First results

TABLE 3. VELOCITY RANGE IN FUNCTION OF THE DISTANCE FROM THE BALDE SURFACE

Distance from the balde (m)	0.00005	0.0001	0.0002	0.0003	0.0008
Maximum velocity heterogeneity (%)	4.2	4.7	3.9	3.4	2.5

This table shows that, along the all blade (crystal, inlet and outlet profiles), the heterogeneity in the boundary layer (up to 0.8 mm from the surface) is less than 4.7%. This first analysis shows that the gas velocity has bulk homogeneity more than 95% and consequently the heat exchanger follows the same law. The temperature gradient will low and the impact on the refractive index will be also low.

5. Cooling loop

5.1. Schematic arrangement

A general scheme of the required cooling loop for high pulsed laser amplifiers is presented in figure 6 with a dedicated forced flow circulation in the amplifier cell.

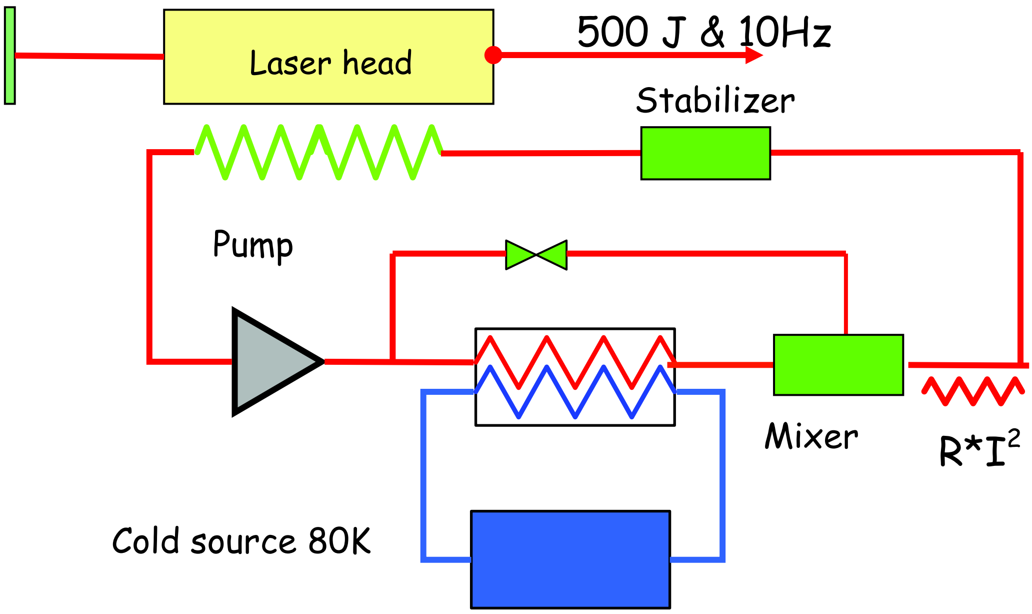

Figure 6. General scheme of the cooling loop

The main components of the loop are: the amplifier cell, a flow stabiliser, the temperature mixing chamber, a fine electrical heater, a circulating pump and a heat exchanger with a cold source. To reach the working temperature of the slab (150-170 K), a cold source at 80 K with a bypass is used. In this way the temperature of the slab can be adjusted in a large range (90K-170 K) for laser performance studies. Additional heating by Joule effect can finely adjust the temperature. The electrical heater will be also be used for the warm-up of the loop at room temperature for maintenance phases.

For ELI project, the duty cycle is 4 runs of 15 minutes at 10 Hz every working day. The conditioning times for steady state and stops are evaluated at 2 hours. Periods of availability

of the laser are not a very strong constraint. For this reason the construction of a cold source based on Brayton cycle is not necessary.
The present proposed solution for ELI facility is the use of a liquid nitrogen bath with an immerged heat exchanger working in the nucleate boiling regime.

5.2. Preliminary analysis for required energy

According the operating temperatures, the total electrical power required to safely operate a high pulsed laser will depend of laser/diode performances and cooling efficiency as detailed in equation (7). Figure 7 presents preliminary estimations of such total electrical power as a function of temperature and efficiency for ELI project (500J at 10 Hz).

$$P_{elec} = P_L * \frac{1}{\eta_D} * \frac{1}{\eta_S} + \frac{1}{\eta_C} * \frac{(300-T)}{T} * \left(P_L * \frac{(1-\eta_S)}{\eta_S} + \frac{1}{\eta_P} * Q_v * \Delta p \right) + \frac{1}{\eta_E} * Q_v * \Delta p \qquad (7)$$

Where, Pelec is the electrical power
P_L is the laser power (in our case 500 J at 10 Hz means 5 kW)
ηD is the diode efficiency (a value of 50 % is taken)
ηS is the slab amplifier efficiency (function of temperature as shown in table 2)
ηC is the efficiency compare to the Carnot efficiency (a value of 30 % is taken)
T is the working temperature
Q_V is the volume flow of Helium
ΔP is the pressure drop for the cooling loop
ηp is the pump efficiency (a value of 75 % is taken)
η_E is the motor electrical efficiency (a value of 98 % is taken)

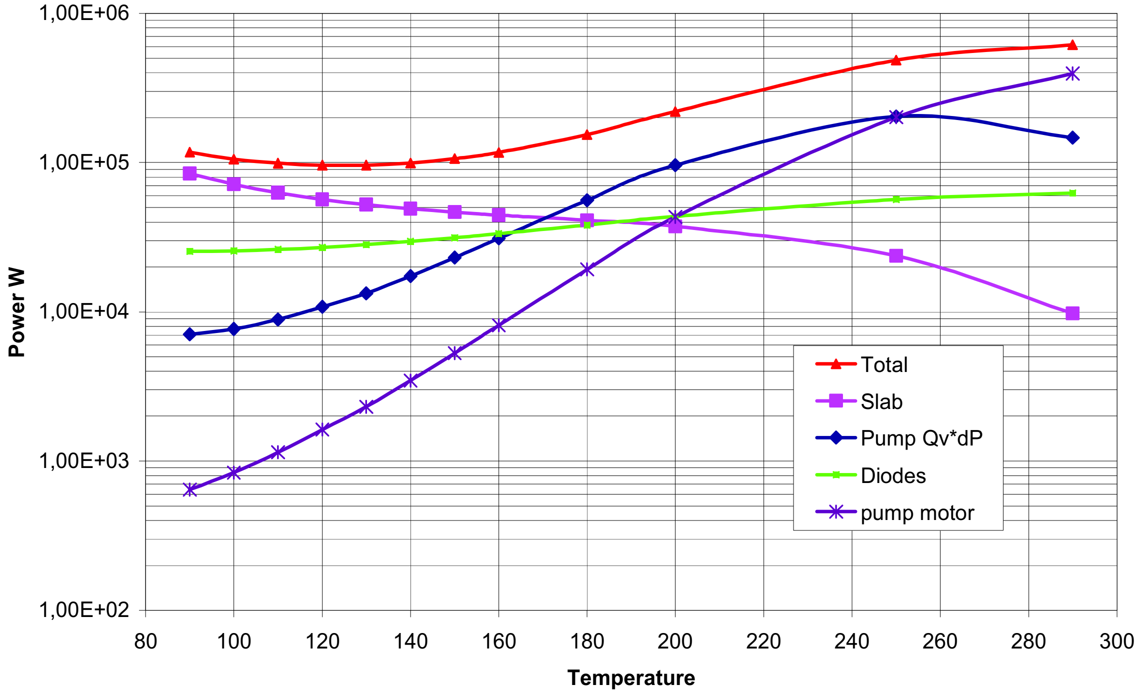

Figure 7. Equivalent electrical power required for a beam laser (500 J at 10 Hz)

Operating at low temperatures will reduce the total electrical consumption of ELI infrastructure (ratio 1:3). One can note that for temperatures below 200 K, the required energy is not very dependent on the temperature. This is explained by the fact that the decrease in Carnot efficiency for the cooling system is partly compensated by the increased efficiency of laser pumping for the lower temperatures.

6. Conclusions

The objective of operating DPSSL at low temperature is to improve the overall performance of these high pulsed lasers. This preliminary study shows that special attention including thermo mechanical analysis is required for the design of amplifiers operating at low temperature. In particular the heat deposition location and the thermal gradient inside the active medium is strongly correlated with the thermal properties of the material and it depends on the level of doping for the lasing phenomenon and doping for spontaneous emission absorption effect. The associated cryogenic system is standard but will require specific studies to fulfil the complex cooling requirements in the amplifier cell. The amplification slab profiles have to be studied with the goal to reduce the turbulences in the cooling gas which can affect the wave front of the laser. Finally, preliminary estimations for operating a cryogenic DPSSL facility have shown that the total electrical consumption is drastically reduced when operating at low temperature. The construction of ELI-Beamlines will give the opportunity to validate the cryogenic design and the performances of high pulsed lasers at low temperatures.

7. References

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