Upgrade of the CLEAR (CALIFES) diode-pumped Nd:YLF power amplifier

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This paper describes a design proposal for the upgrade of the CALIFES laser amplifier, which is currently part of the system utilized as CLEAR facility photo-injector. The primary focus for CLEAR is general R&D and component studies for existing and future machines at CERN. Accordingly, its photo-injector laser system will be upgraded in order to improve its reliability and available power. The design of systems presented here have been developed with a view on improving the CLEAR injector flexibility and reliability while enabling the use of industry standard laser components.

I. INTRODUCTION

CLEAR arises from the experience acquired during the CLIC test facility 3 (CTF3). Before shutdown at the end of 2016, CTF3 demonstrated the feasibility of the CLIC key concepts. The CTF3 developments made available key expertise, space and equipment, which triggered the interest of a broad community within and outside CERN for accelerator R&D. A proposal to adapt and reuse a large part of the CTF3 facility was submitted to the CERN management, which supported the project for an initial period of 2+2 years, with a review between the two terms [1].

The resulting "CERN Linear Electron Accelerator for research" (CLEAR) is a new stand-alone user facility, with the following goals: Accelerator R&D, support of high-gradient acceleration concepts, create a test-bench for beam instrumentation, boost collaboration with other science fields (such as X-ray FELs, medical, space and industrial communities), and maintain training capabilities for the next generation of accelerator scientists and engineers.

Within CTF3, CALIFES (Concept d'Accelerateur Lineaire pour Faisceau d'Electron Sonde) is an electron linac which provided a flexible electron beam for tests built in collaboration among LAL, RAL and CERN [3, 4, 6]. The CLEAR photo-injector is based on the CALIFES RF-gun, and even though it may not be optimal for the CLEAR experimental program, its location, performance, and existing infrastructure make the CALIFES RF-gun a cost-efficient solution for the CLEAR experimental purposes.

The CALIFES RF-gun was constructed with the following parameters:

- Charge of 1.5 GHz electron micro-bunch: 0.6 nC
  Charges exceeding 2 nC/micro-bunch have been observed;
- Macro bunch maximum length: 120 ns (corresponding to 180 micro-bunches);
- Current within the macro bunch: 0.93 A (for a train of 32 bunches);
- Normalized emittance: < 20 π-mm-mrad (for high charge mode, 0.6 nC/bunch);
- Photo-cathode quantum efficiency: QE > 0.3 % (over > 200 hours, initial QE ~ 3%);
- UV laser micro-pulse energy: > 370 nJ;
- Charge stability: < 3% rms.
  Actual measurements (1-2% rms).

It has been observed during experiments in 2019 that the charge stability reaches values of the order of $\sim 1\,\%$ rms when the photocathode operates in saturation mode. The laser system has been identified as the largest contributor to the stability of the charge, and so an improvement in the pulse to pulse stability of the laser system is expected to impact positively the charge stability.

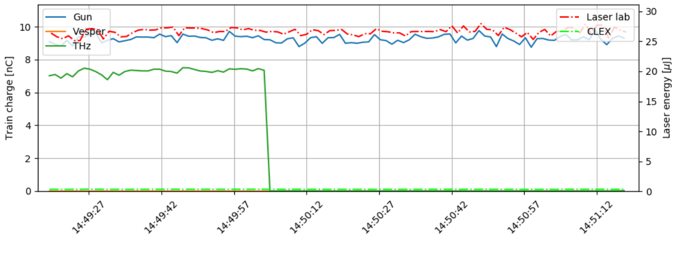

FIG. 1. Bunch charge measured at the exit of the RF gun and laser macro-pulse energy measured at the output of the laser system. Correlations are shifted 1 sample (being the laser energy measurement delayed 1 second) due to acquisition method.

Figure 1 shows the train charge and laser macro-pulse energy correlation during experiments carried out the 22nd of November 2019. Here, the average bunch charge was measured to be $\mu_C = 9.26\,\mathrm{nC}$ with a peak-to-peak and rms stability of 10% and 2% respectively, whereas the laser system produced pulse trains with an average energy of $\mu_L = 26.7\,\mu\mathrm{J}$ and peak-to-peak and rms stability of 11% and 2% respectively. Note that this represents a quantum yield of approximately 0.16%, approximately

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half of the specified QE of $> 0.3\%$. This is possibly caused by operation of the photocathode in saturated mode.

II. LASER SYSTEM ARCHITECTURE

In this section, the main components of the CLEAR photo-injector laser system are described. The current optical chain of the laser is the result of several modifications during the lifetime of the CTF3 facility. Consequently, the aim of this description is to give a comprehensive view of the current state of the laser system and overall performance.

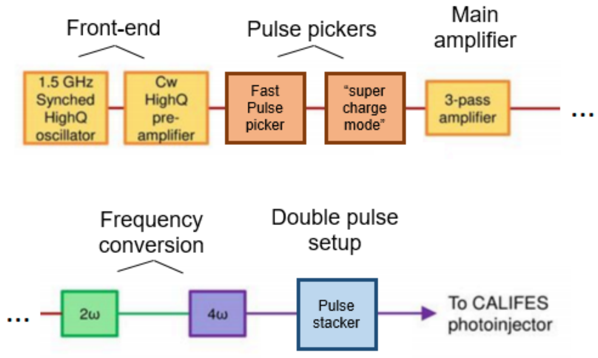


FIG. 2. Simplified schematic of the CLEAR laser setup.

The production of electron bunches in the RF-gun is based on Cs_2Te photo-cathode technology, which generally requires low UV power illumination for operating efficiently [5]. Lifetime of the photo-cathode is one of the main concerns due to the vacuum level in the RF gun. Consequently, the CLEAR RF-gun is equipped with photo-cathode regeneration in-situ by utilizing built-in Cs evaporators. This allows fast recovery of the photocathode quantum efficiency on-demand.

The UV pulses with the required repetition rate and pulse energy are produced by a home-built all-solid-state Nd:YLF system [7]. This laser system is composed of oscillator and pre-amplifier, main amplifier and frequency quadrupling stage as depicted in Figure 2. The UV laser source is centered at 262 nm, with a laser pulse energy of > 370 nJ/pulse (although laser energies of up to 1.5 μJ on the photo-cathode surface have been demonstrated).

The oscillator output pulses are firstly amplified by a Nd:YLF pre-amplifier in order to boost the available average power up to $\sim$ 10 W. The pulses delivered by the pre-amplifier have the same temporal characteristics (5.3 ps pulse duration at 1047 nm) as the oscillator pulses. The tuning of the wavelength of the pumping diodes of the pre-amplifier is performed by temperature adjustment of its chiller with 0.1K increments. This chiller actively stabilizes the temperature of the pumping diode stack enclosure. As the diodes degrade with use, it is required to adjust the temperature set point (usually by lowering it), in order to match the emission wavelength of the diode stack to the peak of the absorption cross-section spectrum of Nd:YLF.

The overall stability of the photo-injector laser relies heavily on the stability of the front-end laser. Accordingly, its output power has been measured continuously for periods of 8 hours. During this test, the power fluctuations were 0.3% abd 2.13% rms and peak-to-peak respectively. Nominally, the output power is 10.14 W, although in order to extend the lifetime of the pumping diodes, the current of the pre-amplifier has been set to 37 A, producing around 7 W of output power. This is enough power for saturated amplification in the main amplifier and efficient frequency conversion to the UV.

The pulse energy was initially regulated by a hard aperture, producing a maximum bunch charge of up to 0.6 nC with a frequency of 1.5 GHz. This aperture was removed from the optical chain during the 2018 upgrades, mainly because the spot size is currently controlled by a variable magnification telescope. This modification allowed to generate up to 1.5 nC/bunch [1] when the spot size on the photo-cathode was magnified. Further foreseen developments include the commissioning of a remote controlled variable size aperture in order to enable the generation of variable size flat-top beams on the cathode with optimized fluence.

Trains ranging from 1 to 300 bunches have been tested successfully, although the current pulse picker system capability limits the pulse train duration to approximately 120 ns (180 bunches). The resulting laser performance parameters are summarized in Table I.

TABLE I. Current CLEAR photo-injector laser parameters.

Laser parameter	**Value range**
Energy onto the cathode [μJ/bunch]	Up to 1.5
Intensity stability rms	<2%
Spot diameter on the cathode σ [mm]	0.8-1.5
Pointing stability onto the cathode rms	<0.2
Wavelength [nm]	262
Micro-bunch length FWHM [ps]	4.7
Micro-bunching frequency [GHz]	1.5
Micro-bunch train length	1-180
Repetition rate [Hz]	0.833 to 5

A. Main amplifier

The output from the pulse picker system is image relayed onto the main amplifier head by employing a 4f telescope. An isolator was placed before the amplifier to avoid potential back-reflections. The beam is then passed 3-5 times through the gain media in order to amplify it (3 or 5 passes maximizes the extraction efficiency of the amplifier without diffraction effects and a reasonable footprint of $0.5 \times 1.5\,\text{m}$). An schematic of the amplifier is depicted in Figure 3.

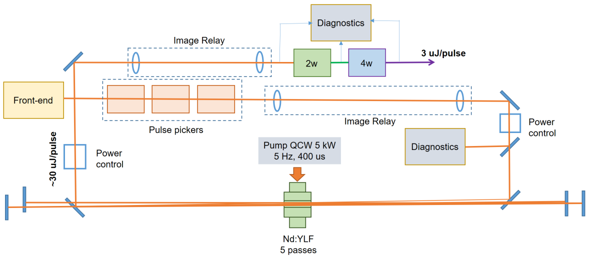


FIG. 3. Schematic of the CLEAR laser main amplifier.

The amplifier is comprised of a 50 mm long, 5 mm diameter Nd:YLF rod (with an Nd concentration of 1.1%), housed in a water cooled copper mount. The rod is side pumped by 5 Quantel QCW diode stacks model QD-Q1707-C (400 μs pulses with 5 kW average power during the pulse) at a maximum repetition rate of 5 Hz. Under these conditions, the single pass gain was approximately 8, whereas the gain after 5 passes was of the order of 10^3. After amplification, the pulses had an energy of approximately 30 μJ at 1047 nm. Power control systems were implemented at the input and output of the amplifier.

Since the aperture of the gain medium is relatively small compared to its length, the multi-pass amplifier was designed in a way so each pass impinges the laser medium with the minimum angle of incidence possible. This was achieved by utilizing both azimuthal and tangential planes for each pass through the gain medium.

1. *Pumping diode stacks*

The gain media is side pumped by 5 diode stacks located 72 degrees between them. These diode stacks were produced by Thales laser diodes SA (document code PIMK 8513) in 2005 although the product was discontinued before this report was compiled. An schematic of the diode layout is depicted in Figure 4. The light produced by the diodes is loosely focused into the Nd:YLF rod by a group of lenses integrated in the gain module, producing an increase in the pumping fluence available. The diodes are connected in serial, and they are rated for operation at 15 VDC (75 VDC in total) and a maximum current of 180 Amps.

In practice, the diode stacks were driven by approximately 120 Amps (66.5 VDC), considerably less than the maximum specified parameters, ensuring long lifetime. So far, these diode stacks have been used for nearly a decade, and still perform up to specification. However, the combination of water erosion and chemical action provoked leaks in the cooling circuit of the diodes, which lead to failure of the main amplifier system several times in 2019. Repair of the cooling circuits (in particular the pipes) was carried out by re-welding replacement pipes into the diode modules. This solutions enabled continuous operation along 2019 with brief interruptions. The current document proposals refer to the substitution of the main amplifier system (including diode stacks, and Nd:YLF rod) in order to avoid potential failure of the repaired units in the near future.

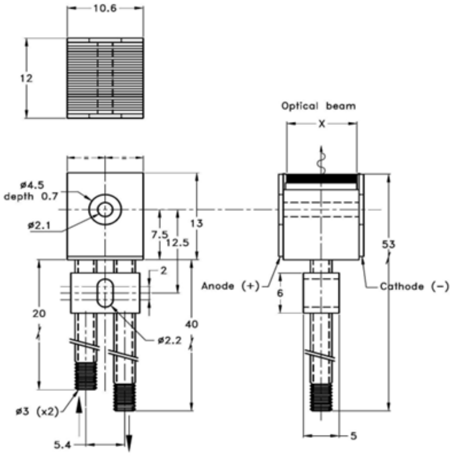


FIG. 4. Schematic of the pumping diodes for the main amplifier. Diode stack shown does not correspond to the existing product (the current stack has only 7 diodes in it).

A summary of the main parameters and performance of the diode stacks is give in Table II.

TABLE II. Technical specification of diode stacks used in the CALIFES main amplifier

Parameter	**Value range**
Case temperature	25 C
Spacing between bars	400 μm
Polarization	TM
Number of diode bars	7
Emitting area	$10{\times}2.4$ mm^2
Optical Power	1100 W
Pulse width	500 μs
Repetition rate	5 Hz
Duty factor	0.25%
QCW Optical Power	1100 W
Current	180 Amps
Voltage	15 VDC
Efficiency	$> 50\%$
Emission wavelength	$805{\pm}3\,\text{nm}$
Emission bandwidth	5 nm
Life-time (at 20% drop)	>500 M shots
Combined pumping power ($\times$ 5)	5500 W

2. *Power Supply*

The main amplifier pumping diodes are currently driven by a Laselec power supply (model QCW 210-120-1), capable of feeding up to 200 Amps of quasi-CW current to the 5 laser diodes modules. Each diode module is has a voltage differential of 14 VDC, and when connected in serial they require a total voltage of 70 VDC to operate at 200 Amps. Note that the original setup was designed to operate with a duty cycle of just 2%, a maximum repetition rate of 50 Hz and a maximum pulse width of 1000 μs. The technical specifications of the power supply are summarized in table III.

TABLE III. Laselec power supply technical specifications

Parameter	**Value range**
Current range	0-210 Amps
Max voltage	96 V
Pulse width	20-1500 μs
Frequency	0-1000 Hz
Max. duty cycle	2% at 100 Hz, 120 Amps
Rise/fall time	$< 20\,\mu$s at 150 Amps

It is clear from this table that the specification of the power supply was over-sized in terms of maximum average power, since the final repetition rate of the laser system was 5 Hz instead of 100 Hz. It is also worth noting that the typical operation point of the power supply was 120 Amps and 66.5 V (an average electrical power during the duty cycle of just 8000 W, which at 50% efficiency produced around 4000 W of combined optical power).

3. *Nd:YLF rods*

Different sets of rods were tested during the commissioning of the amplifier, with a view on optimizing the doping level to ensure efficient amplification with low amplified spontaneous emission. Of the Nd concentrations tested (0.6%, 0.7%, 0.8%, 1.0% and 1.1 %), the latter produced the desired gain results in a simple 3 pass configuration, even though the amplifier was originally conceived for operating in a 5 passes configuration.

The current rod is 5 mm in diameter and 50 mm in length, with a 5 degree opposing tilt in order to avoid ASE build-up. The rod was produced for a-axis pumping (method 5 extended chemical etch) and AR/AR coated at 1047 nm. For more info see Synoptics part No. 455432.

4. *Cooling system*

Currently both the rod and the diode stacks are cooled by the same chiller, although the group of the diode stacks is connected in parallel to the rod chamber. The chiller selected was a Termotek model P307-16103, capable of producing a flow rate of more than 4 l/min at 3.5 bars of pressure. The power rating is 700 W for a stabilized temperature of 22 C (32 C environment). In normal operating conditions, the chiller temperature is set to 30.3 C. Basic specifications of this chiller are given in Table IV.

TABLE IV. Termotek P307 chiller main parameters.

Parameter	**Value range**
Cooling Power (20 C / 20 C)	720 W
Cooling Power (20 C / 35 C)	570 W
Temperature stability	+/- 0.1 C
Regulation of conductivity	1-30 (+/- 1) μS/cm
Flow rate	5 l/min
Water pressure	3.5 bars
Connections	2 × 3/8” internal G thread
Tank volume	2 l

5. *Amplifier pump chamber design*

The amplifier head for the CALIFES system was based in a previous laser project called PILOT. The design is shown in Figure 5. A 5mm diameter, 50 mm long Nd:YLF rod with a wedge to avoid back reflections was orientated with the c-axis horizontal and normal to the rod axis. Five diode stacks were distributed around the rod as described before.

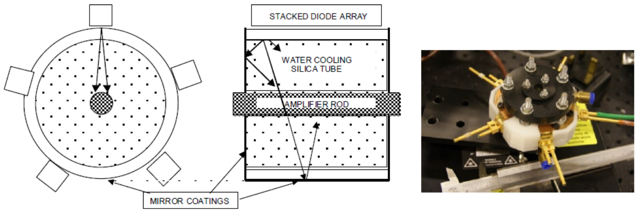


FIG. 5. The PILOT amplifier head design (by Marta Divall).

The larger, 40 degree divergence angle of the diodes was along the length of the rod and was weakly focused by a spherical lens right in front of the diode stack ensuring, that at least 95% of the uncollimated diode output was intercepted by the rod. As the diode stacks have the typical 1 cm array length across the rod, the spherical lens also has helped to focus the beam into the 5 mm diameter rod in the radial direction. Residual un-absorbed pump radiation emerging from the back side of the rod is reflected back into the rod using thin layer aluminium coatings on the outside of the flow tube in regions not occupied by diode arrays. This ensures high absorption efficiency and helps to symmetrise the pump distribution over the rod cross-section. The rod is immersed in water both for cooling and to minimise reflection loss at the surfaces of rod (0.25%) and flow tube (0.2%). In this design the input and output flow tubes were placed at the bottom of the cylinder causing turbulence and allowing air bubbles to sit at the top of the chamber.

B. Empirical measurements of the small gain and saturated gain of the CALIFES amplifier

In the following section, a calculation of the single pass gain for the amplifier module is performed utilizing a theoretical model. This model is based on the more general Frantz-Nodvik model but simplified for the particular case of the CALIFES amplifier. Let us assume we operate in the steady state (constant pump power and resonator losses and constant intensity within the amplifier. In this case the effective gain of the amplifier can be expressed as:

$$g_p = g_0 \frac{E_{sat}}{E_p} (1 - e^{(-E_p/E_{sat})}) \tag{1}$$

Here, g_0 is the initial gain coefficient, which is the parameter that we will estimate, and E_{sat} and E_p are the saturation fluence and pulse fluence respectively. Analogously, by for the case with arbitrarily high gain, one may use directly the Frantz-Nodvik equation:

$$E_{out} = E_{sat} \ln \Big[1 + e^{g_0} (e^{E_{in}/E_{sat}} - 1) \Big] \tag{2}$$

and combining both equations, we obtain:

$$e^{g_p} = \frac{E_{sat}}{E_{in}} \ln \Big[1 + e^{g_0} (e^{E_{in}/E_{sat}} - 1) \Big] \tag{3}$$

Note that in the equations above, g_0 and g_p are dimensionless gain coefficients, not the gain per unit length, and so a direct comparison of the performance of the CALIFES amplifier with commercial gain modules will be possible.

By design, the CALIFES laser exhibited a very high single pass small singal gain of ~ 27, leading to a small signal gain of over 10^5 in 4 passes when pumped over 600 μs. In our experiments, we observed a pre-amplifier CW output power of 7 W, which after the slicing system was converted to a macro-pulse with an energy of 0.7 μJ, containing 150 micro-pulses. In the following we will treat the macro-pulse as a single pulse, neglecting fast picosecond effects in the amplifiers. Taking into account losses in the optical transport chain (including power control and imperfect coupling into the amplifier), the available pulse energy at the input of the amplifier was around 0.5 μJ. The profile of the unamplified beam was Gaussian with a FWHM of 1 mm as depicted in Figure 6. Note that the beam diameter after amplification tends to be super-Gaussian or flat-top like and normally larger than the input beam.

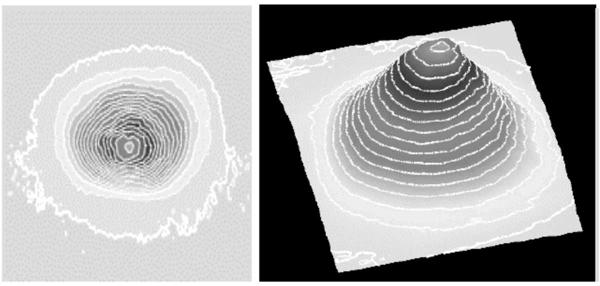
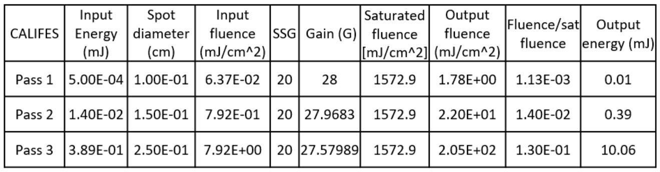


FIG. 6. Unamplified beam profile at the input of the CALIFES amplifier.

The measured output for a 100 ns long train was approximately 10 mJ, and was subsequently converted to the UV, where up to 1 mJ was measured. Amplification was performed in just 3 passes. Matching parameters were obtained assuming a $G = e^{g_0} = 28$. Allowing for tolerances in the measurements, the actual G oscillated between 25-29. The output parameters of the model is shown in Figure 7 for the case of $G = 28$. The total amplification in three passes is of the order of $2{\times}10^5$.



CALIFES	Input Energy (mJ)	Spot diameter (cm)	Input fluence (mJ/cm^2)	SSG	Gain (G)	Saturated fluence [mJ/cm^2]	Output fluence (mJ/cm^2)	Fluence/sat fluence	Output energy (mJ)
Pass 1	5.00E-04	1.00E-01	6.37E-02	20	28	1572.9	1.78E+00	1.13E-03	0.01
Pass 2	1.40E-02	1.50E-01	7.92E-01	20	27.9683	1572.9	2.20E+01	1.40E-02	0.39
Pass 3	3.89E-01	2.50E-01	7.92E+00	20	27.57989	1572.9	2.05E+02	1.30E-01	10.06

FIG. 7. Main parameters of the CALIFES amplifier module for each pass.

III. MAIN SPECIFICATIONS FOR A REPLACEMENT ND:YLF GAIN MODULE

With a view on minimizing the impact to the current laser setup, and the cost to the CLEAR facility, we intend to re-use as many components as possible from the existing CALIFES main amplifier. The alternative Nd:YLF gain module(s) should comply with the current energetic specifications without reducing the performance of the current system, as well as being compatible with the existing power supply, and cooling systems.

The following table (table V contains a summary of performance parameters needed for successful operation in terms of power supply and cooling capability.

Here, the requirement for stored energy is not strict, the value was estimated to ensure that the extraction efficiency remains low, ensuring that the trailing edge of

TABLE V. Summary of technical specifications of the current diode power supply and cooling capabilities. Replacement gain module should be capable of operating within those ranges.

Parameter	**Value range**
Max Current	210 Amps
Max Voltange	96 V
Max Optical Pump Power	6 kW
Duty cycle max	0.5%
Max Pulse width	500 μs
Frequency	Up to 10 Hz
Max Average Power	30 W
Cooling Power	700 W
Flow rate	5 l/min
Input spot size	1.5 mm FWHM
Rod aperture	> 2.5 mm
Small signal gain (in total)	2×10^5
Stored energy	>200 mJ

the macro-pulse experience a gain similar to the leading edge. The stored energy and the small signal gain coefficient are related by the following equation:

$$E_{stored} = \frac{h\nu}{\sigma} g_0 \tag{4}$$

where σ is the emission cross section for Nd:YLF ($\sigma = 1.8\times10^{-19}\,\mathrm{cm}^2$ (E || c)).

IV. PROPOSED REPLACEMENTS

This section is based on commercial diode pumped solid state gain modules available off the shelf. Currently Cutting Edge Optronics (CEO), subsidiary of Northrop Grumman, manufactures modules with similar performance to the CALIFES amplifier, at low cost and with high reliability. CEO offers a variety of gain media, rod diameter, rod length and diode bar count options, enabling appropriate fit to the aforementioned specifications.

In general, there are two main avenues to solve the problem: either by selecting a system that performs similarly to the described above (proposal I), or by selecting a solution optimized to the current operation parameters (proposal II), with an alternative optical layout and number of gain modules.

A. Proposal I

The simplest solution is to acquire a module with an aperture similar to the existing one (5 mm in diameter), and with a total pump power of the order of 5.5 kW. Such module exists in the catalog of CEO, and the exact reference is REA5006-1P200H. This module has the specifications indicated in Table VI.

TABLE VI. Cutting Edge Optronics module REA5006-1P200H

Parameter	**Value range**
Rod diamenter	5 mm
Rod length	126 mm
Current	150 Amps
Frequency	Up to 50 Hz
Pulse duration	400 μs
Pumping diodes	30 × 200 W
Total Pump Power	6 kW
Cooling Power	> 120 W
Flow rate	7.6 l/min
Gain	4.5

In principle, the operating conditions of this module fit well the specifications, although the gain factor of only 4.5 implies modification of the number of passes necessary for attaining a total small signal gain of 2×10^5. The results of the output pulse energy per pass are depicted in Figure 8.

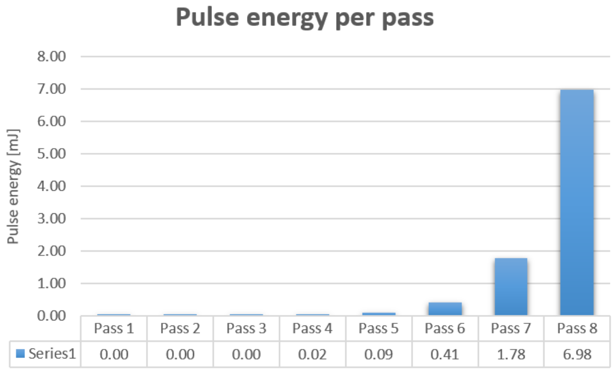


FIG. 8. Macropulse energy per pass for REA5006-1P200H.

From the results, it is clear that this solution is not optimal and could be problematic for the optical arrangement of the passes.

B. Proposal II

A more convenient and cost-effective solution can be achieved by combining two smaller size modules longitudinally and recirculating the amplified pulse through the chain. The limitation here is that the maximum number of passes is four since the aperture of the gain modules is too small to accommodate for passes with a non-perpendicular angle of incidence. A potential layout for the system is give in Figure 9. Additionally, to ensure protection of the front-end laser, it requires Faraday rotators for optical isolation.

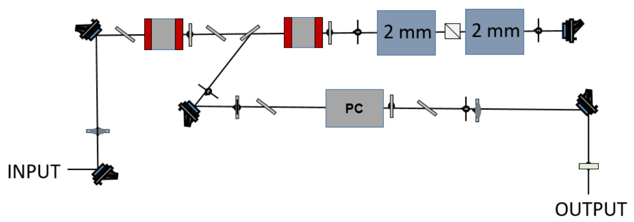


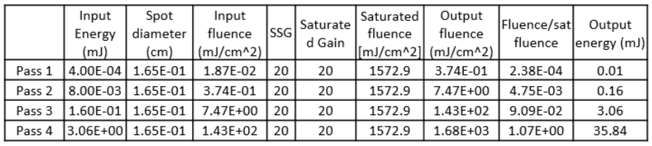
FIG. 9. Proposal for a double pass amplfier based on 2 mm diameter rod gain modules. Elements in red are Faraday rotators. PC: Pockels cell.

The 2 mm rod diameter modules can be of different specifications. Here we show an example module RBAT24-1P200H, with specifications as shown in Table VII. Obviously the combination of two of these modules, produce a total pumping power of 4.8 kW, approaching values similar to the current CALIFES amplifier, and large gain factors of 20.

TABLE VII. Cutting Edge Optronics module RBAT24-1P200H

Parameter	**Value range**
Rod diamenter	2 mm
Rod length	72 mm
Current	100 Amps
Frequency	Up to 50 Hz
Pulse duration	400 μs
Pumping diodes	12 × 200 W
Total Pump Power	2400 W
Cooling Power	> 100 W
Flow rate	3.8 l/min
Gain	20

In terms of usability of the laselec power supply, given that the driving current is 100 Amps and each module delivers a total optical power of 2.4 W, the voltage applied to the module should be of the order of 40V, which probably means that the modules can be connected in serial for both electricity and cooling.



	Input Energy (mJ)	Spot diameter (cm)	Input fluence (mJ/cm^2)	SSG	Saturated Gain	Saturated fluence [mJ/cm^2]	Output fluence (mJ/cm^2)	Fluence/sat fluence	Output energy (mJ)
Pass 1	4.00E-04	1.65E-01	1.87E-02	20	20	1572.9	3.74E-01	2.38E-04	0.01
Pass 2	8.00E-03	1.65E-01	3.74E-01	20	20	1572.9	7.47E+00	4.75E-03	0.16
Pass 3	1.60E-01	1.65E-01	7.47E+00	20	20	1572.9	1.43E+02	9.09E-02	3.06
Pass 4	3.06E+00	1.65E-01	1.43E+02	20	20	1572.9	1.68E+03	1.07E+00	35.84

FIG. 10. Energetics of a double gain module amplifier.

The energetics of this solution are shown in Figure 10. As it can be seen, for a maximum operating current of 100 Amps, the output macro-pulse energy reaches a value exceeding 35 mJ.

The module has a small footprint of only 46.2 x 68.8 mm, while the beam height is only 38.1 mm. Those dimensions are shown in Figure 11. The water connections depicted here are hose barbs for 1/4" ID tubing, whereas the electrical connectors are for screws #8-32 UNC - 2B thread. The mounting holes are spaced 1.88 inches and 2.25 inches, which does not fit directly an optical table. A mounting plate is therefore necessary for installation.

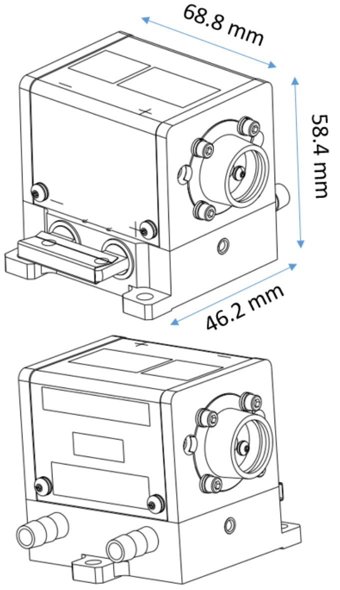


FIG. 11. Sketch of module RBAT24-1P200H.

Figure 12 shows the internal layout of the diode bars alongside with an image of the fluorescence (or ASE) produced by the gain module, which is typically proportional to the gain.

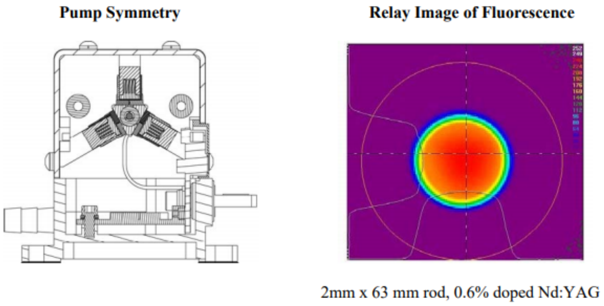


FIG. 12. Sketch of module RBAT24-1P200H and relay image of fluorescence.

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