CERN – European Organization for Nuclear Research

EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CLIC Note 462

Feasibility Study for the CERN 'CLIC' Photo-Injector Laser System

I.N. Ross, Central Laser Facility, Rutherford Appleton Laboratory

Abstract

This study is designed to contribute to the development of the Cern Linear Collider (CLIC). One route to the generation of the required electron injection into this system is through the use of photo-cathodes illuminated with a suitably designed laser system. The requirements of the accelerator and photo-cathodes have led to a specification for the laser system given in Table 1. Because CLIC will not be built directly but in stages, notably via CLIC Test Facilities (CTF), this table also includes the specification for a photo-injector laser system for CTF3 which will be required before the final system for CLIC. Although there are significant differences between these two specifications it will be necessary to design the CTF3 system such that it can be easily upgraded to the system for CLIC and will be able to check all the critical issues necessary for CLIC.

Geneva, Switzerland
5/10/2000

FEASIBILITY STUDY FOR THE CERN 'CLIC' PHOTO-INJECTOR LASER SYSTEM

MARCH 2000

I.N. Ross, Central Laser Facility, Rutherford Appleton Laboratory

1. Introduction

This study is designed to contribute to the development of the Cern Linear Collider (CLIC). One route to the generation of the required electron injection into this system is through the use of photo-cathodes illuminated with a suitably designed laser system. The requirements of the accelerator and photo-cathodes have led to a specification for the laser system given in Table 1. Because CLIC will not be built directly but in stages, notably via CLIC Test Facilities (CTF), this table also includes the specification for a photo-injector laser system for CTF3 which will be required before the final system for CLIC. Although there are significant differences between these two specifications it will be necessary to design the CTF3 system such that it can be easily upgraded to the system for CLIC and will be able to check all the critical issues necessary for CLIC.

2. Objectives

1) To establish whether or not there is a technically feasible and cost effective design of laser system to meet all the requirements of CTF3 and CLIC.
2) To establish a theoretical base for the design and calculate the critical performance parameters.
3) To conduct a survey of the market to determine current sources of relevant equipment and to identify aspects requiring development.
4) To identify critical issues which require resolution to establish confidence in the design, and to propose a development programme aimed at resolving these issues.

3. Specifications

The specifications given in Table 1 are the requirements of the photo-cathode illumination. Since the laser will operate at a longer wavelength than that required for the photo-cathode it is useful to establish the output specifications for the laser. These are given in Table 2, where it has been assumed conservatively at this stage that the efficiency of frequency conversion and beam transport is 5%. This value will be assessed later.

Table 1 Photo-cathode specifications

	CLIC	**CTF3**
UV energy per micropulse	5μJ	0.84μJ
Pulse duration	10ps	10ps
Wavelength	<270nm	<270nm
Time between pulses	2.13ns	0.67ns
Pulse train duration	91.6μs	1.4μs
Repetition Rate	100Hz	5Hz
Energy stability	<0.5%	<0.5%
Laser/RF synchronisation	<1ps	<1ps
Reliability	10^9 shots between servicing	

Table 2 Laser specifications

	CLIC	**CTF3**
Energy per micropulse	100μJ	17μJ
Total pulse train energy	4.3J	32mJ
Pulse train mean power	47kW	25kW
Laser average power	430W	0.15W
Efficiency of IR to UV	5%	5%

4. Key parameters

The key parameters are those which are not readily available from commercial systems or have not been demonstrated to be straightforward and hence whose feasibility needs to be established. These parameters largely determine the system design.

1) Laser energy stability - not only does the 0.5% specification in the UV place a very tight requirement on the laser output, but also it must be able to respond with this accuracy to the varying needs of the photo-cathode due to sensitivity changes etc.
2) Laser synchronisation – the specification is 1ps.
3) Laser average power - the laser is required to deliver 430W, a high value for lasers, and one demanding careful design to prevent beam degradation due to thermal effects.
4) Laser pulse train power – an average output power in the pulse train of 47kW places severe demands on the laser pumping system.

5. Relevant literature and basic data

Before outlining possible designs for the laser system it was necessary to gather together information from the literature to enable informed choices to be made. This section highlights relevant information, with comments aimed at placing the information in context.

Table 3 presents material parameters for possible laser active media, highlighting parameters and values which are important to this design study.

Table 3:	Nd:YLF	Nd:YAG	Nd:glass	Yb:YAG	Yb:glass	TiS	Cr:LiSAF	Alexandrite
λ_{las} nm	1047	1064	1060	1030	1030	800	846	750
λ_{pump} nm	~800	808	800	940	940	550	680	680
t_{min} ps	**5**	**20**	**0.4**	**0.5**	**0.1**	**0.03**	**0.05**	**0.1**
σ x10^{19} cm^2	4.5	6.0	0.42	0.18	0.06	3.0	0.48	0.12
τ_{fl} (μs)	480	230	350	1000	1900	4.3	67	260
$F_{sat} = h\nu/\sigma$ J/cm^2	**0.42**	**0.32**	**4.5**	**10.6**	**32**	**0.8**	**4.9**	**22**
η_p %	76	76	68					
n_2 x10^{13} esu	0.8	4	1.0	4	1	1.3	0.5	0.8
Therm/opt power	**0.32**	0.32	**0.47**	**0.1**	**0.1**	0.45	0.25	0.1
Pump intensity for x2 gain in kW/cm^2	**10**		**45**	**81**	**244**			
Loss rate for x2 gain in kW/cm^2	**3**					**133**	**51**	**59**

where:

λ_{las} = laser wavelength
λ_{pump} = pump wavelength
t_{min} = minimum pulse duration
σ = emission cross-section
τ_{fl} = fluorescent lifetime
F_{sat} = saturation fluence
η_p = pump efficiency
n_2 = non-linear refractive index

5.1 Oscillators

The laser system requires an oscillator operating in the wavelength range 750 to 1100nm, mode-locked at up to 1.5GHz with pulse duration of 10ps or less and delivering as high power as possible. Some examples of oscillators which have been demonstrated to have some or all of these characteristics are:

2GHz operation with pulse duration of 7ps was achieved by Weingarten et al (1).
40W cw operation of Nd:YLF was reported by Cerullo et al (2).
Over 200W cw was demonstrated for a TEM mode oscillator by Hirano et al (3).
A 20W mode-locked and diode-pumped oscillator was reported by Graf et al (4).

5.2 High power laser systems

We are particularly interested in the design and operation of high average power systems of which a number have been reported in recent years:

Several design papers give useful information on the considerations and limits for high average power systems; for example, the work of Basu et al (5), Holleman et al (6) and Brown (7). Laser amplifier heads with stored energy more than 1J (Positive Light) and average power of 500W (CEO) are available commercially.

5.3 Other relevant work

The following literature has been used in the course of this study to provide important information on different aspects of the design. These aspects include thermal effects, pumping efficiencies and pumping schemes.

The principal reference used for estimating the pumping efficiency of diode pumped materials is Barnes et al (8). This calculates the absorption efficiency integrated over the emission spectrum of diodes and the absorption spectrum of the laser medium for different concentration-length products, and where necessary calculates the effect of different polarisations with respect to the crystal axes.
Estimates of thermal lensing follow the measurements made by Cerullo et al. (2), while other thermal effects in high power amplifiers have been treated by Brown (7).
In addition to standard pumping designs used in commercial devices a number of novel schemes have been proposed, generally to try to maximise the pump intensity at the rod. Two of note are the 'lens duct' of Beach et al. (9) and the 4-sided scheme of Hirano et al (3).
The etching technique for enhancing the fracture limit of crystal rods is reported by Marion (10).

6. Basic design features and choices

6.1 Wavelength

The laser wavelength needs to be equal to or a multiple of the required wavelength at the photo-cathode (<270nm). Since efficient high power generators at 540nm or less are not yet available, we are restricted to wavelengths less than 810nm with third harmonic generation to convert to the photo-cathode wavelength, or less than 1080nm with fourth harmonic generation. The former includes titanium sapphire and alexandrite, while the latter includes all the neodymium and ytterbium-doped and some chromium-doped materials. All these are solid state laser media.

6.2 Pump source

The available pump sources for solid state lasers are discharge lamps and diode arrays. We believe that only the diode arrays can meet the shot life requirement of 10^9 and have an intrinsically higher stability and lower thermal deposition in the laser material. The cost is higher but not unreasonably so (see section on commercial equipment) and continuing development will lead to a reduction in the cost differential before the complete CLIC system is built.

In consequence this design study is based on diode pumping.

6.3 Gain medium

There are three principal criteria for selecting the best gain medium for the amplifiers.

The first is that the gain bandwidth must support the amplification of pulses of 10ps or less, which eliminates the materials Nd:YAG and Ruby.

The second is that the material must be able to achieve a reasonable gain (greater than ~2) with quasi steady state pumping, without excessive losses due to the fluorescence decay. This loss is regarded as excessive if it is much larger than the extracted power in the amplified beam. Table 2 indicates a required extracted power of 47kW for the CLIC system. Table 3 gives the loss rate for a rod of diameter 10mm and gain x2. This is seen to be very high for Ti:sapphire, alexandrite, Cr:LiSAF (and other Cr-doped crystals) and we reject them on this basis.

Of the remaining materials Nd:vanadate is not currently available in large enough pieces to be used for the amplifiers and although well suited for the oscillator its wavelength is not matched to the gain wavelengths of the acceptable amplifier materials (except marginally to that of Nd:glass).

The third important parameter is the pump power required to generate a reasonable gain in the material. Table 3 gives the power per unit cross-sectional area required to generate a gain of 2 for a pump duration of 100μs. We see that Yb:glass could only achieve very low gains at acceptable pump rates and could in consequence only be used in regenerative amplifiers. Additionally it is only possible to achieve modest gains with Nd:glass and Yb:YAG.

If high gain amplifiers are preferred Nd:YLF is the best option. It also has very low thermal distortion and its birefringence ensures a well polarised output.

The main potential problem with Nd:YLF is its low thermal fracture point which limits the thermal deposition of power into the rod to a maximum of approximately 20 watt per centimetre length.

6.4 Amplifier type

Rod amplifiers are preferred, being simpler, better for optical quality and less expensive. Slab amplifiers would need to be considered if required pump powers and thermal deposition rates are too high for rod amplifiers. However, as will be demonstrated, this does not seem to be the case for CLIC.

Amplification can be carried out using single, multipass or regenerative amplifiers or seeded oscillators. This study mainly concentrates on single and double pass amplifiers and demonstrates that a system based on them is feasible. Four pass amplification can reduce the number of smaller amplifiers at some cost saving but with increased complexity. An injection-seeded oscillator looks a good option for the first stage of amplification especially if the master oscillator provides only low power since it is well suited to giving high power pulse trains with good stability. It has reduced efficiency due to the cavity losses and greater complexity in comparison with amplifiers and is not preferred for the final amplification stages. Regenerative amplifiers have not been considered further because of the difficulty of operating them with pulse train outputs.

In conclusion this study has chosen to base the design of the photo-injector laser system on single or multipass diode pumped rod amplifiers using Nd:YLF as the gain medium.

7. Commercial systems

7.1 Diode Arrays

These are the building blocks of the laser system and much of the design of the high cost final amplifiers centres around the performance of commercially available diode arrays. All arrays are based on a linear array which is about 10mm long and can be stacked with an array spacing of order 1mm. Quasi continuous (QCW) operation with duration 200μs and repetition rate 100Hz can give powers up to 120W and, when stacked, intensities greater than 1.2Kw/cm^2. Table 4 gives data on a selection of commercial products. It will be seen from the amplifier simulations that the total power requirement for CLIC may be ~80Kw leading to an approximate diode cost of £320k at current prices.

Table 4 Commercial diode arrays

	Peak power kW	Active area mm	Peak intensity k W/cm^2	Cost £/W
Thompson CSF	up to 2.5	10 x 9.6	up to 2.6	4 (bulk) 6.5(ea)
JenOptik (fibre coupled)	2.0	10 x 42	0.48	
Infineon (linear)	0.1	10		
Nuvonyx (complete systems)	up to 4		up to 28 (focused)	
SDL	0.24		0.12 (cw)	
OptoPower (Spectra Physics)	up to 3 1.0Qcw	 10 x 15	0.5 0.67	 8(ea)
Laser Diode Arrays	0.25 (cw)			
IMC	up to 5.6 0.4		1.4 1.0	

7.2 Laser Amplifiers

There are a growing number of commercial amplifiers mainly aimed at the materials processing market as replacements for existing lamp-pumped systems. Most of these use Nd:YAG as the active medium but the design is also suitable for use with Nd:YLF. Commercial systems are designed as oscillators with the result that the head is designed for high power but not high gain and not necessarily maximum efficiency.

A high power commercial system would be an attractive option for a seeded oscillator if this were included in the final system, since it does not require high gain and efficiency is not one of the key performance criteria in the early amplification stage.

7.3 Laser oscillators

Suitable diode-pumped mode-locked oscillators meeting the principle specifications of pulse duration and repetition rate are available. For 1μm oscillators Nd:vanadate is now the preferred material but systems using Nd:YLF are available. Systems currently on offer are low power (1W) compared to several demonstrated in the literature (100W) but it is expected that it will be possible to purchase much higher power within the next few years, particularly if a collaboration can be arranged.

8. System Architecture

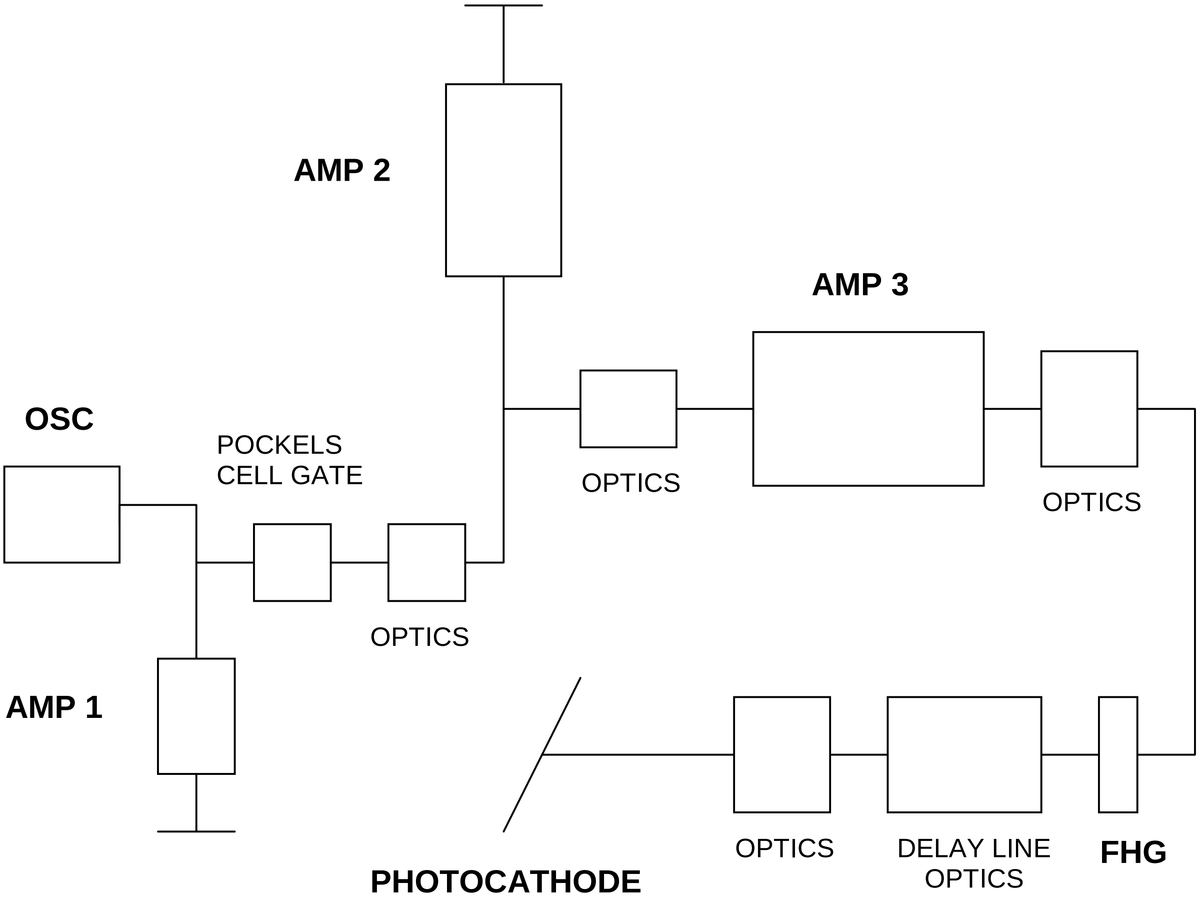


Figure 1 Basic system architecture

An outline design architecture is shown schematically in Figure 1 and demonstrates the key features of the system. The pulse train from a cw oscillator with the correct pulse duration and repetition rate and at the correct wavelength is amplified by a sequence of single or double pass amplifiers to the required pulse energy specification. These pulses are converted to the fourth harmonic in a pair of nonlinear crystals and the resulting UV pulse train is relayed to the photo-cathode. Other features of the system are: beam conditioning optics for beam sizing, relaying and filtering; electro-optic devices both for switching out the required pulse train and for fast feed back amplitude control ; fast feedback control of pump diode array current.

9. Detailed design considerations

The system can be conveniently broken down into a number of aspects for detailed analysis:

1) General amplifier design considerations.
2) Amplifier designs for CLIC and CTF3.
3) Fourth harmonic generation.
4) Laser damage threshold.
5) System staging - including the disposition of the system components and the design of the beam conditioning optics
6) Stability - ways to control the intrinsic instabilities of the design through design changes and through the introduction of feedback mechanisms.
7) Failure modes and protection against these failure modes.
8) Additional comments - on the oscillator and synchronisation.

9.1 Amplification

In this section an analysis is given of the dynamic gain characteristics of both single pass and double pass rod amplifiers subject to a spatially uniform pumping rate and having a spatially uniform input pulse train. Account is taken of: the diode pumping; the amplification of the beam; the depletion of the stored energy by the beam; the fluorescence losses; and the amplified spontaneous emission (ASE).

The approach taken is to specify the output requirements (pulse train power and energy stability) of the amplifier and to look for parameters which minimise the pump energy and maximise the tolerance on the input parameters. The aim is to try to establish 'steady state' operation of the amplifiers since this is most likely to be able to satisfy the stability requirement. An important feature of steady state operation is the time for it to become established, since it is necessary that this is sufficiently short that it does not lead to unacceptably high pumping losses and thermal effects. This stabilisation time can be minimised by allowing the amplifier to be pre-pumped for a time, T_P, before switching in the pulse train.

It should be remembered that the 'steady state' operation does not imply a constant gain coefficient along the amplifier even though the pump rate is constant in this respect.

9.1.1 Steady state operation

A simple and useful relationship can be found for the amplifier in steady state. In this case the extracted pulse train power is balanced by the difference between the pumping rate and fluorescence losses. This can be written:

$$P_{out}(1-\frac{1}{G}) = \eta_p.P_{abs} - \frac{\pi D^2}{4}.F_{sat}.\frac{\ln G}{2}.\frac{(1+B)}{\tau_{fl}} \qquad 1$$

where η_p = fraction of the absorbed power (P_{abs}) reaching the upper laser state and we assume a fast energy transfer between the upper state levels.

F_{sat} = saturation fluence = $h\nu/\sigma$

G = amplifier gain

B = additional losses due to amplified spontaneous emission

τ_{fl} = intrinsic fluorescence decay time

The factor 2 is for a double pass amplifier (1 for single pass amplifier)

For example, inserting the values for Nd:YLF, setting B = 0 and taking the output requirement for CLIC of P = 47kW gives:

$$47(1-\frac{1}{G}) = 0.76P_{abs} - 0.34\ln G.D^2 \qquad 2$$

and for a 1cm diameter rod with gain x4, absorbed power must be = 46.4 + 0.6 = 47.0kW where the second term (+0.6) is the fluorescence loss.

The same calculation for Nd:glass for example gives a required absorbed power = 51.8 + 10.3 = 62.1kW and reflects, through the second term, the high pumping rate needed for this low gain material.

A comparison between single and double pass amplification can also be made using equation 1. For amplifiers with the same gain the fluorescence loss term is a factor of 2 less for double pass operation and consequently requires less pump power to reach the same gain. For the two examples above the difference between single and double pass is only an additional 0.3kW for Nd:YLF but for Nd:glass a significant extra 5.1kW pump power is needed.

9.1.2 Full calculation

The calculation is characterised by the following parameters:

The absorbed pump power P_{abs} which is assumed uniformly distributed over the rod.
The input and output fluences F_{in} and F_{out} of a pulse in the pulse train.
The diameter D and length L of the amplifier rod.
The pulse fluence F(z,t) within the amplifier.
The gain coefficient α(z,t) within the amplifier.

The calculation increments through the pulse train calculating for each pulse its amplification and the resulting gain distribution for the next pulse. There is an underlying assumption that the amplifier deals with each pulse sequentially in time, and this may not be the case for double or multipass amplifiers. However the assumption is valid if, as in the case being considered, the pulse fluence is small compared with the saturation fluence and leads to only a small incremental change in the gain coefficient.

The pulse fluence within the amplifier can be written:

$$F(z,t) = F_{in} \exp\int_0^z \alpha(z,t)dz \qquad \text{for single pass amplification} \qquad 3$$

$$F(z,t) = F_{in}\left[\exp\int_0^z \alpha(z,t)dz + \exp\left(\int_0^L \alpha(z,t)dz + \int_z^L \alpha(z,t)dz\right)\right] \qquad \text{for double pass} \qquad 4$$

The incremental change in the gain coefficient from one pulse to the next has 3 contributions: the increase due to pumping; the loss due to fluorescence enhanced by amplified spontaneous emission; and the depletion by the previous pulse. The net change is given by:

$$\Delta\alpha(z,t) = \frac{\eta_p \eta_R}{F_{sat}}.\frac{4P_{abs}.\tau_S}{\pi D^2 L} - \frac{\alpha(z,t).\tau_S.(1+B)}{\tau_{fl}} - \frac{\alpha(z,t).\eta_R.F(z,t)}{F_{sat}} \qquad 5$$

where: η_R = level splitting ratio in the upper laser state and it is assumed that the equilibrium in the level populations is re-established in a time very short compared with τ_S.
τ_S = time separation of the pulses in the train

The analysis of amplified spontaneous emission (ASE) is given in the following section. In order to include its effect in this calculation an approximate analytic expression is used for B as follows:

$$B \approx 0.05.\left(\frac{D}{L}\right)^{0.3}.G^{0.5} \quad \text{for decoupled double pass amplifiers}$$

$$B \approx 0.05.\left(\frac{D}{L}\right)^{0.3}.G \quad \text{for single pass amplifiers} \qquad 6$$

$$B \approx 0.05.\left(\frac{D}{2L}\right)^{0.3}.G \quad \text{for close-coupled double pass amplifiers}$$

Using these equations the dynamic development of both gain and pulse train fluence was evaluated to provide a solution for a specified output pulse train with less than 1% variation over the required pulse train length. Comparison was made between Nd:YLF and Nd:glass as the active medium, between single and double pass operation and for different rod sizes up to 10mm diameter and 150mm long.

Before giving specific solutions for CLIC and CTF3 there are a number of general conclusions to be obtained from the analysis. To assist with this discussion it is useful to note the features of the solutions. Figure 2 shows an example of the output pulse train for the case of a double pass amplifier with its gain switched on in the presence of the input pulse train. The output pulse energy rises to become stable ('steady state') after a characteristic response time. At later times the output is seen to be stable to a very high degree. The process can be under-, critically- or over-damped (example of figure 2 is over-damped) with the minimum response time for the critically damped case as one would expect. Since the extraction efficiency is given by:

η_{ext} = the output pulse train energy/total pump pulse energy

it is important to minimise the proportion of the pump pulse during which the output is stabilising and is not being efficiently extracted by the pulse train. This is particularly important for CLIC for which the average power is high and the thermal effects are a critical issue. Since for CLIC the pulse train duration is 91μs we would seek a design with the response time much less than this. Evaluating a number of different simulations such as in figure 2 we find the following useful approximations for Nd:YLF double pass amplifiers:

The condition for critical damping appears to be: $\frac{4.P_{abs}}{\pi D^2} \approx 240 kW/cm^2$ 7

with a response time $\approx 10.\ln G \mu s$

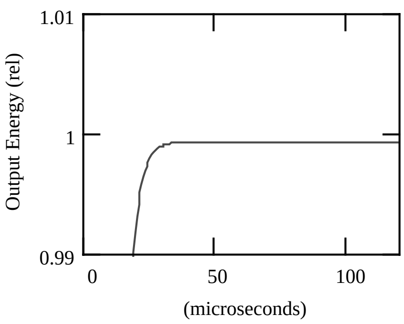


Figure 2 Double pass Nd:YLF diode-pumped amplifier with diodes initiated at zero time and continuous injection of mode-locked pulse train

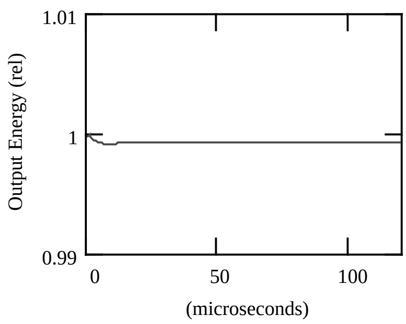


Figure 3 As figure 2 with diode initiation 6.8μs before injection of pulse train

This method of operating the amplifier, with input pulse train continuously injected, is preferred since, as discussed in a later section, it is safer. However if the response time is unacceptably long it is possible to eliminate it by turning on the amplifier before a pulse train arrives. In this case the amplifier is pumped until the gain reaches the steady state value, and if the pulse train is switched in at this time, the time to reach steady state is greatly reduced. Figure 3 shows the example of figure2 but with the amplifier pumped for a period of 6.8µs before injection of the pulse train.

Another feature of the amplifier performance is its sensitivity to variations in the pump power and the input pulse energy. These are illustrated in figure 4 for which the input energy has been decreased by 1% and the pump power is suddenly increased by 1% after 60µs.

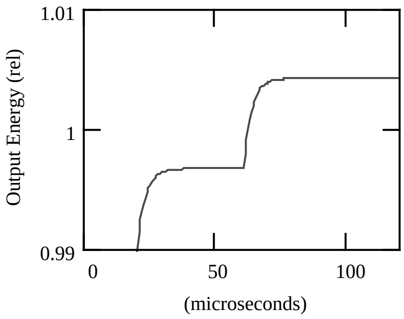


Figure 4 Effect of small changes in input energy and pump power

The conclusions on sensitivity tests are:

Output pulse energy variation = input pulse energy variation / G 8

This is simple to demonstrate analytically by differentiating equation 1. Consequently by extending this argument through several saturated amplifiers the tolerance of the pulse energy increases with the total gain to the output of the system. The requirement for stability of the beam energy and pump power of early amplifiers and oscillator is very much relaxed.

Output pulse energy variation = pump power variation 9

and has a 1/e response time of about 4µs for a sudden pump power change. Consequently we can see that the pump power of the final amplifier is the most critical parameter for the stability, and represents a good route for a feedback mechanism to stabilise the system. This approach can respond to variations on a time scale of a few µs.

A significant difference between single and double pass operation is in the response time to reach steady state. This is illustrated by the single pass simulation shown in figure 5 which corresponds to the double pass case of figure 2. The response time is 50µs compared to 25µs for double pass and is consequently significantly less efficient in its usage of pump power.

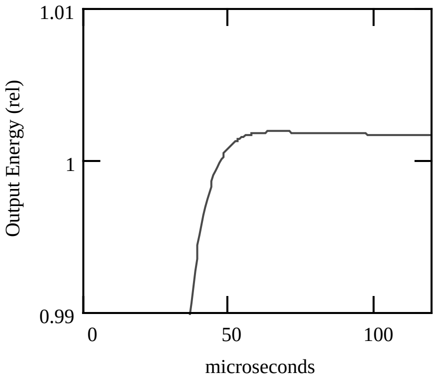


Figure 5 As figure 2 for single pass amplifier

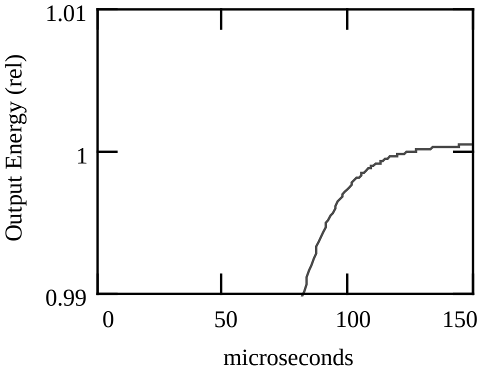


Figure 6 As figure 2 for Nd:glass

The comparison between Nd:YLF and Nd:glass is illustrated by the simulation shown in figure 6 which has the same amplifier specification as that for Nd:YLF, shown in figure 2. The two main differences are a 21% higher pump power requirement to achieve the same pulse output energy and a very long response time of 120μs.

We can conclude from the above analysis that:

Good output energy stability can be achieved at the output energy required with an acceptable initial period of pumping to converge to steady state operation. If necessary this initial response time can be eliminated by pumping the amplifier for a short period before switching in the input pulse train.

Double pass amplification gives slightly better performance than single pass but involves, of course, additional optical elements.

Nd:YLF looks to be a better active medium than Nd:glass for this application.

9.1.3 Amplified Spontaneous Emission (ASE)

An amplifier is a generator of photons at the laser wavelength through fluorescent decay of the upper laser level. This emission is amplified by the amplifier in which it is generated and a fraction is in the direction to be amplified by subsequent amplifiers. There are two principal effects of this ASE.

It may generate sufficient pre-pulse energy at the workpiece/target to interfere with the laser application. This will not be a problem for the photo-injector because this low intensity background will be decoupled from the photo-cathode by the nonlinear fourth harmonic generation process.

The second effect is potentially more troublesome. The effect of the ASE in the amplifier is to increase the rate of depopulation of the upper laser state and we can describe it in terms of a reduction in the upper state lifetime. The effective lifetime can be written as:

$$\tau_{eff} = \tau_{sp} / 1 + B_P \qquad 10$$

where: $$B_P = f.\alpha.\int \frac{\exp(\alpha.r)}{4\pi r^2} dV$$

and the integration is carried out over the volume contributing to the ASE at the position P. α = gain coefficient; f = the fraction of the excited state population which fluoresces at the laser wavelength and r = distance from the point P

Using this integral B was evaluated for a rod amplifier similar to the output amplifier for CLIC in single and double pass and with either a polished or diffuse barrel surface. Figure 7 shows, for several cases, the variation of B with rod amplifier gain G. We have seen from equation 2 that for a Nd:YLF amplifier satisfying the requirements for CLIC the effect of the fluorescence term is small and its ASE enhancement by a factor of even two would not greatly affect the amplifier performance. Figure 7 would suggest that in this case a double pass amplifier with a gain as high as 100 is possible. The maximum amplifier gain would, using a similar argument, be less for a single pass amplifier and much less for a Nd:glass amplifier.

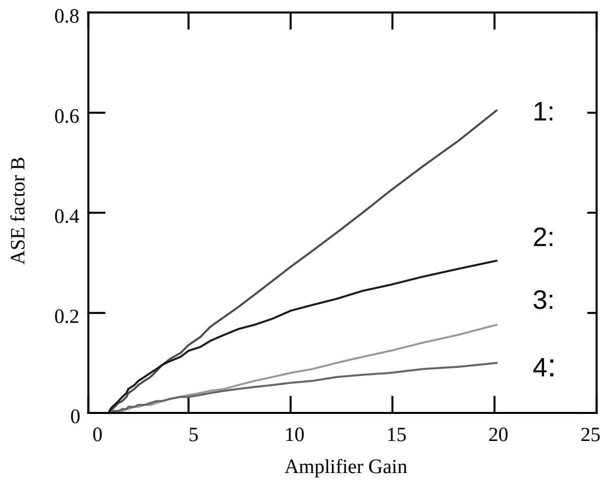


Figure 7 Amplified spontaneous emission factor B for diode pumped rod amplifier
1: (Red) – end of single pass amplifier with polished barrel
2: (Blue) – centre of single pass amplifier with polished barrel
3: (Green) – end of single pass amplifier with ground barrel surface
4: (Mauve) – output end of double pass amplifier with polished barrel

9.1.4 Diode Pumping of the Rod

This section considers the feasibility of generating sufficient absorbed pump power in the rod to meet the amplification requirements. We concentrate on the requirements for the final amplifier in CLIC since these are likely to be the most difficult to meet and section 9.1.1 estimated that an absorbed pump power of 47kW would be required. The problem is reduced to finding the simplest design of pumping chamber which will contain a sufficient number of diode arrays, will couple the diode power efficiently to the rod, and will allow efficient cooling of the rod.

The maximum thermal loading on the rod for the final CLIC amplifier is given by:

$$\text{Thermal Power} = \text{Output Optical Power} \times \frac{1-\eta_p}{\eta_p} \qquad 11$$

$$= 0.32 \times \text{Output Optical Power} \quad \text{for Nd:YLF}$$

Since the average output power requirement is 430W, the thermal deposition rate is 140W. This places only a modest cooling requirement on the amplifier head and can be satisfied using water immersion and a low flow rate.

The absorption efficiency of the rod is not simple to estimate since it depends on various factors such as the emission spectrum of the diodes, the absorption spectrum of the amplifier medium, the diameter and active medium concentration of the rod and the distribution of the pump beam over the surface of the rod. In particular the diode spectrum is broader than the principal absorption line of media such as Nd:YLF and also, for this material, the absorption is polarisation dependent. Fortunately much of this analysis has been carried out by Barnes et al. (8) and for the case being considered (Nd:YLF at 1% concentration, diode bandwidth = 5nm, average of both polarisations) their results can be reduced to the approximate expression:

$$\eta_{abs} \approx 1 - \exp - \left(D/_{0.42} \right)^{0.77} \qquad 12$$

For example, if the absorption efficiency is required to be greater than 80% the rod diameter must be greater than 0.78cm and this is larger than some of the designs being considered. For this reason the pumping chamber is designed so that residual un-absorbed pump radiation is reflected back into the rod for a second pass and the effective diameter is twice its actual diameter. In this way we can achieve 80% absorption efficiency with rods of diameter 0.39cm.

The coupling efficiency from the diode arrays into the rod also needs to be as near 100% as possible. To this end the design is required to couple all rays into the rod which leave the diode within the angular range 80 x 20 degrees (typically the 95% included angular range). Other coupling losses, due to surface reflections, must also be minimised.
The use of liquid immersion not only reduces these reflection losses but also helps to refract rays into the rod. For Nd:YLF in water for example the surface reflectivity is reduced to 0.2%.

The pumping chamber must be able to contain a sufficient number of diode arrays to provide the power requirement and, at this stage, it is best to use the parameters of commercially available arrays. The design here is based on the arrays of Thompson CSF.

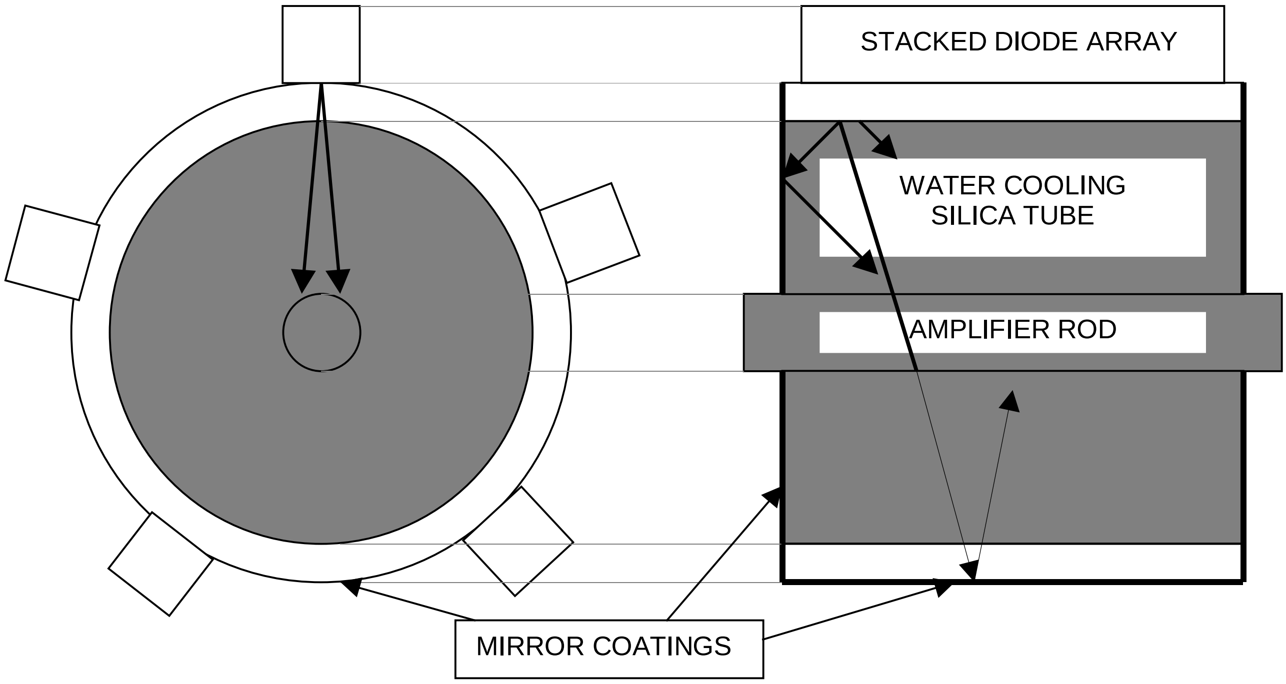


Figure 8 Schematic of diode-pumped amplifier head

Figure 8 illustrates a simple design suitable to meet the requirements of the CLIC photo-injector system. This design couples together 1 x 1cm arrays to form 3 off 1 x 9 cm stacked arrays which surround a 1cm dia. x 10cm laser rod, thus providing at a maximum of 2.5kW QCW per array a maximum total output of 67.5kW. The linear arrays are orientated tangentially with respect to the rod to enable the rod to collect, with the assistance of end reflectors, the full 80deg angular range from the diodes. With this orientation the pump rays arriving at the rod are a mixture of both polarisations. The estimated coupling efficiency of this design is 85% and the estimated absorption efficiency is 96%. The projected maximum absorbed power for this arrangement is consequently 55kW, well in excess of the estimated requirement of 47kW.

The proposed pumping scheme as shown in figure 8 can be adjusted to provide efficient coupling to smaller diameter rods if the diameter of the flow tube is reduced and additional positive cylindrical or spherical lenses are introduced between each diode array and the rod.

9.1.5 Thermal Effects

Three aspects of the thermal effects must be taken into account to ensure that they are accommodated by the system design.

Rod cooling

The cooling rates for rods in water are in the range 1-10W/cm^2 degK, for flow rates of 4-40 l/min. If we assume the lower end of this range and an average thermal deposition rate of 140W into a 1cm dia. x 10cm rod, the temperature rise of the water would be approximately 5deg.

Thermal Fracture of the rod

There is some uncertainty in the value of this parameter for YLF. If we take a lower value of 17 W/cm length of rod, the maximum acceptable thermal deposition in a 10 cm rod, for example, is 170 W.

It has been demonstrated for YAG and GSGG that etching the rod barrel surface to eliminate micro-cracks can increase the fracture limit by an order of magnitude, so it is expected that a similar process with YLF would increase the fracture limit substantially.

Note that glass has an even lower fracture limit than YLF and would be required to withstand a higher thermal loading.

Beam distortion

A significant advantage of YLF is its low value of thermal focusing. From Murray's paper (11) we derive the following relationship for the thermally induced focal lengths in the 'o' ('σ') and 'e' ('π') planes at the principal wavelength of 1047nm:

$$f_o = 2.2.D^2/P_{th} \quad \text{and} \quad f_e = -0.65.D^2/P_{th} \quad \text{respectively} \qquad 13$$

for D in mm and P in W

or, more simply,

the maximum wavefront error, $\delta_0 = 0.05P_{th}$ or $\delta_e = -0.19P_{th}$ μm respectively

For example, for D = 1 cm and P = 150 W:

f_o = 1.5 m; f_e = -0.44 m; δ_0 = 8.6 μm; δ_e = -28.5 μm

Although Nd:YLF has less thermal distortion than other materials it is still necessary to use spherical and cylindrical optics to correct for the resulting aberration.

9.2 Design of amplification system

The considerations of the previous section can now be incorporated into a specific design. The more demanding design is for CLIC and this will be addressed first. The design for CTF3 will follow, its principal requirement being that it should be readily upgradeable to the CLIC system.

Note that pump powers refer to the absorbed pump power. The diode output power is higher than this by a factor = $(\eta_{abs}$ x pump cavity coupling efficiency$)^{-1}$. For the design rod diameters of 0.7cm and 0.5cm and assuming a coupling efficiency of 85%, this factor is 1.28

and 1.37 respectively.

9.2.1 Design for CLIC

The specification for the CLIC system is given in Table 2. A laser output pulse train of duration 91µs, having a pulse energy of 100µJ (IR), and a mean pulse train power of 47kW is required at a repetition rate of 100Hz, and it is important to minimise the required pump power. A key parameter is the total gain of the amplifier system which depends on the available output from the oscillator. Given that suitable oscillators up to 100W output power have been demonstrated we assume for this design study that 30W is available. If this is not the case adjustments to the design can be readily made. 30W input and 47kW output leads to the requirement of a gain of 1600. Figure 9 shows schematically three configurations to achieve this based on the amplifier simulations and the expected gain limits. All are possible but the three amplifier case is preferred here because it is more conservative and places less demands on pump power and gives less thermal effects in the final amplifier. The total pump power requirement is almost the same for all the three schemes.

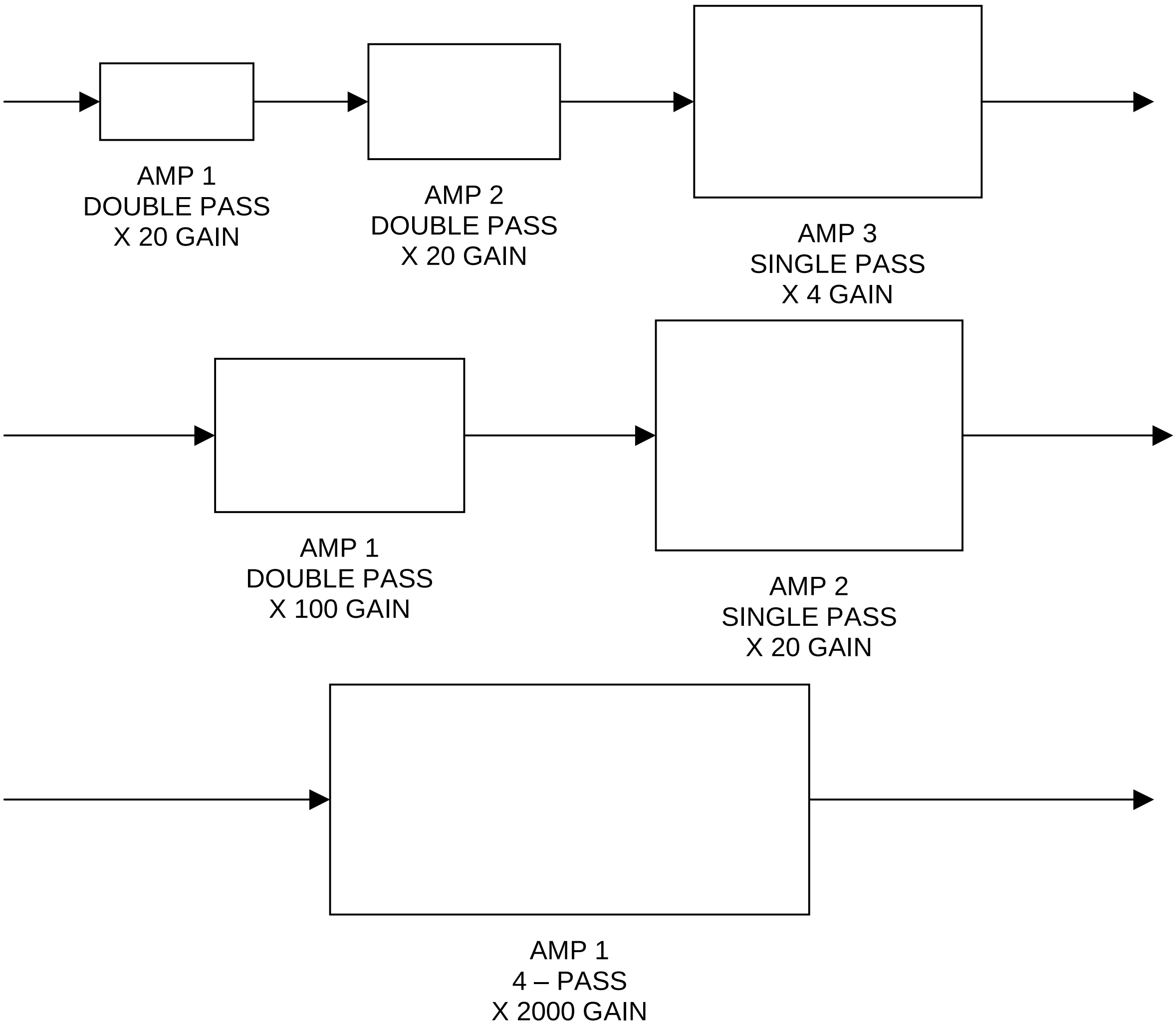


Figure 9 Three possible amplifier arrangements for CLIC

The performance of the final amplifier is illustrated in figure 10 by the dependence of the output train pulse energy on the time after initiation of the pumping, and in the presence of a constant energy input pulse train. The pump power required to achieve the specified performance is 48kW with a rod geometry of 0.7cm dia. x 14cm. The pump pulse duration required to give a 91µs output pulse train with high stability is 140µs and at 100Hz the average thermal deposition in the rod is 15W/cm which is less than, but quite close to the thermal fracture limit of Nd:YLF. Operating the final amplifier in double pass would result in a shorter time to reach the steady state and reduce the thermal stress on the rod by about 18%, but at the expense of increased complexity.

The penultimate amplifier operating in double pass with a gain of 20 is also illustrated in figure 10. The required pump power is 16kW for a 0.5cm dia. x 10cm rod. In this case, to ensure that the steady state is reached before the pump for the final amplifier is initiated, the pump pulse duration must be 210µs with a resulting thermal loading on the rod of 11W/cm.

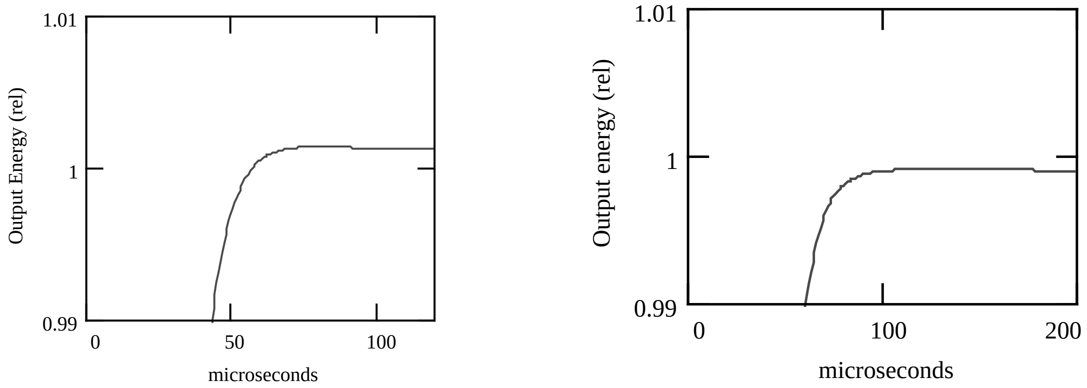


Figure 10 CLIC final amplifier (single pass) CLIC penultimate amplifier (double pass)
Gain = 4 Gain = 20

The requirements on the first of the three amplifiers are much reduced and will not pose any significant problems. The pump power for this amplifier will be approximately 1kW.

9.2.2 Design for CTF3

The CTF3 laser is required to deliver a pulse train of duration 1.4µs, with pulse energy of 17µJ(IR), a mean power of 25kW and at a repetition rate of 5Hz. If, in common with CLIC, the oscillator is assumed to generate a mean output power of 30W, the gain of the CTF3 amplifiers must be x830, about a factor of 2 less than for CLIC. Although the low repetition rate and pulse train energy result in very low average power and thermal deposition rate, the high pulse train power and gain lead to a design similar to the design for CLIC. The selected design is the 2-amplifier design of figure 9. The rod and chamber designs are the same as those for the final and penultimate amplifiers respectively for CLIC but with reduced pump power, making the system easily upgradeable to the CLIC system.

Figure 11 shows the output energy vs. time curves for the CTF3 amplifiers. The required pump powers are 33kW and 5kW respectively making a total of 38kW as compared with the total of 65kW for the CLIC system.

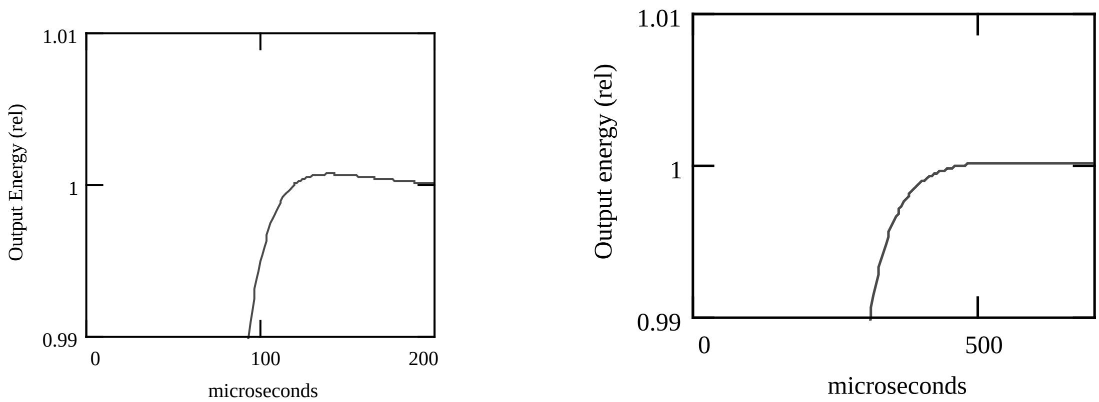


Figure 11 CTF3 final amplifier (single pass) CTF3 penultimate amplifier (double pass)
Gain = 20 Gain = 50

9.2.3 Extraction efficiency

Since the real beams will not exactly fill the aperture of the amplifiers, stored energy will not be extracted over the full rod area. The maximum beam diameter for good beam propagation (see section on staging) is ≈94% of the rod diameter and consequently the maximum extraction efficiency is ≈88%.

9.3 Fourth harmonic generation

The requirement for a wavelength 280nm on the photo-cathode has resulted in a design which includes fourth harmonic generation of the laser output. The laser specification is based on an assumption of 10% conversion efficiency for the fourth harmonic process. While it is sensible to assume a conservative estimate for this design study it is also important to improve on this efficiency since this would lead to a significant reduction in the cost and difficulty of the laser and in the loading of the final amplifier.

Fourth harmonic generation (FHG) uses 2 second harmonic generation (SHG) crystals in series and, in principle, each SHG process can be100% efficient for pulses square in space and time. For many systems 50% is routinely generated which would lead to a FHG efficiency of 25%, but to do this it is necessary to be able to achieve the correct conditions at the crystal. These are:

for high efficiency: $\left(\frac{\lambda_3 d_{eff}}{\lambda_1 \lambda_2}\right)^2 .IL^2 \succ 0.04$; 14

for sufficient bandwidth: $\Delta\lambda.L$ < value for crystal and wavelengths 15

for sufficient angular tolerance: $\Delta\alpha.L$ < value for crystal and wavelengths 16

where: d_{eff} = effective nonlinear coefficient in pm/V
I = incident intensity in GW/cm^2
L = crystal length in cm
subscripts 1,2 and 3 refer to the input wavelengths and the sum frequency
$\Delta\lambda$ = input pulse bandwidth in nm
$\Delta\alpha$ = input beam divergence in mrad

Equation 15 determines the maximum length of crystal acceptable for the bandwidth of the laser. In this case the minimum bandwidth is 1.5cm^{-1} which is the transform limit for a pulse of duration 10ps. Having determined the crystal length, or less if appropriate, equation 14 is used to determine the pulse intensity required to achieve high efficiency. Finally, equation 16 determines the acceptable divergence of the input beam. A comparison between the resulting values for the most suitable crystal materials is shown in table 5.

Table 5 SHG and FHG of 1047nm pulses in different crystals

	BBO type I		LBO type I	KDP type II		KTP type II
	SHG	FHG	SHG FHG	SHG	FHG	SHG FHG
Crystal length mm	**10**	**10**	10	30	**30**	5
Intensity GW/cm^2	0.042	0.019	0.26	0.17	0.032	0.078
Beam diameter mm	**3.5**	**3.7**	1.4	1.7	**2.8**	2.6
Divergence limit mrad	**0.56**	**0.18**	4.5	0.81	**0.61**	14.7
Diffraction limit mrad	**0.3**	**0.14**	0.75	0.62	**0.19**	0.4
Walk-off mm	0.5	0.8	0.1	0.7	0.3	0.03

These values suggest that it should not be difficult to achieve at least 50% conversion at each stage and an overall conversion efficiency to the fourth harmonic of 25%, a factor of 2.5 higher than was used as the basis of this design study. The use of BBO for both stages looks a good option since it allows the beams to be larger and have the same size. The most critical parameter is likely to be the beam divergence requirement at the fourth harmonic stage as this must be close to the diffraction limit to achieve maximum efficiency. If this proves a problem then KDP offers an attractive alternative.

It has been noted that the highest efficiencies are only achieved using flat top beams in space and time. The reduction in efficiency due to the beam having profiles which are Gaussian in space and time are as much as a factor of 2 and √2 respectively. It is particularly important to design the system such that the spatial profile at the crystals is a close as possible to a flat top over the entire beam area, and this requirement is addressed in the following section.

9.4 Optical Damage Requirement

Estimated minimum damage threshold (for anti-reflection coatings) for the CLIC output pulse train (4.2 J in 91 μs) is 40 J/cm^2. Allowing for a safety factor of 4, maximum fluence is 10 J/cm^2 and minimum beam diameter is 7 mm. This criterion allows us to have a calculated beam non-uniformity of 2:1 and still have a factor of 2 in hand. This is important because we want to have as near to top hat beams as possible in the amplifiers and harmonic crystals, but this leads to beams with peak intensities higher than the average at other planes. For a perfect top hat these peaks can be 4x the average and are not acceptable. Modelling has been carried out to determine the maximum edge steepness that can be supported so that the peaks that appear as a result of propagation are restricted to no higher than twice the average. Further discussion is given in the following section.

9.5 System Staging

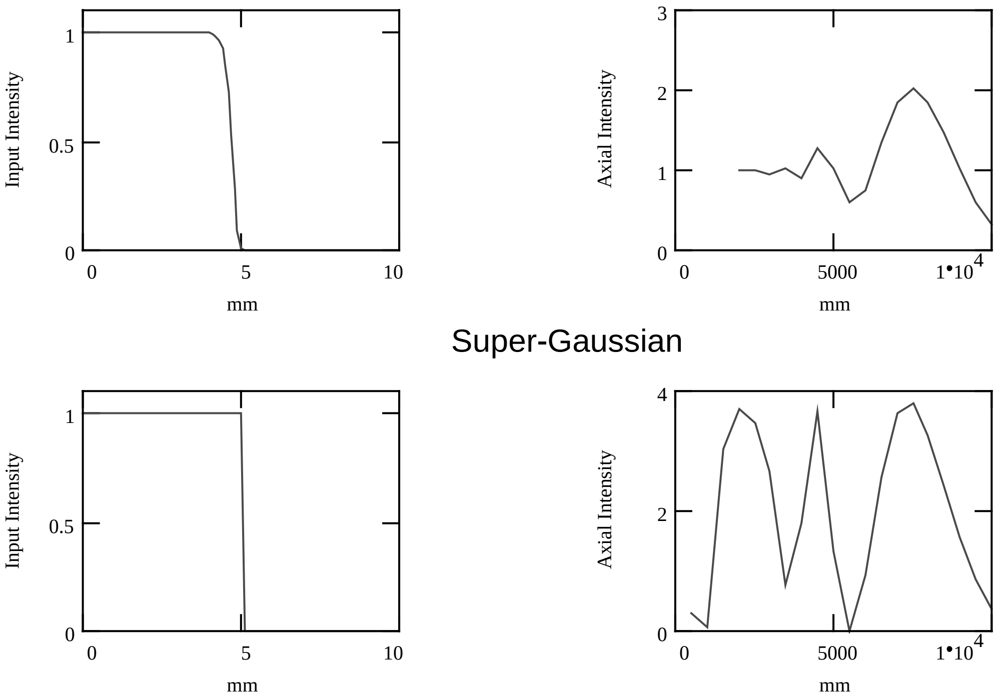
The layout of the system and its optical design are determined by the requirements of beam size and profile at all points in the system. These requirements are:

The oscillator to generate a single mode beam.
The beam diameter to match that of the amplifiers.
For maximum efficiency the beam profile to be close to top hat at the final amplifier and at the harmonic crystals.
The beam profile at the photo-cathode should also be close to a top hat.
To minimise the risk of component damage, the peak to average intensity in the beam at all components should be less than 2.

These can be satisfied if:

The single mode generated profile is converted to as close to top hat as possible before the high efficiency amplifier stages. Subsequently this profile is image-relayed to subsequent amplifiers, into the harmonic crystals and onto the photo-cathode. The image relays also enable the beam diameter to be matched to the following stage.

A true top hat profile is probably not acceptable because, as shown in figure 12, it generates peak intensities a factor 4 above the average at non-image planes down-stream. The closest it is possible to approach a top hat distribution and meet the requirement that the peak to average intensity must be nowhere greater than 2 is demonstrated in figure 12 for a ’super-Gaussian’ profile. In this case the profile FWHM is 9.4mm or 94% of the final amplifier aperture.



Flat Top

Beam after final amplifier Axial intensity downstream of amplifier

Figure 12 Diffractive propagation of a super-Gaussian and flat top circular beam. Peak intensity always occurs on axis.

A number of possible devices or 'apodisers' are available to generate the super-Gaussian profile from a Gaussian profile. Because the amplifiers are heavily saturated the output profile will be dominated by the pump profile in the amplifier and, if this is flat, the output profile will be much flatter than the input profile. This is a useful additional process for converting the Gaussian to a super-Gaussian.

A schematic of the proposed optical layout of the system is shown in figure 13.

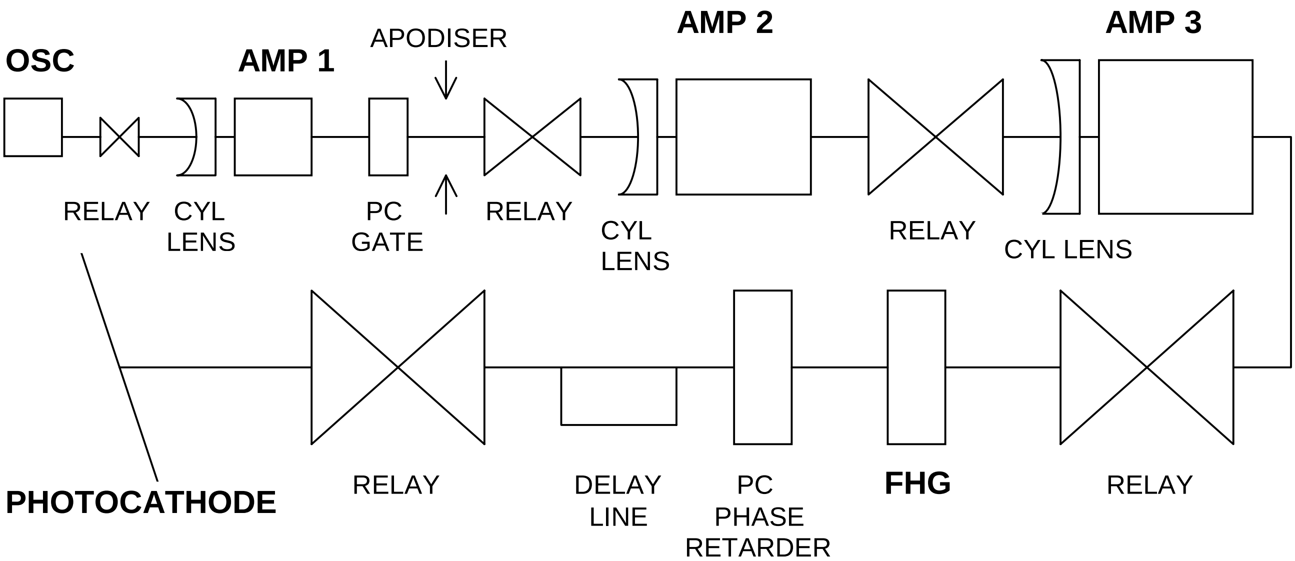


Figure 13

<u>9.5.1 B-integral</u>

A principal consideration in the design of any high power laser system is the need to suppress the build-up of nonlinear effects leading to self-focusing and self-phase-modulation. The parameter which characterises these effects is the B-integral (B), given by:

$$B = \frac{2\pi}{\lambda}\int n_2 E^2 dl \qquad 17$$

B is just the intensity dependent phase change due to the nonlinear refractive index n_2 and E is the electric field.

Since E^2 is proportional to intensity, B can be written as:

$$B = k\int Idl$$

A significant advantage for YLF is its particularly low value for n_2, giving, at its operating wavelength, $B = 0.014\int Idl$

The effects of the nonlinear propagation are small if B < 1.

Evaluating B for the CLIC drive beam gives B = $2\text{x}10^{-3}$ and there will be no significant nonlinear effects at this level.

9.6 Stability and Controlability

One of the principal requirements of the photo-injector laser systems is the need for an extremely stable and reproducible pulse energy. Further than this, it is also necessary to be able to control the energy to the same level of accuracy to compensate for downstream changes such as the photo-cathode sensitivity.

We have already addressed this requirement in the design of the amplifier system and shown that, by operating the amplifiers in a 'steady state' mode, very stable outputs can be obtained with low sensitivity to the stability of earlier amplifiers and with a 1:1 sensitivity to the final amplifier pump rate. This is the best that can be expected from such a system.

The fourth harmonic stability is also a potential problem since it is a nonlinear process and as such tends to enhance instabilities. At low efficiency (<10%), $\Delta E_{4\omega} = 4\text{x}\Delta E_{\omega}$, but at high efficiency, $\Delta E_{4\omega} \approx \Delta E_{\omega}$. It is consequently important to operate the fourth harmonic process at high efficiency, not only to minimise the energy requirement for the laser system, but also to ensure the best stability of the energy onto the photo-cathode.

Feedback systems will be required to enable fine control of the delivered energy to the photo-cathode. One has been noted already. This allows a feedback signal to control the drive current to a sub-set of the pump diode arrays in one of the amplifiers. Since this adjusts only a fraction of the total pump output for that amplifier it need not be controlled as accurately as the required control of the amplifier output. We previously calculated a response time of a few microseconds for this control process enabling it to respond to most sources of instability. A second feedback system should also be considered as a back-up and to allow control at a faster response rate. This is an electro-optic system using a fast Pockels' cell gate, which can have a sub-nanosecond response time and give a control sensitivity at the percent level. If placed early in the system this could result in control of the output energy to a level as low as 0.1%.

Although these mechanisms can generate the required stability and control, they will not be effective unless the detectors used to generate the feedback signal have sufficient measurement accuracy.

9.7 Failure modes

The laser system must be designed to protect itself as much as is possible against failure modes, especially those which can result in damage to a part of the system.

The most likely damage is optical resulting from excessive fluence on one or more vulnerable components in the system. We have already ensured that under normal operation of the laser there is an adequate safety factor to protect against optical damage. However we must consider the possibility of fault modes which result in much higher fluences leading to damage. The principal hazard in the CLIC system occurs if the amplifiers are pumped in the absence of the input pulse train. This pulse train clamps the gain so that it does not exceed a steady state value. Without the pulse train the high pump intensities lead to very high gains in the amplifiers and without proper design this can lead to self-lasing with the generation of excessive beam fluences. One way to eliminate this hazard is to use Brewster angle ends on the amplifier rods, giving low loss for the pulse train but a reflectivity of 4% for beams normal to the ends. A self-generated beam normal to the end-faces will self-lase when the single transit gain along its path exceeds 25, and because its path length in the rod is $Lx(\sec\theta)$, where θ is the Brewster angle, the axial single pass gain is clamped to a value of $25^{\cos\theta} = 14$ (for Nd:YLF). The self-generated beam is not axial and will not couple through the following amplifiers to yield high fluences downstream. However there is still a hazard if the pulse train is switched through the amplifiers late, at a time of high gain, resulting in high energy pulses at the start of the pulse train before the steady state is established. This mode must be prevented and this is perhaps best achieved by maintaining a cw pulse train through the amplifiers and ensuring that the pump diodes cannot be activated in its absence.

9.8 Other comments

Two critical aspects of the system have not been addressed – the oscillator and the specification of the accuracy of timing the laser pulses to an external signal. Our minimum requirements for both of these can be purchased commercially so it is not expected that development is essential to the demonstration of feasibility. However collaboration with a supplier can lead to significant improvements – a higher average power from the mode-locked oscillator and a more precise and responsive timing control.

10. Conclusions and Key issues

Based on a survey of the commercial state-of-the-art, on demonstrated performance and measured parameters from the literature, and on our own simulations, a design for a laser system has been proposed to meet the specifications appropriate for both the CLIC and CTF3 drive beams. The feasibility of this system both in terms of performance and cost have been demonstrated.

There are uncertainties which must be resolved and aspects of performance demonstrated before a definitive design can be realised. These key issues are as follows:

The performance of the fourth harmonic conversion at the working levels.

A number of features of the amplifier operation require verification, these to include: the realisation of high coupling efficiency of pump beams into stored energy in the amplifier rods; the demonstration of high gain; the measurement of the pulse train gain dynamics leading to 'steady state' operation with high extraction efficiency; and the assessment of the thermal fracture limit of Nd:YLF.

The measurement and compensation for thermal optical distortion in the amplifiers.

The demonstration of reliable high power 1.5GHz operation from a Nd:YLF oscillator, and the ability to synchronise it to an external signal to sub-picosecond accuracy over long periods of time.

The demonstration of fast and accurate feedback control of the amplifier output energy through either the diode array current or a Pockels' cell gate.

The ability to build a fast feedback system sensitive to one part in a thousand.

The verification of long-pulse-train laser damage thresholds of optical components.

11. Development Programme

The first major photo-injector deadline in the CLIC development programme is the need to have built a laser system to meet the requirements of CTF3 by 2004. This timescale allows for a 2 to 3 year development programme to resolve the key issues. This can be achieved and is best carried out jointly at RAL and CERN to make the most effective use of available equipment and expertise.

11.1 Current tests at CERN

Pulses are currently available to test the fourth harmonic process with pulses of similar characteristics to those for CLIC and CTF3. The aim will be to optimise the efficiency using short pulses with a top-hat spatial profile.

Initial diode array pumping investigations to be carried out using a 0.5kW array to generate gain in a Nd:YLF rod. This should give information on pumping efficiency and the generation of gain.

11.2 Future programme at CERN

Much of this to make use of experience in power generation and control.

High stability diode array drivers to be designed and built to provide the primary source of power for the test amplifiers. One driver to include a rapid current control responding to a feedback loop.

A feedback loop to be built and demonstrated with the aim of stabilising either the laser output or the electron beam current to an accuracy of 0.1%. This requires a fast detector capable of measuring the pulse energy to one part in a thousand.

Purchase of a 1.5GHz mode-locked oscillator and synchronisation unit to enable a thorough investigation of the performance of the oscillator at this and at the frequency (0.47GHz) for CLIC, as well as an assessment of the short and long term synchronisation of the oscillator output to an external synchronisation signal.

11.3 Programme at Rutherford Appleton Laboratory

This programme to concentrate on the investigation and assessment of the proposed high power amplifier design. In order to enable this to be done at a reasonable cost, a set of experiments have been designed to test the amplifier geometry and much of the amplifier performance using approximately 10% of the diode array power required for CLIC. The primary means of being able to do this realistically is by reducing the length of the amplifier. This scheme would also enable the measurement of thermal effects in the amplifier.

11.4 Collaborative programmes

Communication has been established with a number of research groups who may be interested in contributing to one or more aspects of the proposed system and these discussions will continue.

In particular a new programme has been funded at the Institute of Photonics at the University of Strathclyde to develop high power mode-locked oscillators, and one of the aims of their programme will be to meet the requirements of the CLIC photo-injector system.

12. References

1) K.G.Weingarten et al. Optics Letters 15, 1990, 962
2) G.Cerullo et al. Optics Commun. 93, 1992, 77
3) Y.Hirano et al. Optics Letters 24, 1999, 679
4) T.Graf et al. Optics Commun. 159, 1999, 84
5) S.Basu et al. SPIE 2989, 1997, 2
6) G.Holleman et al. SPIE 2989, 1997, 15
7) D.C.Brown, IEEE JQE 33, 1997, 861
8) N.P.Barnes et al. IEEE JQE 26, 1990, 558
9) R.Beach et al. Optics Letters 18, 1993, 1326
10) J.Marion, Appl. Phys. Lett. 47, 1985, 694
11) J.E.Murray, IEEE JQE-19, 1983,488.