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Laser requirements for the CLIC and CTFIII projects

S.C.Hutchins

The proposed Compact Linear Collider scheme[1] (CLIC) is based on developments made in the Clic Test Facility (CTF) over the last 10 years. The current CTFII configuration uses two laser driven photoinjectors, one for the Drive beam (power train) and a second for the Probe beam. The proposed CLIC scheme breaks with this approach, as thermionic injectors are preferred, this is due to the belief that laser technology is not able to provide the required beam parameters. This note aims to show that although the laser specification would be unique, the operating conditions fall within the envelope of currently accessible technology, and that for a reasonable amount of development, photo-injectors could provide a solution.

One difficulty that remains for the thermionic gun option is the machine requirement of phase-jumping sections of the pulse train. These are shifted by 1 RF period of the 937MHz linac, which would be inefficient and difficult using linac technology. The laser solution would offer the possibility of simply switching the optical beam between two paths of different lengths using a Pockels' cell, the repetition rate of the laser being one half of the linac frequency. This is currently done in the CTFII to suppress an unwanted second Probe beam pulse, where the pulse separation is 4ns. In the CLIC drive linac the pulse separation would be 2.1ns, with the further requirement that the switching be made on a single pulse so that it is evenly divided between the two paths. Some development work is therefor needed to produce an electronic pulse generator with the appropriate form.

Only currently available devices and previously demonstrated technologies will be considered to prove the feasibility, realisation of a practical system will require study however, as the specific requirements for the CTFIII/CLIC laser are unique.

The CTFIII development will be a proving ground for the materials to be used in the future collider, so the requirements for both machines are considered. The Drive Beam for the CTFIII/CLIC accelerators consists of a long burst of pulses, (each of 25ps width) at a high repetition rate, which are then folded into shorter bursts of pulses with very short separations (24 and 30GHz). The single bunch charge of 4.8nC can be produced using current photocathodes with a laser pulse of 4.1µJ at 262nm. A very high level of stability is required of the energy between pulses within the burst, less than 0.3%, as well as stable operation for long periods of time.

In order to estimate the size and complexity of the laser required for a future photocathode-RF gun, the power aspects of the laser are considered. Only the Drive beam power requirement is summarised here, the actual laser system has many other features such as pulse cutting and switching, generation of pulses for the Physics beam and phase stability. These have not been considered in detail, but are in areas where CERN has a great deal of experience, and are assumed to be within our capabilities, as the same requirements for fast high-voltage switching and RF manipulation are used at present.

	Pulses	Frequency	burst length	repetition	energy/pulse
CLIC	42880	468.75MHz	92µs	100Hz	4.1µJ- UV
CTF III	1500	1.5GHz	1µs	10Hz	4.1µJ- UV

The 4uJ/pulse energy is required in the UV, between 240- 290nm due to the use of Cs2Te photocathodes. As no laser materials are currently available at these wavelengths, conversion from other wavelengths will be needed, with an associated increase of energy produced in the laser due to the conversion losses.

The present CTFII laser system

The present CTFII laser[2] is a "Master Oscillator- Power Amplifier" (MOPA) system in which 2 pulses are selected from a 250MHz Nd:YLF mode locked oscillator. Their separation is 4ns; the pulse length 8ps and they have an energy of only 0.5nJ per pulse. They are amplified in a Regenerative Amplifier (RA), followed by power amplifiers to attain the level of 8mJ per pulse, which is a gain of over 10^7, then the wavelength is converted from 1047nm to the $4^{Th.}$ harmonic at 262nm. These 2 pulses are then progressively "split" with appropriate delays in a "Pulse Train Generator" (PTG) to generate a train (burst) of 48 pulses at 333ps separation. The amplifiers are all pumped by flashlamps. The pulse to pulse energy stability is a major problem for the current system and although a pulse energy stabiliser is being developed, it is not yet proven.

The MOPA-PTG system cannot be extended to the CTFIII case for several reasons. Firstly, the number of pulses required and their spacing, which would need optical path delays in a PTG of hundreds of meters. The longest delay that is practical is about 2.5m or 15ns, due to alignment problems. The need for all the pulses to have the same position and distribution on the cathode also limits the practical length of the PTG system due to the difficulties of imaging paths with different lengths.

The second difficulty is the Regenerative Amplifier which currently selects 1 or 2 pulses and amplifies them by a factor of 1,000,000 during the 65 round-trips in the cavity which takes about 600ns. In the CTFIII system, the frequency of the pulses and the length of the burst preclude the use of a RA system, as there is insufficient time to make a large number of passes in a cavity.

Choice of pumping source

The option is taken of laser diodes pumping the gain material, as opposed to flashlamps. This is due to the requirements of cooling of the laser material, reliability and the stability needed for machine operation[3].

Flashlamps generate a large energy over a spectrum ranging from the UV to the Infra-red, in a pulse that is 300 to 400us long. Some of this energy is absorbed into the required excitation levels in the laser medium, the rest is lost as heat in the material and must be removed. The long pulse is approximately matched to the florescence lifetime of the laser material, so that the absorbed energy is integrated and stored until it is required for use. The flashlamp pumping efficiency is less than 1%; a water cooling circuit removes the unabsorbed power. In conventional flashlamp pumped lasers, energy is stored in the laser medium and the optical pump energy is extracted by a single pulse, in this way the florescence lifetime of the gain medium integrates all of the variations in pump source intensity.

In the CLIC/CTF case a long series of pulses must be amplified, to achieve an equal amplification over the length of the burst, each pulse must experience the same conditions; this is different to a classical laser where there is only a single pulse. Several groups have attempted to extend the flashlamp pumping system to a pulse train[4] using feedback systems[5], these have not demonstrated the pulse to pulse energy stability required for CTFIII. The difficulties of applying the pulsed laser approach to what is a nearly continuous or CW system lead to problems of modulation of the pulse train, as equilibrium conditions are not achieved. The CTFIII/CLIC system approaches the CW as the inter-pulse spacing is only 667ps, as opposed to the 1μs of the Tesla laser. CW lasers exist, originally they were powered by arclamps, but their stability and performance was greatly improved when diode laser pumping was introduced.

The output from flashlamps is less well controlled due to variations in the discharge through the gas, random "filamentation" of the discharge current through the lamp and pressure variations caused by temperature changes. The discharge itself pollutes the gas and reduces the transmission of the glass envelope. The lifetime of flashlamps is limited to 1 year of operation at 10Hz, from our experience with the CTFII laser; this would indicate flashlamp changes every 2 weeks in the CLIC system. As previously mentioned, one of the major problems of flashlamp pumping for pulse trains is that of heating of the laser medium, causing its properties to change during the length of the pulse train.

Laser diode pumping has the advantages of very long diode lifetime[6] certainly many years continuous operation, our own experience with the Lightwave oscillators, which are diode pumped, is of 7 years operation with only a slight drop in output power. The short-term stability is dependent on the drive circuit, control of better than 1% is easily achievable. These features are required for a low-maintenance, stable system. In addition the pump laser wavelength is matched to an absorption peak of gain medium, so that optical efficiencies of 50% are possible. The heating in the material is 100 times lower; this figure will be recalled in the conclusion to justify the choice of Laser diode pumping due to the cooling requirement of the laser heads.

A further advantage of diodes is that they operate at low voltage and currents as opposed to high voltage flashlamps and as high frequency feedback circuits will be used to achieve the specified stability, these will be easier to implement in diode systems. The diode current would be switched on some short time before the pulse burst is required, with the injection seeding present. In this way stable operating conditions could be achieved. The length of time that the pumping would be present is short, again reducing thermal effects. The high intensity of pumping power in the final amplifier stages would require that they are switched on an off in a controlled way to minimise thermal shock.

CTFIII/CLIC laser configuration - using available technology (1998)

The possibility which is considered is an extension of the MOPA scheme using currently available technology, as reported in conference proceedings of CLEO 1998 (Conference on Lasers and Electro-Optics). This is not a design proposal but is a demonstration that there are no technological barriers to the construction of such a laser.

Starting with the mode locked oscillator, for which commercial units already exist at 500MHz as needed for the CLIC option; several manufacturers would be capable of providing a 1.5GHz unit as required for the CTFIII. The reduction in pulse interval implies a reduction in the oscillator cavity length, but there are only two elements inside the cavity, the laser rod and a mode-locking oscillator, both of which are less than 10mm long. Electro-optic modulators at over 2GHz are commercially available[7]. The requirement for stability and control of the active piezo elements controlling the cavity length would be increased by a factor of 3 over the currently used systems. The energy per pulse out would be the same as at present, as average output levels of 700mW are now produced[8], compared to the 100mW of our 250MHz units.

The number of amplifiers which are then required depends upon their gain, simply, $G^n = A$, where n is the number of amplifiers. The overall amplification, A, is in our case 100,000 as the output of high-frequency mode-locked oscillators is only some 100's of pJ and the IR pulse needed is about 20μJ.

For the most efficient extraction of the laser energy, Chirped Pulse Amplification (CPA) would be employed; this enables the bandwidth of the laser emission spectrum to be fully used. An imaged anti-parallel grating pair[9] would be inserted at the oscillator output to provide the positive group velocity dispersion, and a parallel grating pair at the output of the final amplifier to compensate back to a short pulse, as in the present CTFII system. The peak energy of the IR pulses is well below the damage threshold of the gratings; the average energy should not present any problems either. The amount of chirp that can be accommodated is limited as the inter pulse spacing is short, but any increase in the spectral width of the amplified pulse will increase the amplification efficiency, the pumping efficiency and reduce the effect of pulse shape distortion (see next par.).

The range of available single pass gain is also limited, on the low side by the requirement of having the least number of stages, and on the high side by several effects, such as pulse shape distortion, parasitic oscillations and spontaneous emission in the laser gain material[10]. Pulse shape distortion occurs when the amplified pulse removes a significant fraction of the stored energy in the laser medium, the back of the pulse is then less amplified than the front, producing a "tail" on an asymmetric pulse. Parasitic oscillations occur when the laser material is in a high gain state, then less common modes can propagate inside the rod, these could longitudinal or even radial, in all cases the stored energy is reduced.

The gain should be limited to x3 or x4, and a mixture of optical isolators, saturable absorbers and spatial filters will be required between the amplifier stages. As an indication, if all amplifiers had a gain of x3, 10 single passes would be required, for a gain of x4, 8 are needed. For this feasibility exercise the amount of pumping power is limited to published and well-described figures. This causes the amplifier chain to be limited in gain at the higher power end due to the available optical pump power. If higher gains in the amplifiers were to be found possible, they could only be used to eliminate one of the lower power units, so that any economy would be welcome but marginal.

Starting with the energy at the cathode, the required laser energies can be estimated.

Cathode		4.1μJ/pulse	UV
UV transmission and monitoring	30% loss	6 μJ	UV
conversion Green- UV	50%	12 μJ	Green
conversion IR -Green	60%	20 μJ	IR
Optical extraction efficiency (laser)	70%	34 μJ	Diode
Pump injection efficiency	70%	40 μJ	Diode

The estimation of UV transmission and monitoring losses of 30% results from the elimination of a Pulse Train Generator, and a minimal path to the RF gun. The laser should be installed at ground level close to the RF gun, as the requirement of position stability on the cathode can only be met with a short path length, a minimal number of mirrors and mounts, and when on the same base structure as the cathodes.

The conversion efficiencies used are achievable with lasers having good quality, uniform energy distribution outputs. The pumping efficiencies are less than those published for the best optimised systems, which are over 80%[11 12].

The amplifiers would be pumped continuously during the pulse burst, so that the 40μJ that will be used or lost from the laser medium will have been deposited during the inter-pulse period, 666-25= 640ps in the CTFIII case. This gives a pumping power requirement of 62.5kW. For the CLIC case less pumping would be required, as the inter-pulse time is longer. At 468MHz, 2133-25=2108ps, giving 19kW peak pump power, but the overall duty cycle would be 1000 times higher at 100Hz and a burst length of 100μs. The average power for the CTFIII laser is less than 2W, but for the CLIC an average of 200W cooling is needed.

In searching the current literature for a suitable model for the optical and thermal aspects of the amplifier, one desirable feature is that of having a "good" beam profile, as only with this condition can the amplifiers be cascaded. A good profile would be symmetric so that it could be passed through spatial filters to remove transverse intensity variations across the pulse.

The highest power laser-diode-pumped rod laser found was an experimental unit at 4.5kW peak pump power, duty cycle of 3.5% and average pump power of 168W[13] (Y.Hirano, Mitsubishi). This unit used Nd:YLF as the laser medium and worked at an optical efficiency of 49% when used as a laser at 150pps of 250μs. An average output power of 72W was generated. Its performance was limited by the available diode pumping arrays, not by the level of energy injected into the laser materiel or the ability of the cooling system to maintain equilibrium conditions. The potential of this module is limited in our case, as 17 amplifiers would be required to attain the energy needed for CTFIII.

Other units[14] exist with higher pumping power, but are not well described and have not been used as the basis for this study; further information is awaited about the pumping system of one unit (J.Unternahrer, General Electric/Fibertek) which had an average output power of 550W.

An alternative laser structure is the “slab” type, which is pumped via 2 faces and cooled through the other two. This has the advantage of allowing higher pumping energies but at the cost of beam quality. To use the pumped volume effectively the beam zig-zags through the slab, which leads to a rectangular beam profile. (N.B. even this is better than the current beam profile of the CTF laser). A MOPA system using slabs of Nd:YAG was presented at CLEO[15] by K.Tei, of the Japan Atomic Energy Research Unit, in which a single slab used as an amplifier had 20kW of pump power from 928 laser diode bars. The system was a very high power MOPA constructed with 4 diode pumped slabs, one of which was an oscillator the remaining three were used as amplifiers in a multi-pass configuration. The pump pulse length was 250µs at over 100Hz repetition rate. The average output power was 200W from this system, which will provide 2 Joule pulses at 532nm as a pump source for a Titanium –Sapphire laser.

If the G-E/Fibertek laser is discounted, the remaining two pumping configurations can provide a basic solution for the CTFIII laser. Both of these units are limited by the available pumping power rather than their cooling ability. They also work at a repetition rates of 150Hz- 15 times higher than the CTFIII laser, and 50% higher than the CLIC laser, so that in taking these units without scaling the pumping power to our repetition rates (i.e. scaling for constant average pump power) this becomes a very conservative estimation for the thermal aspects of the system.

The output power stage of the CTFIII laser could therefore be constructed using three slab lasers pumped at 20kW each (fig.1). The gain of these high power sections would be low, being limited by the available pumping power. Each section would add 6µJ to the amplified pulse, the first section would have an input energy of 2µJ giving a gain of 4, the second would then have a gain of 1.8, and the third a gain of 1.4.

These could be preceded by a single pass amplifier (amp.4) of the radial (Mitsubishi) type, pumped at 4.5kW, this would have a gain of 3, and give the required output energy of 2µJ. This stage will add 1.4µJ to the amplified pulse, so it follows that its input energy is 0.6µJ.

As we progress back along the amplifier chain the next element (amp.3) could be of the same radial type but with only 2kW of diode power, this would be sufficient to achieve a gain of 4x4 in a two pass configuration. One further limitation exists if a 2-pass amplifier is used, the distance between pulses is only 20cm, so the length of the 2-pass section should be short, to avoid having pulses crossing in the amplifier which would cause amplification instabilities of a “mode-beating” nature, causing a modulation on the amplitude of the burst envelope. For the best control of amplification, energy distribution and pulse shape, single pass amplifiers should be used, with relay imaging, spatial filters and optical isolators between the stages.

The amplifier preceding this (Amp.2) could be of a more simple pump design, as it would only require about 200W of power to achieve 4x4 gain as a two-pass amplifier.
Finally, the first double-pass amplifier in the chain for which the same gain of 4x4 needs 15W of diode pumping.

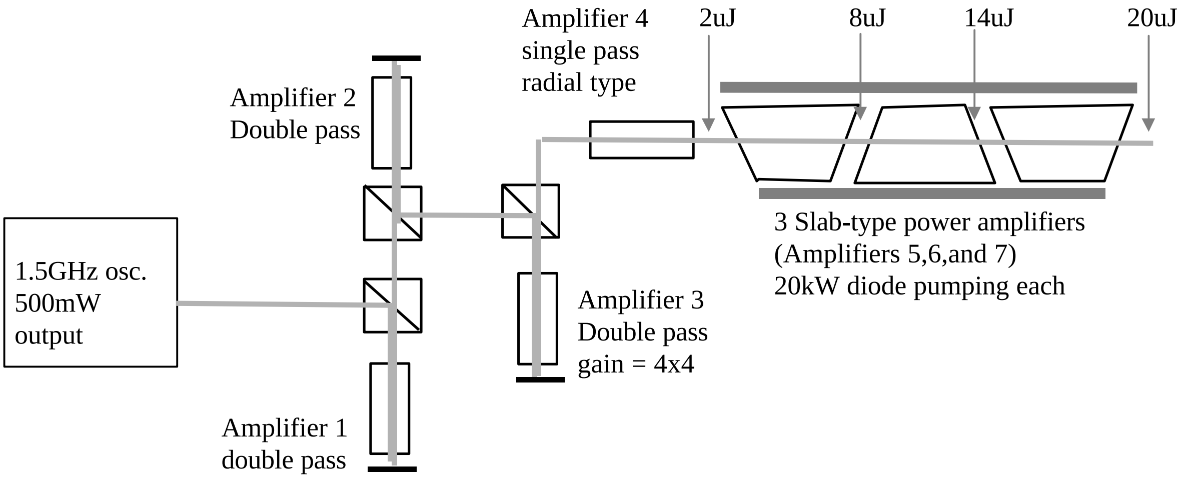


Fig.1: The basic MOPA-train scheme

Development of a practical system

The main change that can be expected in the next 3 years is that the efficiency and power density of the diode lasers will improve. The performance limitation of the radialy-pumped rod laser is due to the pumping density that can be installed. Diode bar arrays of 200W/cm length will be available in the near future, this and development of radial pumping arrays could enable this type of module to perform the entire amplification load. The resulting beam profile would be greatly improved.

Two G-E/Fibertek pumping chambers could comfortably replace the three slab lasers indicated in the diagram, if their average power is used as a guide, their pumping power is over 40kW. The double pass amplifiers could be replaced by single pass ones to maximise beam quality for the harmonic conversion process.

An important development that will be required, is that of a pumping chamber design of the radial type, driven at a level of 25-30 kW and optimised for the energy levels of the CTFIII/CLIC system. The laser pulse energy will be far lower than in the single pulse lasers for which the 4.5kW Mitsubishi chamber, or the 40?kW GE/Fibertek laser were designed. The lower pulse energy leads to smaller diameter beams, giving smaller diameter laser rods that increase the ease of heat extraction, but also increases the energy density on the surface of the rod. This design would be the basis of any future laser system that was to be developed.

Data is also needed on the effect of fast risetime, intense pumping on the laser rods. One danger is that the thermal shock of such a pulse would cause acoustic vibrations in the laser material, which would give rise to instabilities. These would probably not be a problem in the CTFIII case as the entire pulse train is passed in 1μs, but could be important in the 100μs CLIC pulse train. The other effect of fast pulse pumping is that relaxation oscillations may be generated, these are variations in gain which occur before equilibrium conditions are attained. They usually have a period of 20-60kHz depending on the pumping level, and would not be expected to cause problems in a 1μs pulse, but no information is available for our particular case. It may be sufficient for both effects that the pumping be progressively applied, and that feedback systems control the gain of the system.

The diode lasers' output is coupled to the laser material via fiber optic lines. This separates the cooling requirements of the diodes from that of the laser system. The electrical to optical efficiency of current laser modules is over 20%, so that the average cooling requirement for the diodes would be reasonable. 100kW of heat would have to be removed from the power amplifier pump section, but this would not affect the laser material, it should be noted that this is the amount of drive electronics that will need to be installed.

The absorption peak of some laser materials is narrow (e.g. Nd:YAG) and the pumping diode wavelengths are fine-tuned by adjusting the cooling water temperature. Nd:YVO operates at the same wavelength (1064nm) but has a wider absorption peak, which could avoid this requirement. The choice of laser medium would also depend on thermal effects, as in the CLIC case, a significant amount of heat must be removed from the amplifiers.

Laser materials with operating wavelengths closer to the UV could be investigated, as, if a suitable UV wavelength could be achieved in one harmonic generation stage, a 50% reduction of input power would result. Titanium-Sapphire operates at visible wavelengths, but must be optically pumped with green light, so that an extra stage of harmonic conversion would be needed. The other main advantage of this material is its ability to generate femto-second pulses, which is not relevant to the CTFIII project, as the optimum pulse length for the accelerator is about 25ps. Pulse train amplification does not profit from a long exited-state lifetime in the laser medium, this is a feature, which is important for single-pulse lasers, and materials with short lifetimes may be available but relatively unknown.

Other system configurations could be considered, for example the use of intra-cavity harmonic generation, which has become a very common system for CW pump sources[16 17] and lower power pulsed lasers. The harmonic generator is placed inside the oscillator cavity (fig.2), which is then "closed" to the fundamental wavelength, only the generated harmonic exits the laser. As harmonic conversion is not 100% efficient (usually about 50%), if the converter is outside the cavity half the energy is lost. With intra cavity conversion this is not the case, the energy at the fundamental wavelength continues to circulate in the cavity and is re-amplified on each passage through the laser material. This gives a 50% reduction in the total pumping energy of the system.

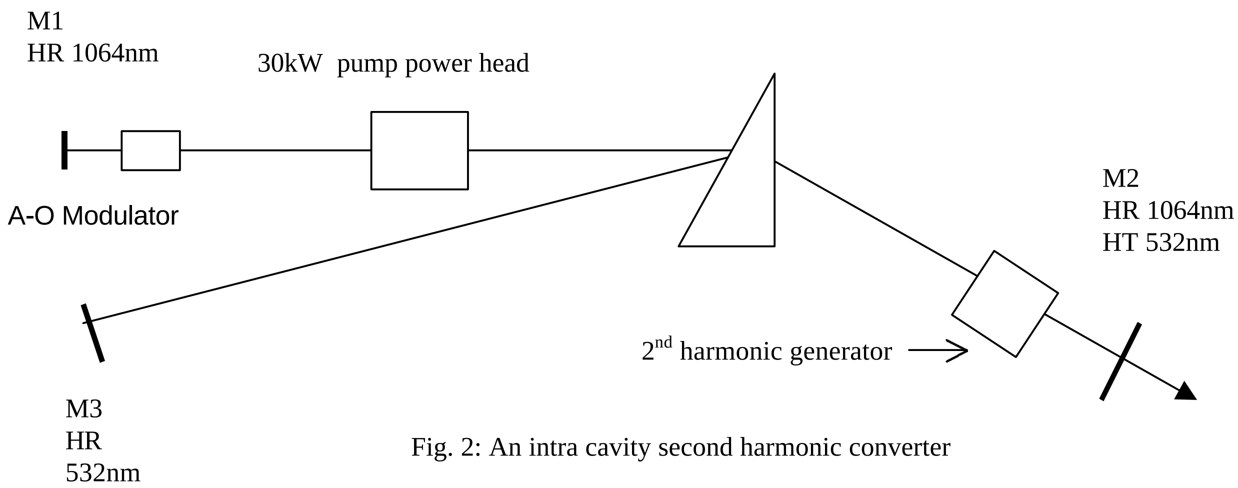


Fig. 2: An intra cavity second harmonic converter

The path to M3 is a further energy saving feature, second harmonic light would be generated on the forward and backward passages of the circulating pulse through the harmonic generator, the backward –travelling pulse is reflected back to add to the following forward-travelling pulse.

The oscillator cavity would be pumped at a low level continuously to assure stable operation and pumped at the high level for the time required to stabilise the output and produce the pulse train.

To avoid the complication of the second arm of the laser, a ring configuration could also be used (fig.3), in which a pulse circulates in one direction only.

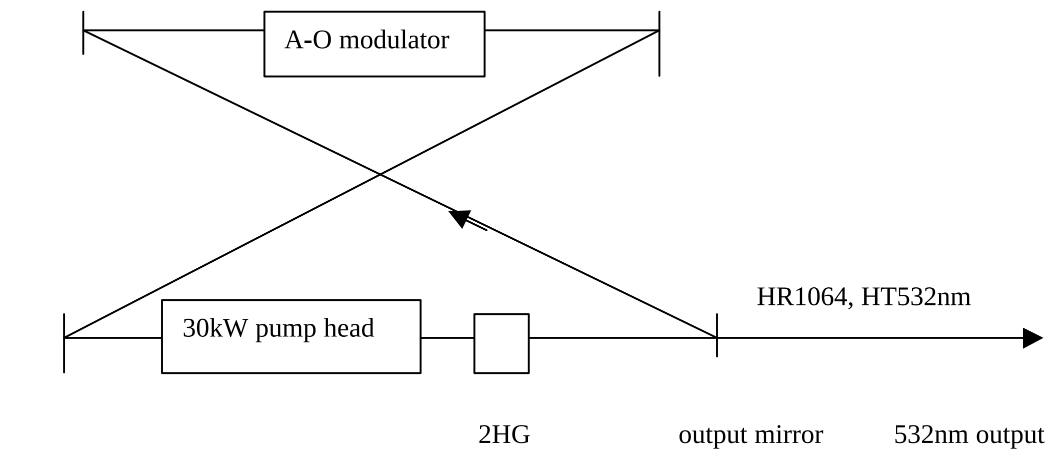


Fig.3: A ring oscillator system with intra-cavity second harmonic generator

The system could also be developed for 4th harmonic generation, with a corresponding decrease in the required pump power (fig.4).

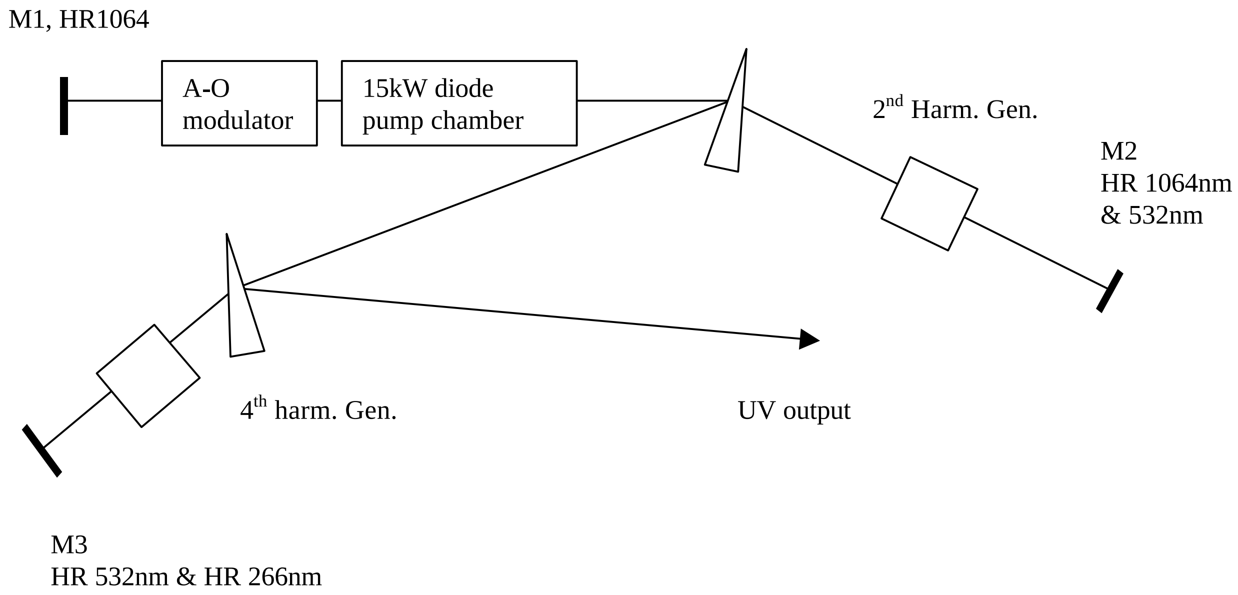


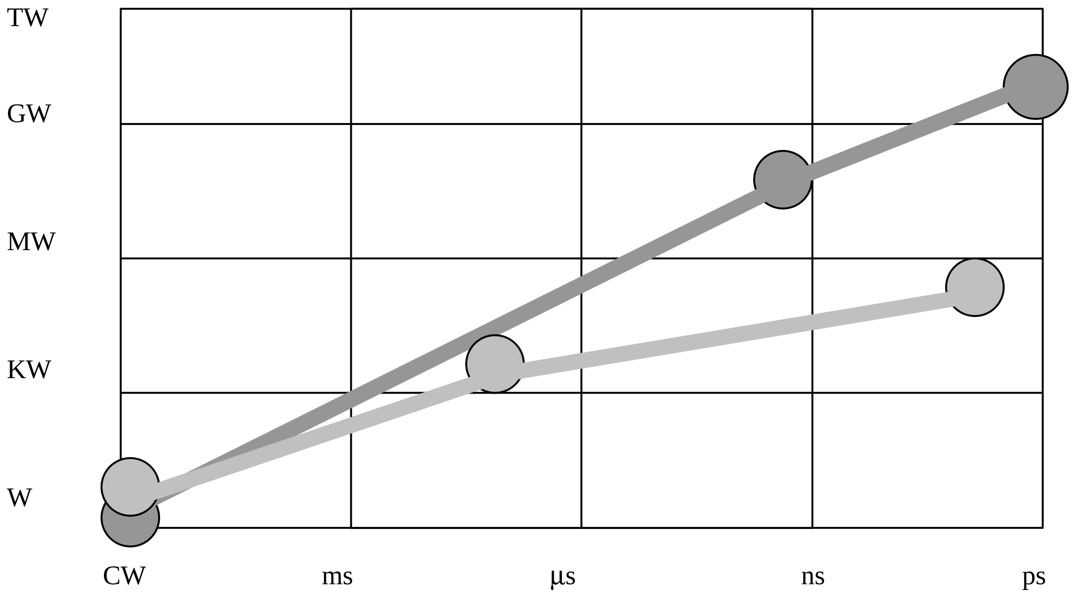
Fig.4 Dual cavity mode-locked oscillator with UV output

The fundamental wavelength cavity is between M1 and M2, mirror M1 would be mounted on a piezo element to maintain the mode-locked cavity length, M2 is fixed. The second cavity contains light pulses at 532nm between mirrors M2 and M3. This cavity would also be modelocked with M3 mounted on a piezo element. The physical size of a high power pumping chamber would limit the size of the cavity to some length longer than 40cm, which would give a fundamental cavity frequency no greater than 400MHz. To attain the 1.5GHz output frequency for the CTFIII, the modulator would operate at a harmonic of the cavity length with 4 or 5 pulses circulating in the fundamental cavity.
Apart from the saving in laser diode costs, the coupled cavity system could give better stability from pulse to pulse within the pulse “burst” as the coupling between output energy and pump power is very strong. Feedback systems could control a fraction of the diode power to stabilise the amplitude of the train.

Conclusion

The laser required for the CTFIII and CLIC can be produced using current technology, the peak pulse energy in the laser would be low, as would the stored energy in the laser material. Self focusing and depolarisation due to stress induced birefringence should not present any problems, as the peak pulse energy will always be low compared to normal single pulse lasers. The peak energy circulating in the CTFII regenerative amplifier is over 800µJ, for the output of the final amplifier stage of fig.1, only 20µJ would be present. The laser-photocathode-RF gun can also provide an elegant solution to the sub-bunch phasing and cutting requirement as explained earlier.

One way of situating the operating envelope of the CLIC laser is in the following graph, the darker dots represent regions where normal benchtop lasers operate, picosecond lasers can give TW pulses, nanosecond lasers usually operate with GW pulse intensities, and cw lasers are confined to the single Watt regime. The CLIC laser (in light grey) has a conservative single-pulse operating point, if the 92µs pulse burst is considered, commercial laser performances are approached, and in the CW or average power case "normal" laser performances will be exceeded.



Laser diode pumping is the only viable option for the CLIC laser, as an average cooling of 200 W is needed with laser diodes. If flashlamp pumping were to be used this figure would be 100 times greater at over 20kW (in the amplifier chain scheme), which would be difficult to achieve. Laser diode pumping also improves the energy stability of the output, commercial diode-pumped Q-switched systems now produce high-power pulses at less than 1% pulse to pulse variation[18]. The CTFIII laser will operate in a more favorable mode close to CW, where stabilities of intra-cavity UV OPOs have variations of less than 0.4%[19] and commercial benchtop units[20] have specified less than 1% amplitude variation for the last 10 years. The remaining causes of instability are understood[21] to be due to thermal and mechanical instabilities and acoustic vibrations, all of which can be treated in a permanent installation.

The huge cost savings that the intra-cavity harmonic generating lasers offer demands that they be seriously studied. There are extra problems in the high-power oscillator schemes such as the effect of heating on the oscillators stability. Some results[22] from studies of CW lasers show good results for 20W output power, but it is not possible to extrapolate to the 10kW power that would exist during the pulse burst in the oscillator. The present cost of the materials for the multi-stage amplifier would be about 3.5MCHF; the intra-cavity scheme could reduce this cost by a factor of 3. The material costs are expected to become lower with time and with the quantity that will be used in the system.

A design study must be started soon, as the system would be unique and has aspects which have not previously been used, such as very short bursts of intense pumping energy. Its design, development and commissioning could easily take 4 to 5 years. The laser will be required to perfect other aspects of the system, such as the pulse cutting and switching at the 1.5 GHz rate. The optimised pumping chamber would be required to confirm assumptions about the lasers behaviour and fix the final design.

The design and manufacturing group should include European laser companies as well as academic groups with experience in this technology. A considerable input should also be made by CERN, where the electrical, electronic and mechanical expertise in unmatched. The CERN team that will eventually run the laser should be closely associated in its development to avoid the pitfalls seen with "turn-key" systems[23].

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