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EXPLORATION OF A KLYSTRON-POWERED FIRST ENERGY STAGE OF CLIC

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INTRODUCTION

The beam is accelerated in the CLIC [1] main linac by normal-conducting X-band accelerating structures. The necessary RF power to feed these structures is extracted from a drive beam, which runs in parallel to the main beam, by Power Extraction and Transfer Structures (PETS). However the RF power could also be produced by klystrons. In the past, this has indeed been proposed in the JLC-X and NLC [2] designs, which also used normal-conducting X-band accelerating structures but fed by klystrons. Two clear advantages of a klystron-based design over a two-beam based design at low energy is that the technical development of full RF unit prototypes is nearly done and that they can be tested more easily. The production of the high-current drive beam for two-beam power generation is relatively costly but is to the better option for a high-energy facility.

Consequently the power source of a normal-conducting linear collider may be adapted as a function of beam energy in a staged implementation. The first stage could be klystron powered – which is already nearly completely demonstrated and has a relatively lower initial cost. Above a certain collision energy, which is probably in the range of a few 100 GeV, the machine would switch to two-beam powering to take advantage of the much lower cost per additional GeV as energy is increased. This is schematically illustrated in figure 1. In addition to providing the desired physics at low energy, running the high-power and high-gradient normal-conducting rf system along with a low-emittance linac will provide important direct experience and input to preparation for more demanding higher energy stages and give more time to complete technical developments for the two-beam system.

The implications that the choice of RF power source has on the CLIC design at low energy in order to identify the advantages and drawbacks of the various possible RF power sources are considered. We evaluate the 500 GeV case; lower-energy first stages are just scaled down proportionally. This case is more favourable for the klystron-based scheme than the 3 TeV case, because in the klystron-based machine the installed RF power is proportional to the final beam energy. The drive-beam based design is documented elsewhere [3]. In this document the focus will be on the exploration of the klystron-based design.

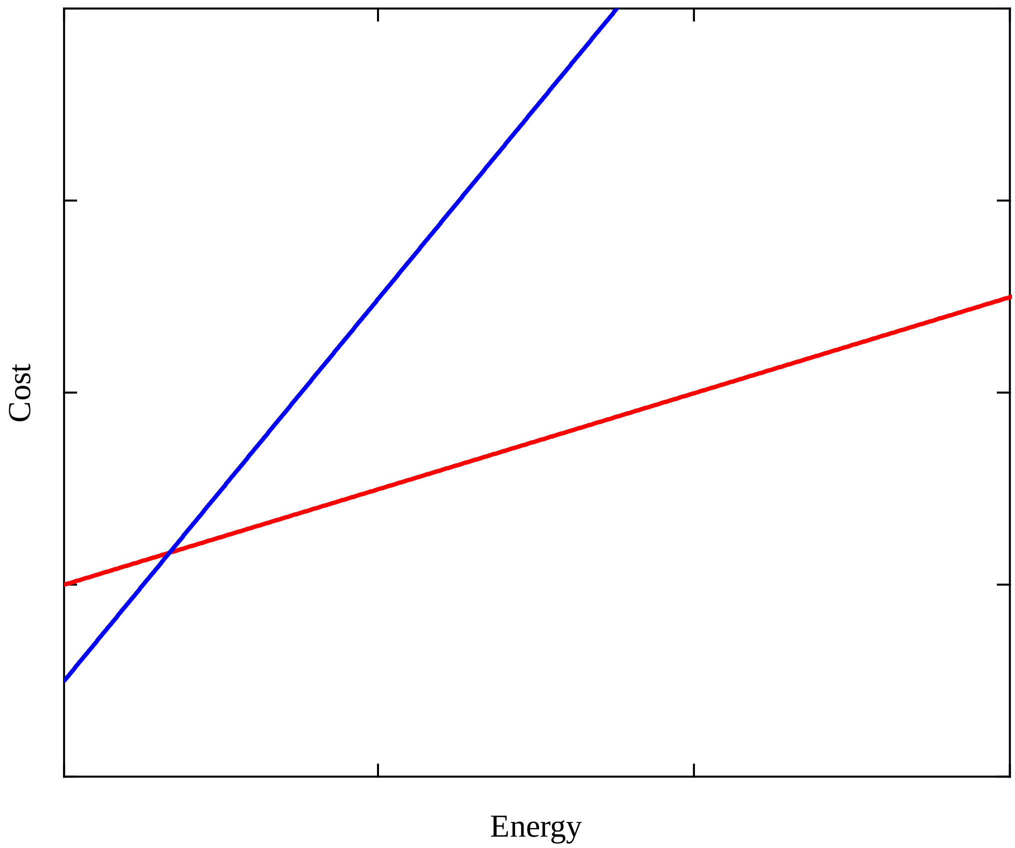

Figure 1: A schematic representation of cost scaling of a klystron-based linear collider [blue] and a two-beam linear collider [red]. A klystron-based machine has a lower initial cost but higher marginal cost.

In the past a very important R&D programme has been carried out for klystron-based X-band accelerators, in particular the NLC and JLC-X studies. In addition the current high-gradient testing of CLIC accelerating structures is made on klystron and pulse-compressor based rf power plants which are very similar to linac rf units. Machine layouts have been developed of the machines that were optimised for cost. Individual components have been developed, tested and in some cases industrialized. In fact a commercial version of the SLAC XL-5 klystron will be delivered to CERN in early 2013 (although it should be noted that this particular study is based on the NLC/JLC 75 MW tube). The results of these programmes are the basis for this work. The main differences between the CLIC approach and the NLC and JLC-X projects is that in CLIC strong damping and higher gradients are employed in the accelerating structures. This strategy generally leads to the need of shorter and more intense RF power pulses, which the drive beam scheme can easily satisfy.

Currently, two strategies have been followed to determine the possible adaptation of CLIC to klystrons:

- In the first approach, the current CLIC 500 GeV design is fully maintained, except that the drive beam is replaced by klystrons as the main linac power source. This choice minimises the design modifications. As will be described below, the number of klystrons required is 1000, which appears very large.
- In the second approach, some optimisation of the CLIC parameters is performed in order to reduce the number of klystrons. However, the design strategy of the accelerating structure remains unaltered, i.e. strong damping of

the higher-order transverse modes is used. In contrast, NLC and JLC-X considered only weak damping and detuning. The total number of klystrons needed with the two strategies appears to be very similar.

In the following, a short introduction into the parameter and structure optimisation of CLIC at 500 GeV is given for the drive-beam based case followed by a summary of our assumptions for the klystron, modulator and pulse compressor performances. Based on this input potential parameter sets are discussed for the klystron-based CLIC.

CLIC STRUCTURE OPTIMISATION PROCEDURE

The CLIC parameters and the accelerating structure for a centre-of-mass energy of 3 TeV have been optimised in order to find a good compromise between minimum project cost and maximum power efficiency. The resulting structure design is called CLIC_G. A 500 GeV centre-of-mass energy two-beam design has been optimised in a similar fashion [4], resulting in the structure design CLIC_502. Since no cost model has been available for this energy, the optimisation focused on power efficiency and a limited site length. The 500 GeV optimization is recalled here. A klystron-based machine is then optimized using only the accelerating structures found by the 500 GeV two-beam optimization. Of course in the future, a full optimization of the klystron-based machine will have to be made.

Beam Dynamics Constraints

The basic parameters at the collision point are determined by the different accelerator systems:

- The bunch charge N and length σ_z are mainly a function of the linac design. The longitudinal single bunch wakefield makes the bunch length a function of the charge $\sigma_z(N)$ in order to limit the final beam energy spread. The transverse wakefield effects then limit N, via the wakefield kick which is proportional to $NW_T(2\sigma_z)$.
- The horizontal emittance is mainly a function of the damping ring performance, with some contributions from other systems.
- The vertical emittance depends on damping ring and the transport from the damping ring to the interaction point.
- The effective vertical and horizontal beta functions are functions of the final focus system and have lower limits.

Some parameters have been chosen to be more relaxed than for CLIC at 3 TeV:

- Larger horizontal emittance at the interaction point of 2.4 μm instead of 0.66 μm has been assumed to relax the damping ring design requirements.
- Larger beta-functions have been assumed at the collision point to relax the beam-delivery system requirements.

The bunch charge in the main linac has been chosen as for the 3 TeV case but taking into account that the machine is significantly shorter. This has two main consequences. First, this allows tolerating a constant local transverse wakefield kick, even at lower gradients. In case of the 3 TeV design the wakefield kick had to be reduced with the gradient since the length of the machine increased. Second, it allows having a factor of about two larger local wakefield kick from one bunch to the next than at 3 TeV. In addition, the requirement for the quality of the luminosity spectrum at the interaction point has been made more stringent, in order to make the degradation of the spectrum quality due to beam-beam effects and the unavoidable initial state radiation comparable. As a figure of merit we use the luminosity delivered within a band of ±1% around the nominal centre-of-mass energy.

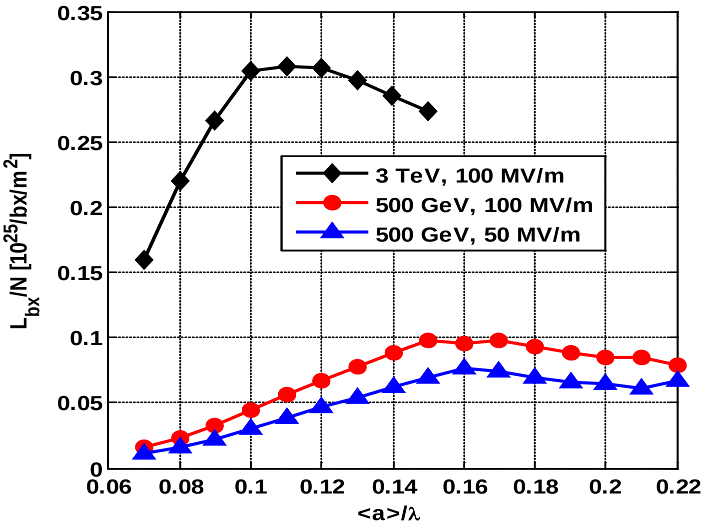

Figure 2: Luminosity per bunch crossing in 1% energy spectrum divided by the bunch population L_{bx}/N *versus average aperture to the wavelength ratio* $<a>/\lambda$ *is plotted.*

In order to illustrate the difference between the two cases of 3 TeV and 500 GeV, luminosity per bunch crossing in 1% energy spectrum divided by the bunch population L_{bx}/N versus average aperture to the wavelength ratio $<a>/\lambda$ is plotted in Fig. 2 for three difference cases: 3 TeV, $<E_{acc}> = 100$ MV/m; 500 GeV, $<E_{acc}> = 100$ MV/m; and 500 GeV, $<E_{acc}> = 50$ MV/m. The black diamond curve represents the nominal case where the optimum $<a>/\lambda$ is 0.11. Using the nominal structures optimized for 3 TeV in the 500 GeV main linac would result in luminosity loss of about factor 6 from 0.3 to 0.05. This loss can be partially compensated by using accelerating structures with larger aperture since for 500 GeV the optimum $<a>/\lambda$ is close to 0.16. In addition, Fig. 2 shows the difference in the L_{bx}/N for 500 GeV between 100 MV/m and 50 MV/m accelerating gradients coming mainly from the linac length, red circles and blue triangles, respectively.

RF constraints

The following three rf constraints have been used in the optimization:

1. Surface electric field: $E_{surf}^{max} < 260$ MV/m
2. Pulsed surface heating: $\Delta T^{max} < 56$ K
3. Power: $P_{in}/C\cdot\tau_p^{1/3}\cdot f < 156$ MW/mm/ns$^{2/3}$

Here E_{surf}^{max} and ΔT^{max} refer to maximum surface electric field and maximum pulsed surface heating temperature rise in the structure respectively. P_{in}, τ_p and f denote input power, pulse length and frequency respectively. C is the circumference of the first regular iris. These constraints are the same as used in the optimization of the 3 TeV CLIC main linac accelerating structure [5,6]. This means that the structure high-gradient performance is as challenging to achieve as for the 3 TeV case. In addition, two values for the rf phase advance per cell in the structure have been investigated: 2π/3 and 5π/6.

The successful increase of gradient demonstrated in the 100 MV/m unloaded gradient in a TD24 (damped) and 120 MV/m in T24 (undamped) [3] structures provides a very good justification of the validity of the predicted performances of the new structure designs presented in this report. The high-gradient scaling laws have been improved [13] and these will be implemented in future optimizations.

Design Constraints driven by the 3 TeV Upgrade

In addition to the beam dynamics and rf constrains, there are a number of constraints which has to be applied to the 500 GeV CLIC if it would be built as the first stage of 3 TeV CLIC and if one wants to re-use the components efficiently. In the case of the use of a drive beam as a main linac rf source, there are several parameters that need to be consistent with the 3 TeV design, which has: a bunch separation N_s of 6 rf cycles, an rf pulse length t_p of 242 ns and a structure active length L_s of 230 mm. These should be kept constant or changed by a factor 2 for the 500GeV stage. In case of a klystron powered first stage more flexibility is possible, which will be explored at a later stage. The list of different cases studied in this paper is presented below:

1. N_s = free; $L_s > 200$ mm; t_p = free
2. $N_s = 6$; $L_s = 230$ mm; $t_p = 242$ ns
3. $N_s = 6$; $L_s = 480$ mm; $t_p = 242$ ns
4. $N_s = 6$; $L_s = 480$ mm; $t_p = 483$ ns

where the first case represents the 500 GeV CLIC optimum without taking into account 3 TeV design constraints. It is used as a reference to indicate how much the performance is reduced due to the 3 TeV design constraints.

Optimisation Results at 500 GeV

The 500 GeV CLIC main linac accelerating structure optimization has been performed in a range of $\langle E_{acc} \rangle$ from 50 to 100 MV/m, always at 12 GHz. The figure of merit (FoM) $\eta L_{b\times}/N$ has been maximized as in [4,5], where η is rf-to-beam efficiency. For fixed centre-of-mass collision energy this quantity is proportional to the average luminosity divided by the average rf power which has to be provided for acceleration.

The results are presented in Fig. 3 where all 4 different combinations mentioned in the previous section have been analyzed for two different values of rf phase advance per cell and are marked as shown in the legend. In addition, two cases are presented which correspond to the 500 GeV CLIC built using nominal 3 TeV structure (CLIC_G [6]) at the nominal and double pulse lengths.

Based on the results one can draw the main conclusions:

- Case 1 yields the highest efficiency and is somewhat more efficient at lower gradients.
- Case 2 yields almost the same efficiency as case 1 at 80 MV/m. The efficiency does not increase toward lower gradients.
- Case 3 and case 4 yield somewhat better efficiencies than case 2 at lower gradients but are worse at gradients above 60 MV/m.

Based on these results, the 500 GeV structure has been chosen using the conditions of case 2 and a gradient of 80 MV/m for the drive-beam based design.

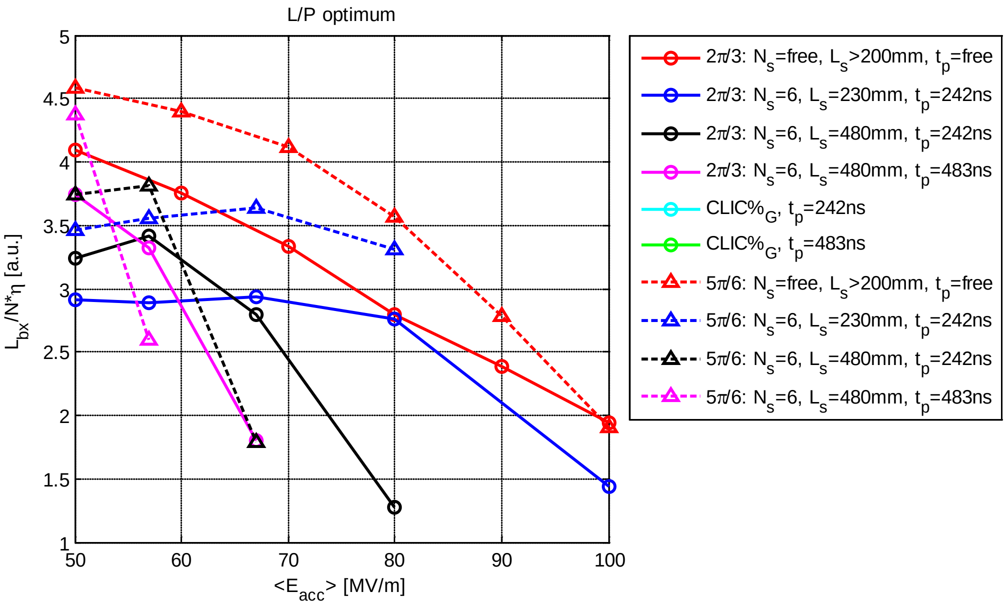

Figure 3: The ratio of luminosity to main linac power consumption (in arbitrary units) for different structure design constraints as a function of gradient.

KLYSTRON AND PULSE COMPRESSOR DESIGN

For NLC and JLC-X a very important R&D programme has been executed on klystrons, modulators and pulse compressors. We base our assumptions on this knowledge as detailed in the following.

X-band Klystron and Modulator Design

There are a number of ‘reference’ klystrons which can be considered for this design investigation. The most conservative is the existing, and operating, XL-5 klystrons produced by SLAC and, by early 2013, CPI. A more aggressive choice would be the NLC/JLC klystron for which development was nearly complete at the time when the program was stopped. NLC/JLC klystrons are described below. However we continue our analysis with a reduced specification version of the final NLC/JLC tube in order to avoid spurious discussion of whether the klystron specifications had actually been met by the end of the program. Specifically we reduce the peak power from 75 to 65 MW,pulse length from 1.6 to 1.5 µs and repetition rate from 60 to 50 Hz. Should a future, more detailed, evaluation indicate that parameters closer to those of the NLC/JLC should be considered, the performance of the klystron-based machine would be improved.

The initial baseline design for the klystron modulators for NLC /GLC comprised 75 MW Klystron (approx 2000 per linac) with the following main characteristics:

- Solenoid focusing (25 kW per klystron)
- 55% efficiency
- 2x10^{-4} duty cycle (120 Hz, 1.6 µs)
- Average RF output power of klystron 14.4 kW
- 1 kW heater power per klystron

The line type modulators (1 per klystron) have:

- Pulse transformer ~ 20% wasted power with rise and fall time
- Thyratron switch, 600 W per thyratron
- Power factor correction from AC to DC for modulator ~0.97

This gives an overall power requirement for NLC/GLC of 59.33 kW per klystron modulator and for CLIC 500 operating at 50 Hz would correspond to 40.7 kW per klystron modulator.

Although the power requirements are very high this is a proven technology and we know that it works and could be implemented today.

Circa 2002 after some years of development the NLC/GLC baseline was changed to the following

- 75 MW klystron (approx 2000 per LINAC)
  - PPM periodic permanent magnet focussing (no solenoids)
  - 55 % efficiency
  - 0.0002 duty cycle (120 Hz, 1.6 μs)
  - Average RF output power of klystron 14.4 kW
  - 1 kW heater power per klystron
- Solid-state Modulator (1 per two klystrons)
  - Pulse transformer 20 % wasted power with rise and fall time
  - Switch-mode charging power supplies to convert AC to DC power factor correction ~0.85

Using these parameters the overall power requirement for NLC/GLC would be 38.5 kW per klystron modulator and for CLIC 500 operating at 50 Hz this would correspond to 17 kW per klystron modulator.

The major advantage for this model is that the solenoid focussing power is removed but unfortunately the development of the PPM klystron was not completed when the NLC/GLC program ended. If PPM magnet focussing is to be revisited the following issues still have to be resolved

- Full pulse width still to be achieved
- high repetition rate
- peak power

These goals, although not achieved yet, should not pose a problem with further investment into the klystron development and design. In addition the possibility of replacing the normal-conducting solenoid of the initial klystron with a superconducting solenoid with a closed-circuit refrigerator should be revisited.

More effort should also be put into increasing the modulator efficiency, as a 1 % gain in efficiency here is significantly more beneficial than on the klystron. The main actions to achieve this would be to improve the power factor correction for the capacitor charging power supplies and also to study methods for either reducing the leakage inductance in the pulse transformer design or even removing the pulse transformer altogether. Some progress has been made recently with the Marx generator type modulators [7] but remain insufficient for achieving a reliable functioning modulator with the required pulse-to-pulse stability and the required voltage waveform.

Another issue in the klystron modulators not mentioned above is the low-level RF where the klystron driver technology is a TWT, for the moment. These tubes are expensive and have reliability (lifetime) problems compared to the klystron. There should be some investment into looking at some solid-state amplifier design (there are now some transistors on the market that can operate in the X-band frequency range but have not yet been developed or commercialised to make them a viable option).

High-power X-band RF pulse compression system analysis

In the NLC/GLC design, the SLED II pulse compressor [8] was adopted as a part of the RF power production station [9], as is shown in Fig. 4. The SLED II is a passive waveguide circuit that stores RF energy in a pair of resonantly tuned delay lines for several roundtrips, until a phase reversal in the input pulse causes it to be expelled in a compressed pulse of increased power. The lines are iris-coupled at one end to a power directing hybrid and shorted at the other. To reduce losses and to enhance power-handling capabilities, the delay lines are overmoded. The length of the each line is chosen in a way that the round-trip time delay is equivalent to the duration of the compressed pulse. In order to reduce the physical length of the waveguides, multi-moded systems can be used [10]. In these systems, the waveguide is utilized multiple times, often carrying different modes simultaneously. Such a pulse compressor was built and tested at SLAC [11]. It produced close to 550 MW of output RF power with a pulse-width of 400 ns and a repetition rate of 60 Hz. The measured breakdown trip rate trip at this peak power level was about 7.5×10^{-7}/pulse.

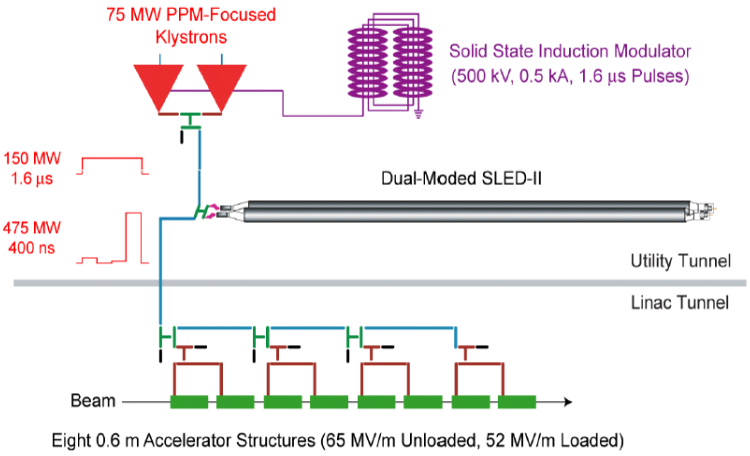

Figure 4: Schematic of the main linac RF unit for the NLC/GLC.

In its original design, the SLED II operated with a factor 4 pulse compression (the ratio between the input and the output pulse durations). We have analyzed the power gain and efficiency of a similar system, but for different pulse compression ratios. In our analysis we have used the following assumptions:

- Similar to NLC/GLC, two combined 75 MW × 1600 ns klystrons were used.
- The ohmic losses per meter length of the delay line were scaled from 11.424 GHz to 12 GHz for the same delay line circular waveguide aperture.
- The attenuation of the waveguide system is assumed to be 0.92, the same as the NLC/GLC design value.
- The peak RF power of the pulse compressor is limited to a critical value. It is determined using a semi-empirical approach [12], which allows us to extrapolate the existing experimental results: $P_C < 550\ \mathrm{MW}\times(T_C/400\ \mathrm{ns})^{1/2}$, where T_C is the compressed pulse length and P_C is an extrapolated RF peak power limit at a given (7.5×10^{-7}/pulse) breakdown trip rate.

The results of this analysis are summarized in Table 1 and shown in Fig. 5. The points on the curves in Fig. 5 correspond to different compressions.

Table 1: The SLED II RF pulse compressor performance

Compression factor	3	4	5	6	7
Pulse length (ns)	533	400	320	267	228
Delay line length (m)	40	30	24	20	17.1
Power gain	2.47	3.21	3.78	4.21	4.56
Efficiency	0.823	0.8	0.756	0.702	0.651
Peak power/unit (MW)	341	443	567	630	684
Power limit (P_C) (MW)	476	550	614	673	730

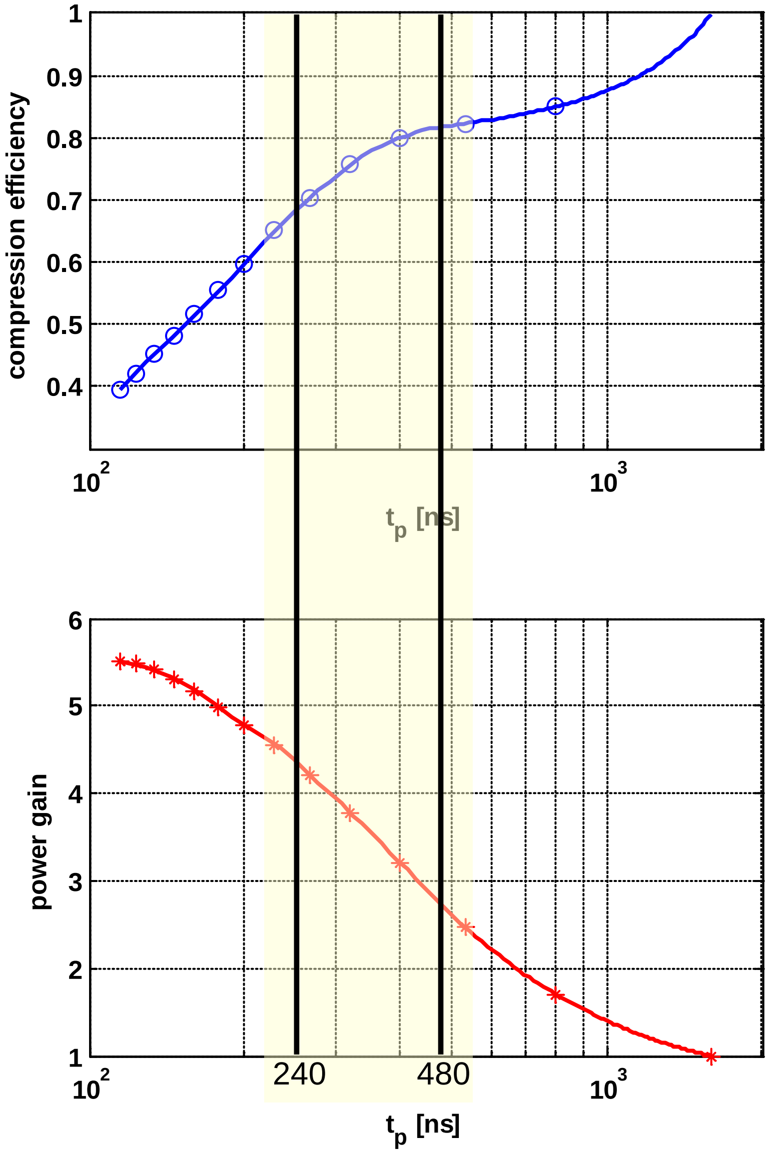

Figure 5: Compression efficiency (blue) and power gain (red) versus pulse length.

COST ESTIMATE

No detailed cost model is currently available for the klystron-based machine. In order to obtain rough estimates, a model has been used that is only based on the total number of klystrons $N_{klystron}$ per linac and the total length of each linac L_{linac}. We express the cost in units of the cost for one RF unit, which consists of one pair of klystrons, their modulator and pulse compressor. The cost is then given by:

$$Cost = N_{klystron} + h \cdot L_{linac}$$

The parameter h is estimated at h=1/(2.3m). The linac cost includes the cost of the tunnel and of the module with the accelerating structures. As the parameter shows, we assume that the cost 4.6 m of tunnel and accelerating structures approximately equals the cost of one RF unit. The length of each linac is given by the centre-of-mass energy and the gradient G:

$$L_{linac} = 1.1 \frac{\frac{1}{2}(E_{cm} - 18\mathrm{GeV})}{0.8 \cdot \mathrm{e}G}$$

The "filling" factor 0.8 is a result of the fact that 20% of the linac length cannot be used for acceleration since it is occupied by other components such as magnets, flanges and instrumentation. The factor 1.1 accounts for the energy overhead foreseen in CLIC. 18 GeV corresponds to the centre-of-mass energy that is obtained from the injection energy of the two linacs.

The number of klystrons which are necessary to feed a 250 GeV linac is calculated using the above described parameters for the klystron and rf pulse compression system and using the following formula:

$$N_{klystron} = 1.1 \frac{\frac{1}{2}(E_{cm} - 18\mathrm{GeV}) n_b N}{\eta_{RF \to beam} \eta_{klystron \to SLED} G_{SLED} P_{klystron} \tau_{RF}}$$

where E_{cm}= 500 GeV centre-of-mass collision energy, N is the bunch population, n_b is the number of bunches, G_{sled} is the pulse-compressor power gain, which is the function of pulse length τ_{RF}. The transfer efficiency through the waveguides from the klystron to the pulse compressor and from the pulse compressor to the accelerating structure $\eta_{klystron \to SLED}$ is assumed to be 92 %.

In should be noted that in a real design the pulse compression ratio must be an integer value and a pair of klystrons must feed an integer number of structures (preferably a power of two). For simplicity we ignore these requirements for this exploration. This can be corrected later by slightly adjusting the parameters, i.e. the klystron output power and pulse length.

The total linac cost is shown in Fig. 6 for the structures that have been optimised for luminosity efficiency.

PARAMETERS OF KLYSTRON-BASED DESIGNS

Based on the above model we find the following parameter sets

- A 500 GeV design based on CLIC_G requires 61.3 MW input per accelerating structure. Hence a pair of klystrons can feed about ten accelerating structures and one needs about 4700 klystrons in total. In practice it may be more convenient to use 60 MW klystrons and feed eight structures per pair.
- A 500 GeV design based on CLIC_502 requires 74.2 MW input per accelerating structure. Hence a klystron pair can power 8.2 structures. About 7200 klystrons will be needed in total for this case.
- For a number of other structures, the cost is shown in Fig. 7 as a function of the figure-of-merit. Of particular interest are the structures marked with arrows, which provide a very good compromise between cost and luminosity efficiency. These structures have twice the length of the current CLIC structure.

The detailed parameters for these structures are listed in Tab. 2 together with CLIC_G and CLIC_502. The luminosity for each parameter set is given assuming a pulse frequency of 50 Hz and a horizontal emittance of $\varepsilon_x = 2400$ nm and $\varepsilon_x = 660$nm, which corresponds to the CLIC energy staging scenarios A and B respectively [1]. The luminosity is normalized to the first stage of scenario A.

Based on these results one can draw the following conclusions

- A number of different structures lead to comparable costs for a klystron-based CLIC linac. The luminosity is comparable to that of the drive-beam based design. The pulse length in all cases is the same as for the drive-beam design.
- A design based on CLIC_G, the current structure design for 3 TeV, would be on the lower end of the cost band. It would achieve the same luminosity as the drive-beam based first energy stage of CLIC in the staging scenario B, which uses the 3 TeV structure also for the first energy stage.
- At least half of the cost of the main linac is in the rf powering systems, which replace the drive beam.

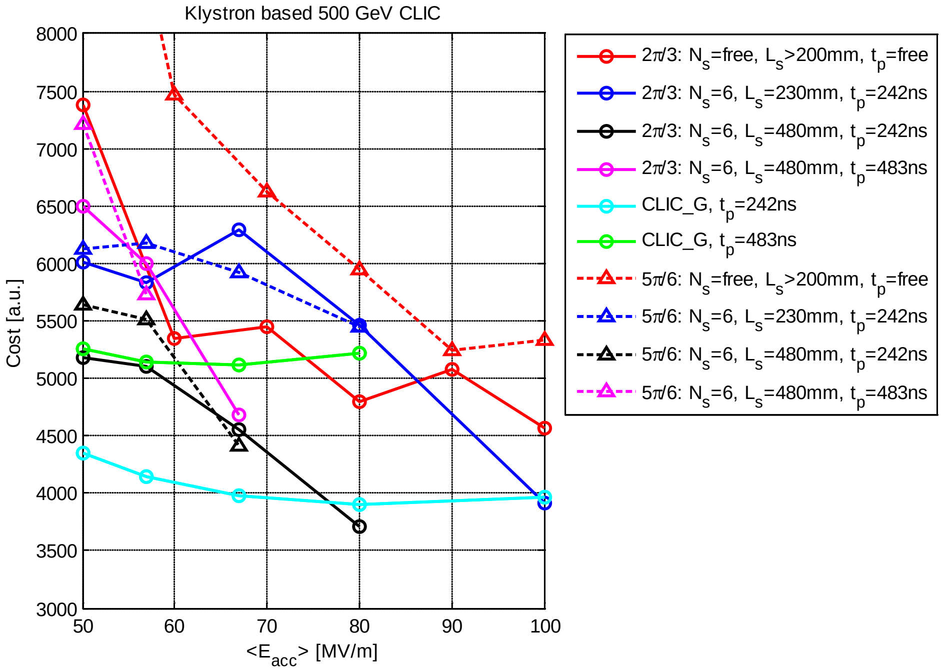

Figure 6: The linac cost (in arbitrary units) for different structure parameters.

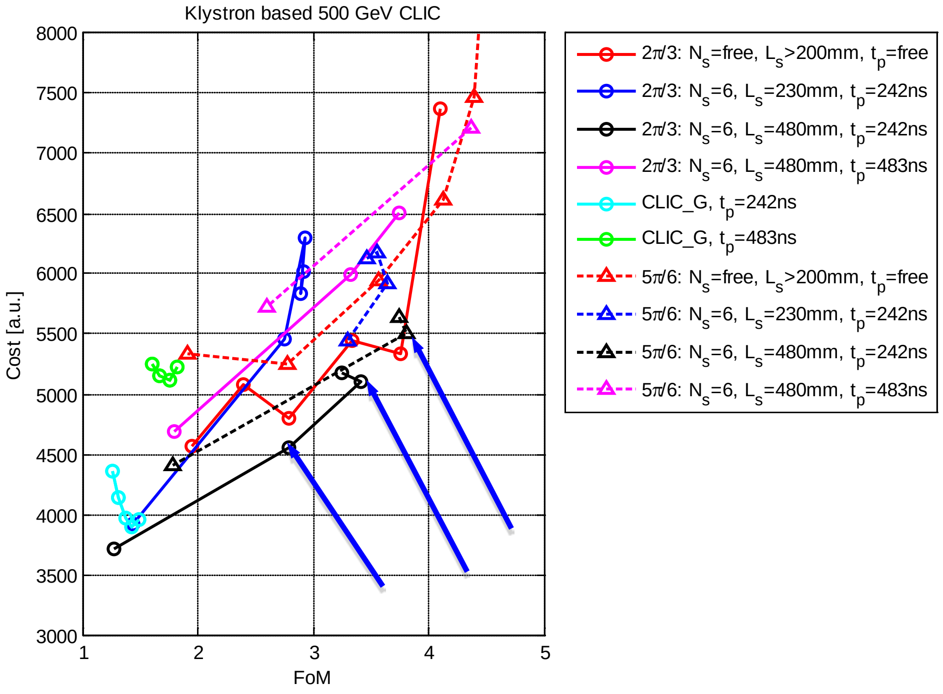

Figure 7: The linac cost vs. the figure of merit for different structure parameters. The structures marked with blue arrows are detailed in Tab. 2.

Table 2: Parameters of the CLIC structure for use of the drive beam together with possible structures for the klystron based 500 GeV CLIC. The luminosity is given relative to the one obtained with a drive beam-based design using CLIC_502 and a horizontal emittance of 2.4 μm, which corresponds to the CLIC energy staging scenario A. The the scenario B, which is based on the use of CLIC_G and a horizontal emittance of 660 nm, the luminosity would be 48 % of this value.

Case	CLIC_502	1	2	3	CLIC_G*
Average accelerating gradient: $<E_a>$ [MV/m]	80	67	57	57	100
Rf phase advance: $\Delta\varphi[^o]$	150	120	120	150	120
Average iris radius/wavelength: $<a>/\lambda$	0.145	0.14	0.145	0.16	0.11
N. of reg. cells, str. length: N_c, l [mm]	19, 229	56, 480	56, 480	45,480	24,229
Bunch separation: N_s [rf cycles]	6	6	6	6	6
Bunch population: N	6.8×10^9	4.95×10^9	5.49×10^9	7.01×10^9	3.69×10^9
Number of bunches in a train: N_b	354	335	382	337	312
Pulse length: τ_p [ns]	244	244	244	244	244
Input power: P_{in} [MW]	74.2	84	76	89	61.3
Max. surface field: E_{surf}^{max} [MV/m]	250	260	215.6	260	245
Max. temperature rise: ΔT^{max} [K]	56	43	27.6	42	53
Efficiency: η [%]	39.6	41.9	49.5	48	28.5
Figure of merit: $\eta L_{b\times}/N$ [a.u.]	3.3	2.79	3.41	3.81	1.5
Relative Luminosity @ 50 Hz [%] For ε_x=2400nm	100	55	73	94	31
Relative Luminosity @ 50 Hz [%] For ε_x=660nm	100	69	87	98	48
Number of klystrons per linac N_{linac}	3520	2292	2454	2850	2359
Cost for linac tunnels and modules (arb. units) hL_{linac}	1801	2150	2528	2528	1441
Total cost in arbitrary units	5321	4442	4982	5378	3800

CONCLUSION

One possible initial energy stage of a klystron-driven CLIC has been investigated. We estimate that 4700 and 7200 klystrons are required for 500 GeV centre-of-mass energy using CLIC_G and CLIC_502 type structures, respectively. Other practical designs are based on structures that are longer but have a lower gradient. The total number of klystrons is in this case within the same range. The structure that is used for the 3 TeV stage of CLIC, CLIC_G, yields the cheapest machine.

The example parameters presented in this report are only indications of the potential of a klystron-based design. They have been derived to be able to roughly identify the parameter space and to provide a lowest-order comparison to the drive-beam based option. Improvements are necessary to arrive at a realistic design which can be compared to the drive-beam based option and superconducting machines of the same energy:

- A more reliable cost model is required.
- Different pulse compressor design options should be investigated, some promise to avoid to have to build a second tunnel;
- The parameters for the klystron performance should be reviewed to find an optimum trade-off between cost and risk.

In addition it will be necessary to review the initial energy of the machine and to consider the different options to upgrade it in energy. For the upgrades it appears necessary to use a drive beam to power the main linacs.

On the whole we find that it appears worthwhile to study in more depth an initial energy stage CLIC powered by klystrons. The machine is extendible into higher energies by switching to two-beam power generation but while maintaining the basic technology of high-gradient normal-conducting rf. The initial stage is technically very mature and is likely to be competitive in cost below about 500GeV.

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