CLIC Accelerator Study – Review of objectives for the MTP 2016-2019

March 1st, 2016

Report from the Review Panel

Members: O. Brüning; P. Collier, J.M. Jimenez, R. Losito; R. Saban, R. Schmidt;
F. Sonnemann; M. Vretenar (Chair).

Introduction and general remarks

The Panel was very impressed by the enormous amount of work that was presented, by the enthusiasm of the CLIC team and by the wealth of knowledge accumulated by the CLIC study. The CLIC accelerator study has reached a high level of maturity and has been able to establish a large community consisting in about 50 collaborating laboratories and universities, working together on a number of technical challenges

After the publication of the Conceptual Design report in 2012, the CLIC Study is presently in the Development Phase, to prepare a more detailed design and an implementation plan for the next European Strategy Upgrade in 2018-19. This phase is expected to be followed by a Preparation Phase covering the period 2019-25; in case of a positive decision, a construction phase could start in 2025.

The Panel acknowledges the tremendous amount of work that has been achieved by the CLIC collaboration in the detailed design and optimization of all aspects of the 3 TeV machine. This work formed the basis for the CLIC CDR and has been continued since in particular for the drive and main beam production and transport as well as the design of the main accelerator and final focus. The initial design of CLIC was based on the maximum energy and scaled down for possible initial low energy stages; a lower energy option was not studied to the same level of detail.

The new strategy of the CLIC team is of presenting at the next European Strategy Upgrade a staged approach starting with the construction of a collider optimised for 380 GeV cm energy, aiming at Higgs and top physics. After this initial stage, the following stages at 1.5 and 3 TeV cm energy could be implemented during shut-downs of acceptable (4-5 years) length.

Comments:

The Panel welcomes and fully supports the present CLIC strategy of ***optimising the accelerator for 380 GeV*** and work out the path from such machine to an accelerator with much higher energy. Since CLIC is a completely new technology, its design should be demonstrated with an accelerator operating at reduced energy with reduced investment; depending on the physics outcome of LHC, such accelerator could be very interesting for particle physics and would be operated for a number of years. An upgrade to 1.5 or 3.0 TeV is expected not to be a simple staging, but rather a machine which is optimised based on the experience of the 380 GeV collider, re-using as many systems as possible. In particular, successful operation of a 380 GeV collider would give confidence that the design parameters for the high energy machine can be achieved.

The Panel encourages the CLIC team to produce an optimised 380 GeV design and to define ***two sets of beam parameters**,* a 'nominal' set of parameters that are within reach with the present knowledge of the final focus as well as an 'ultimate' set of parameters that could be potentially achieved with further developments. In particular the very small beam size together with the proposed beam current seems difficult to achieve, and a more conservative set of parameters for the initial operating phase would reduce the risk of not meeting the expectations of the physics community. The energy sensitivity of the design solution must also be studies to give the range over which this configuration can be operated. The upgrade path from this configuration towards the full 3 TeV machine should then be developed further.

The ***optimisation of cost and power consumption*** of the 380 GeV collider will be of extreme importance in view of the ESU: activities aimed at addressing cost drivers and at increasing power efficiency should have the highest priority between now and 2019. In particular, the estimated power consumption of 252 MW seems to be very high, compared to the power consumption for the higher energy machines, but also considering that the beam power is not more than 6 MW for each beam.

The Panel has been impressed by the excellent work carried on so far on ***high-efficiency klystrons*** and is fully convinced by the need to proceed with the R&D phase till 2019. This is justified both by the expected progresses on the technology but also by the diversity of domains of applications of these improvements. The Panel recommends to reinforce whenever possible collaborations with Institutes and Industry. The Panel recommends to continue the R&D with possibly more prototyping to address more quantitatively the efficiency, the operability and the reliability. Moreover, the Panel thinks that these activities shall be continued beyond 2019 in a wider frame of CERN R&D activities.

Although a preliminary study indicates that for 380 GeV a ***klystron-based version*** would have a similar cost as the dual-beam version, the Panel considers that the initial low energy stage should already address the issue of dual-beam acceleration in preparation for the following stages and that this should remain the baseline. Study of a klystron-only version should continue as an alternative option that could be considered for further optimisation during the Preparation Phase.

The CLIC design involves a large number of different ***technological aspects***; several challenges have been addressed in the past, and others are being addressed today. It is not possible to work on all of them in view of limited resources, and the Panel considers that most can be addressed later during the Preparation Phase, since based on the knowledge acquired so far one can be confident that the challenges can be mastered, either based on previous experience, from scaling or from the information obtained at other accelerators. The Panel recommends the CLIC team to concentrate on demonstrating that there are no showstoppers and on addressing new designs that could drastically impact cost or power consumption. Technological developments could be done at a later stage.

In terms of risk for the feasibility of the project, the Panel considers that the ***beam delivery system and the final focus*** represent the most visible concern that needs to be studied in more detail, in particular for the 380 GeV machine. Current studies include participation to the ATF2 experiment and further contacts with the ILC community should be actively pursued.

It was considered that some improvement could possibly come from a more detailed analysis of the ***background vibrations***. This represents a concern for the project and has a strong impact on the cost of the alignment and stability systems. A more detailed study could provide opportunities to simplify the module design and reduce cost in case vibrations would turn out as a lower concern than what presently expected.

1. Current status of development of knowledge in the accelerator domain as a result of CLIC studies

The Panel noted that while many parts of the design are well in hand, others will require further work to achieve the design parameters set. The two most notable examples here are the main beam generation & transport with the subsequent emittance preservation to prevent beam loss and the final focus for the main accelerator.

Finally it was noted that work could continue on the drive beam accelerator, together with the combiner rings and beam transport, although this was felt to be of a lower priority by the reviewers. The combiner ring design from the CDR leads to a large emittance growth already on paper. A new design will be needed to overcome this and deliver the drive beam characteristics needed without significant losses.

2. Status and goals of the collaborative studies related to development and demonstration of key CLIC technologies

The accelerator development features collaborations with approximately 50 institutes and the detector development a collaboration with approximately 27 institutes. The study features around 80 PhD students in 2015. X-band structures are prepared and tested in 8 institutes around the world and studies for developing X-band facilities (mainly FEL type projects) exist in 12 institutes around the world. Three X-box test stands exist at CERN and complementary test stands exist at KEK and SLAC. Tsinghua University and SINAP have both ordered X-band klystrons and Trans-National access for X-boxes has been included in the ARIES Integrating Activity proposal.

The CTF3 facility has been built and operated though international collaborations and includes significant hardware investment from partner laboratories; this test programme is complemented by tests at other international test facilities, e.g. FACET at SLAC and ATF2 at KEK and damping ring concept demonstrations at ANKA, ALBA, MAXIV, CESRTA etc.

The recently launched HEIKA network for supporting 'High Efficiency International Klystron Activity' represents an impressive new collaboration effort that has been launched with the help of the CERN CLIC study and brings together collaborative partners from laboratories, Universities and Industry. The PACMAN network represents as well an impressive international collaboration and training network in the domain of accelerator component alignment that has been spearheaded by the CLIC study.

Comments:

The CLIC study features an impressive number of international collaborations and has managed to develop a well-matured network with partner institutes and the number of CLIC related PhD thesis underlines the importance of the study for academic accelerator studies at universities.

The development of X-band klystrons and the Xbox concept provides the possibility for building test stands even at smaller partner laboratories and for developing further the international collaboration (network) of X-band structure development. The inclusion of Trans-National access for X-boxes in the Aries EUCARD proposal is a very attractive step for strengthening such efforts.

The Panel observes that in some areas (e.g. UK collaborations) the collaborations consist mostly in K-contracts with financial contributions from CERN. While this scheme is attractive to manage in-kind contributions during the construction phase of a project, its value is less obvious during the preparatory phase of a project where the collaborations depend on the less stable R&D budget.

3. Knowledge gap to be filled to be ready for the next European Strategy Upgrade

The beam size at the final focus is extremely small, requiring the production of very small emittance beams. This raises several questions concerning emittance preservation from the damping rings to the main linac, considering that beams are extracted and injected with kickers, transported in long transfer lines, etc., and emittance preservation in the linac itself. The very small (few nm) beam size in the final focus is a major concern, suggesting to consider the consequences in case some of the parameters cannot be achieved, leading to a lower luminosity for physics. The emittance in most advanced synchrotron light sources are still somewhat larger, e.g. for MAX4 a factor of 3 in the horizontal plane, but rapidly evolving. Collaboration with colleagues from advanced synchrotron light sources is important, and tests at other labs should be considered, to demonstrate that the very small beam size can be achieved. The beam delivery system and final focus need to be studied in more detail, in particular for the 380 GeV machine, and an outlook should be presented to indicate what emittance can realistically be achieved in about 10 years.

The CLIC accelerating structures are required to have an effective gradient of 100 MV/m, an efficient pulse length of 180 ns and a breakdown rate of less than 3x10-7/pulse/m. Since beam loading reduces the effective field, the gradient should be about 20% higher when operating without beam. When structures are tested at higher gradient to measure the breakdown rate, scaling with an empirical equation to lower rates is applied. Conditioning with a time constant of the order of 1e8 pulses is observed. However, it appears that the mechanisms for conditioning are not well understood and mastered, in particular considering possible long-term effects. Tests with a large number of pulses were performed, but even those tests still correspond to less than one year of real accelerator operation; in this sense, a very promising development is testing at higher repetition frequency. A test campaign of a few identical modules to a number of pulses corresponding to the lifetime of an accelerator (20-30 years, e.g. more than 2e10 pulses) should be considered.

Conditioning of the accelerating structures will be required, for several tens of thousands of such structures. An operational scenario for conditioning the machine should be worked out, indicating what tests of structures / modules need to be performed before installation in the accelerator tunnel, and what can be done in the tunnel. This operational scenario should be part of a complete scheme for the operability of such an accelerator, addressing aspects of availability, commissioning and operation.

High priority should be given to the development of highly efficient klystrons at different frequencies, in particular around one GHz and 10 GHz, and to a measurement of their efficiency. The Panel understood that only a few of such klystrons are being prototyped. Since this is such an important development, it should be considered the gain of getting a larger number of prototypes to address efficiency, operability, and availability. The development of klystrons is an ideal topic for collaborations, since many labs are interested in this technology.

The CLIC drive beam is a novel concept that has not been used at any other accelerator. While the basic performance is studied in detail in CTF3, much less is known about operability and availability of this part of the accelerator in a full scale implementation. It is suggested to study the availability of the drive beam, as well as on the consequences of specific failures on the luminosity (classification: no impact, limited impact, preventing operation).

There are a number of different types of two beam modules. The design is foreseen to be improved with the objective of producing less expensive modules, hence providing a base for improved costing/power estimates for the ESU and future industrialization beyond the ESU.

The stability of the CLIC accelerator is extremely challenging, in particular of the quadrupole magnets for the high energy beam. It is required to understand if further studies are necessary for 2018.

4. Activities corresponding to the knowledge gap, criticality and prioritization

- *Activity on parameters, design and implementation, performance*: **must**

The goal of producing an optimised staged design centered on the 380 GeV option in time for the European Strategy Upgrade is a clear priority for the CLIC team. For 380 GeV the accelerating structures will be longer and some changes are required in all systems. Several elements need to be developed and improved in the design.

- *RF structures design, production and testing*: **must**

The accelerating structures are crucial for reaching the design performance; the recent testing programme has allowed accumulating some statistics (5xCDR) and to prove that the gradient is within reach. 10 structures of 3 design generations were tested so far, showing a clear progress; the structures in production in several laboratories should all be thoroughly tested. It is important at this stage to consolidate the high gradient results and to develop conditioning strategies that will be essential for the commissioning. Alternative construction technologies aiming at a reduction in cost should continue to be explored.

- *X-band test stands (Xbox):* **must**

Three klystron-based test-stands have been equipped to test around 40 structures in the present project phase. They constitute an important investment and they represent an essential tool to prove the feasibility of the gradient, to develop conditioning strategies and to develop collaborations including laboratories interested in X-band FELs. Transferring one (or two) of the test stands to collaborating institutes would give the opportunity to engage them more closely into the development and to reduce the CERN resources required for their operation.

- *High-efficiency Klystrons*: **must**

The new MBK bunching concept with core oscillations is expected to boost efficiency from 70% to the 90% level, reducing the grid power required for RF from 290 MW down to 190 MW. Although the production cost of the klystron would be higher, the expectation is that the gain coming from higher peak power per unit and reduced modulator voltage will offset this increase in cost leading to a significant increase in efficiency at practically no cost.

This principle should be thoroughly studied, and its economics assessed in time for the ESU. Together with the impact on CLIC, the development of an L-band high-efficiency MBK could benefit to several projects (ESS, FCC, ILC).

The establishment of the HEIKA Network has the full support of the Panel as an important stage towards pushing these studies further. The Panel encourages as well the CLIC team to investigate the added value of producing more prototypes.

- *Full klystron version*: **should**

A 380 GeV CLIC version with klystrons should be further developed, but at the present stage the Panel would not recommend it as the baseline to be presented at the ESU. If needed, this version could be rapidly optimised during the Preparation Phase.

- *Drive beam front-end test facility (12 MeV):* **could**

An important investment has been already made to order components for the Drive Beam Test Facility. Although the drive beam generation and stability is an important concern for CLIC, the overall feasibility of drive beam generation is considered as proven, and testing with beam aiming at improving and optimizing the performance would be possible only from 2018, too late to integrate the results in the ESU documents. While it can be important to test the new commercial high-efficiency (70%) klystrons before the ESU, the Panel supports the CLIC plan of not starting beam test at the front-end test facility before the ESU.

- *Additional experimental verification activities*: **must**

The final focus is a critical element of the CLIC design. In ATF2 the $beta^*\_y$ is slightly above the CLIC goal but for a shorter L*, consequently the chromaticity in CLIC will be a factor 4 larger than in ATF2. Two octupoles recently manufactured at CERN will be tested at ATF2 to explore if one can reach ultra-low beta*_y, to have the same chromaticity as in CLIC. Participation to ATF2 must continue and be possibly improved, to provide important answers in time for the ESU.

- *Damping ring*: **could**

The parameters of the CLIC damping rings are similar to those of advanced synchrotron light sources. It is important for CLIC to continue the collaboration with the low-emittance ring community, but a direct involvement in the testing programmes of this community is not considered as a priority for CLIC. CERN should follow the activities of the community aiming at achieving very small emittances without investing substantial resources in the experimental testing programmes.

- *Technology developments*: **could**

A long list of technological developments was presented, covering beam instrumentation, warm magnets development, superconducting wigglers, mechanical pre-alignment, quadrupole active stabilization, R&D on new alignment concepts, vacuum technology, fast pulsed kickers, module R&D, main dump design, control system approach for main linac, modulators for the drive beam klystrons, and RF system prototype (extreme beam loading) for damping rings.

Some of these are pursued as part of the experimental system tests (modules, kickers, partly magnets and stability/alignment systems), or for costs and power reasons (modules, magnets, modulators and instrumentation partly); several technical developments address specific performance issues (instrumentation partly, controls, wigglers, stability/alignment partly, vacuum, RF for extreme beam loading).

In this latter category most of the components have feasibility demonstrated and are fairly mature at this point, and they have a small impact on the overall cost or power consumption of the CLIC accelerator; in many cases the technical solutions are very similar to what is done on other machines. The Panel considers that globally these activities could wait for the necessary industrialization phase that would take place during the preparation period after the ESU.

For the ESU, priority should be given only to developments aimed at cost and power reduction; an example are the permanent magnet quadrupoles that can potentially provide a 10% power reduction if implemented generally for the CLIC magnets. The Panel was however surprised of their high cost related to the complex design required for field adjustment and encourages the CLIC team in looking for simpler designs, involving both beam dynamics experts and magnet designers.

- *CLIC module development*: **should**

The design of the CLIC module should be adapted to industrial production, documenting and analyzing the results from the on-going experimental programme and PACMAN studies to revise and optimize the current design. Industrial production of such modules is however not considered as a priority until the ESU. The dominating cost item in the module are the accelerating structures that will continue to be optimized independently from the module. The industrialization of the module could be effectively done during the preparation phase based on an updated module design resulting from the ongoing studies. With a possible construction approaching, more companies are expected to show interest thus increasing competition and reducing costs.

5. Accelerator reports to be presented at the next ESU

The following set of documents concerning the CLIC accelerator is foreseen for the ESU:

- Summary project plan document (physics, machine parameters, cost, power, site, staging, construction schedule, brief summary of main technical issues, preparatory phase summary, detector studies (document of 50-80 pages with a shorter executive version as needed);

- Preparation phase plan document (critical parameters, status and next steps 2019-2025, strategy, risks management plan involving CERN, collaborators and industry (document of around 50 pages);

- Detailed set of documentation across project based on EDMS/WBS (existing but needing update, already used for cost and power). To be used by 2019 for consistent technical documentation, tender/commercial documents (protected), results, notes/publications for each WP and/or activity.

Comments

The proposed documentation is certainly sufficient for the strategy upgrade; in line with the previous recommendations the Panel considers that “Summary project plan” should give enough relevance to the proposed staged approach, presenting with a sufficient level of detail and approximation the parameters (including cost and power consumption) of the optimised low energy stage and with lower detail and approximation the case for the later upgrades at higher energy. Similarly, the “preparation phase plan” document should concentrate on addressing the technical challenges for starting by 2025 the construction of the initial stage.

6. CALIFES

The Panel was presented a plan to operate the CALIFES electron linac, presently used as the probe beam line of CTF3, as a stand-alone user facility from 2017 onwards after CTF3 has completed its planned operations. Although this topic is not in its mandate, the Panel considers that a possible continuation of CALIFES is part of the overall strategy for CLIC activities until 2019 and intends to express its opinion on this subject.

In general terms, the Panel does not see an immediate need to continue the operation of CALIFES for specific CLIC studies as no further tests absolutely required in view of the ESU have been presented.

However, in more general terms and with a wider perspective, the uniqueness of this infrastructures is an asset and the committee recommends studying the funding till 2018 to keep it running at CERN with the aims of:

- Keeping at least an electron machine at CERN;
- Keep competences at CERN;
- Foster experts and keep the existing community alive.

To make the operation of CALIFES compatible with the other CERN programmes, the Panel recommends to involve collaborating institutes in the operation, with the goal of reducing the CERN personnel required for operation; the present estimate of 5.5 FTEs is considered as not affordable in the next years and should definitely be reduced. Moreover, it is recommended to check that expert resources for CALIFES operation are not already committed on AWAKE.

Appendix 1

Mandate

Introduction

The Compact Linear Collider (CLIC) is a TeV scale high-luminosity linear e+e- collider under study and development in the framework of an international collaboration with more than 70 participating institutes from 25 countries. The accelerator is based on a novel two-beam acceleration technique, which could, in stages, reach a centre-of-mass energy up to 3 TeV.

After the conceptual design report published in 2012 and the European Strategy update in 2013, the CLIC studies are now focused on developing a project implementation plan for CLIC as a future energy frontier option at CERN after LHC. The time-period considered is up until the next European Strategy update in 2019. The study covers accelerator, detector and physics studies. The CLIC work-programme, technical R&D and design studies are carried out by the collaboration with CERN as leading institute and host of the study. High-gradient technologies are pursued in particular, as well as the development of the associated detector systems and studies of the CLIC physics potential.

Further to recent discussions held in the framework of the MTP, a review is called by the Director for Accelerators and Technology to assess the current status and in particular provide recommendations on the targets to be achieved that will be instrumental for the next European Strategy Update of 2019. The review will concentrate on the CLIC accelerator programme.

The review

The panel members are asked to:

- Assess the current status of development of knowledge in the accelerator domain, as a result of studies pursued so far in the CLIC framework;
- Assess the status and goals of the collaborative studies between CERN and its partners related to development and demonstration of key CLIC technologies;
- Identify the knowledge gap that remains to be filled to be ready for the next European Strategy Upgrade;
- Identify activities corresponding to this knowledge gap; assess the criticality and give recommendations on the prioritization and phasing of these activities to be ready for the ESU – these activities must be classified as (MoSCoW method):
    - Must have: critical to be a success at the ESU (Vital);
    - Should have (if at all possible): important but not necessary to be a success at the ESU (Essential);
    - Could have (if it does not affect anything else): desirable but not necessary to be a success at the ESU (‘Confort’), will typically be included if time and resources permit;
    - Won't have (but would like in the future): least-critical or not appropriate activities before the ESU.
- Review and provide guidance concerning the content of the accelerator report(s) to be presented at the next European Strategy Upgrade.

Appendix 2

Agenda

09:00 - 09:10 Introduction and mandate *10'*

Maurizio Vretenar (CERN)

09:10 - 09:40 Project overview: structure and status, objectives for 2018, long-term *30'*

Steinar Stapnes (CERN)

09:40 - 10:10 Status and plans of X-band test-stands and structures *30'*

Walter Wuensch (CERN)

10:10 - 10:40 Status and plans of klystron developments, including high-efficiency *30'*

Igor Syratchev (CERN)

10:40 - 11:00 Coffee Break

11:00 - 11:30 Status and plans of drive beam components design and test *30'*

Steffen Doebert (CERN)

11:30 - 12:00 Completion of CTF3 program in 2016 and further CLIC experimental verification activities *30'*

Roberto Corsini (CERN)

12:00 - 12:30 CLIC performance, ongoing verifications and remaining concerns *30'*

Daniel Schulte (CERN)

12:30 - 13:30 Lunch

13:30 - 14:00 Status and plans for CLIC advanced technical components *30'*

Hermann Schmickler (CERN)

14:00 - 14:30 Status and plans of the module development programme *30'*

Steffen Doebert (CERN)

14:30 - 15:00 Proposal for the future operation of the CALIFES linac *30'*

Erik Adli (University of Oslo (NO))

15:00 - 15:15 CLIC resource plans until 2018 *15'*

Steinar Stapnes (CERN)

15:15 - 15:45 Coffee and questions time

15:45 - 18:00 Closed session (Reviewers only) *2h15'*