

SUSTAINABILITY STUDIES FOR LINEAR COLLIDERS

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Abstract

Sustainability has become a prioritized goal in planning and implementation of future large accelerators. ILC and CLIC, two linear collider projects proposed as a future Higgs factory and collaborating in many areas, have extensively studied novel design and technology solutions to address power efficiency and reduce the environmental impact of the facilities. The sustainability considerations, in addition to the more traditional cost concern and need for developing core technologies, are today primary R&D drivers for the projects. Approaches to improved sustainability range from overall system design, optimization of subsystems and key components, to operational concepts.

1. INTRODUCTION

Ten years after its discovery by the ATLAS and CMS collaborations at the LHC collider at CERN, the Higgs boson that gives mass to all the elementary particles remains the most mysterious particle in the Standard Model of high energy physics. A dedicated “Higgs factory” accelerator producing Higgs bosons in electron positron collisions is therefore considered the highest priority project for a new energy frontier accelerator [1]. Such a Higgs factory produces Higgs and Z^0 bosons in conjunction in the process $e^+e^- \rightarrow h Z^0$, which requires a centre-of-mass energy of 250GeV. The physics programme of such a facility would be completed by studying the properties of the Top quark, requiring 350 to 380GeV, and measuring the coupling of the Higgs boson to the Top quark (in the reaction $e^+e^- \rightarrow h t \bar{t}$) and to itself (in $e^+e^- \rightarrow hh Z^0$), at 500GeV or more of energy.

Accelerators for high energy physics have been built and operated for over six decades and have always been pushing the limits of what was feasible technologically (and financially). Thus, conserving the resources necessary for the construction and operation has always been a driver in the accelerator design. Today, resource conservation is considered not only a financial necessity but a societal obligation, and sustainability is an important goal in the development of new accelerators [1].

Two large electron-positron linear colliders are currently being studied as potential future Higgs-factories, the International Linear Collider (ILC) in Japan [2-5], and the Compact Linear Collider (CLIC) at CERN, Switzerland [6-9].

In this study we present activities in the design and R&D efforts of both accelerator projects that contribute to the goal of sustainable construction and operation of these facilities. These activities entail the optimisation of

- the overall system design with the goal of resource conservation in construction and operation,

- the design of subsystems and components,
- the concept for operation and interaction with the surrounding site and society.

These aspects are discussed in turn in the following.

2. OPTIMISATION OF THE OVERALL SYSTEM DESIGN

The two most important key performance indicators of electron positron colliders for high energy physics are the centre-of-mass energy, which determines which production channels are kinematically accessible, and the luminosity, which determines the number of reactions taking place and thus the sensitivity to rare events and the statistical accuracy of the experimental results.

For a symmetric collider the centre-of-mass energy is twice the beam energy. In a circular electron/positron storage ring, the beam energy is ultimately limited by the synchrotron radiation power that needs to be constantly replenished to keep the beam circulating, which grows proportional to E_{beam}^4/R , with R being the effective bending radius of the machine. Balancing the growth of construction costs (proportional to the ring size, given by R) and operation costs (proportional to the power consumption) leads to a quadratic increase of both, radius and power, with beam energy for circular colliders. For the Main Linac of a linear collider, on the other hand, power consumption and overall length rise linearly with beam energy, so that eventually linear accelerators become the most economical solution.

For linear colliders, the Main Linacs are the dominant systems in terms cost and power consumption, and therefore the target of intense R&D to optimise their performance.

A reduction of construction costs requires high acceleration gradients g to achieve the desired beam energy. The power losses in the cavity walls per unit length, however, grow quadratically with gradient, leading to a linear increase of power losses with gradient g for fixed beam energy $E_{beam} = gL$. To counter this effect, ILC and CLIC have vastly different approaches: ILC utilises superconducting cavities to reduce the primary energy loss in the cavity walls to almost zero, at the prize of a limited gradient and a large cryogenic infrastructure; CLIC operates at room temperature with high rf frequency and extremely short pulses, made possible by a unique two-beam acceleration technology. After an optimisation of costs and power consumption, both concepts arrive at almost identical values for the overall power consumption (110-111 MW) for their respective baseline designs, as shown in Fig. 1.

In order to maximise the delivered luminosity for a given beam power, both concepts utilize and collaborate on the nanobeam technology, where damping rings provide extremely low emittance beams and a highly optimised final focus system squeezes the beams down to nanometre beam sizes.

In the following, the two concepts, whose key parameters are listed in Tab. 1, are presented in turn.

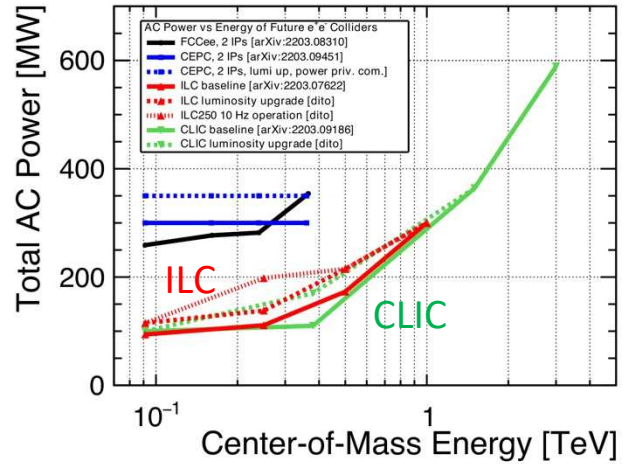


FIG. 1: Total site power versus centre-of-mass energy for linear (ILC, CLIC) and circular (CEPC, FCCee) e⁺e⁻ colliders under investigation [5].

TABLE 1. KEY PARAMETERS OF ILC [5] AND CLIC [9]

Quantity	Unit	ILC	CLIC
Centre-of-mass energy (baseline - max)	GeV	250 - 1000	380 - 3000
Luminosity (at baseline energy)	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.35	2.3
Length	km	21	11.4
Accelerating gradient	MV/m	31.5	72
Particles per bunch	10^9	20	5.2
Bunches per train	1	1312	352
Pulse length	μs	727	0.244
Pulse repetition rate	Hz	5	50
Beamspot size	nm^2	516×7.7	149×2.0
Average beam power at initial energies	MW	5.3	5.6
Site power (baseline configuration)	MW	111	110

1.1. The International Linear Collider (ILC)

The ILC [2, 3] is a proposed superconducting linear e^+e^- collider, operating as a Higgs factory [4] with a centre-of-mass energy of 250GeV and a luminosity of $1.35 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ in the baseline configuration. It is upgradeable in energy up to 1TeV and in luminosity (at 250GeV) by a factor of four in several stages [5]. The overall site length is 20.5km, dominated by the two Main Linacs that comprise (depending on the final gradient) 859 to 939 cryomodules, each housing 8 or 9 superconducting niobium cavities running at 1.3GHz and 2K operating temperature. Rf power is provided by 202 to 220 10MW pulsed klystrons with Marx modulators.

Electrons with 80% polarisation are produced by a laser gun with a strained GaAs/GaAsP photocathode, positrons with 30% polarisation in a rotating conversion target illuminated by a polarised photons from a helical undulator driven by the electron Main Linac beam. A central damping ring complex at 5GeV beam energy provides low ($4\mu\text{m}/20\text{nm}$ normalized horizontal/vertical) emittance beams, which are transported to the starting points of the Bunch Compressor / Main Linac section. The final focus provides a $516 \times 7.7\text{nm}^2$ beamspot for the experiments, at a total beam power of 5.3MW.

In the baseline configuration, the total electric power consumption is 111MW.

For a linear collider, the luminosity L can be expressed as

$$L = \eta \frac{P_{AC}}{E_{CM}} \cdot \frac{N_e}{4\pi\sigma_x^i\sigma_y^i} H_D$$

in terms of the Main Linac wall plug power P_{AC} , the Main Linac efficiency η for the transfer of wall plug to beam power, the centre-of-mass energy E_{CM} , the single bunch charge N_e , the beam size $\sigma_x^i \times \sigma_y^i$ and the enhancement factor H_D . The basic choice of the

superconducting TESLA technology [10] is based on the goal of maximising the efficiency η . The quality factor Q_0 , which is highly dependent on the surface properties (see below), is also affected by fundamental system decisions on rf frequency (1.3GHz) and operating temperature (2K). Operational parameters such as operating gradient, bunch charge and spacing, and pulse length all have been considered in finding a suitable working point within the technological limits.

The trade-offs that need to be considered are between losses in the cavity walls, electrical power for liquid helium cooling, field energy lost after each pulse, size of damping rings. Technological limits for rf pulse lengths, damping ring currents, achievable gradient, cryogenic plant size in terms cooling power and helium mass flow pose various limits on the parameter space.

For example, there is a balance between investment costs for cavities and cryomodules, which are reduced at higher accelerating gradients, and cost for cryogenic plants, which grow with gradient. For the high quality factors of 10^{10} or better targeted at the ILC, the optimum is beyond the gradients that are achievable today [11]

1.2. The Compact Linear Collider (CLIC)

The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider under development by the CLIC accelerator collaboration. The CLIC accelerator has been optimised for three energy stages at centre-of-mass energies 380 GeV, 1.5 TeV and 3 TeV [9]. CLIC uses a novel two-beam acceleration technique, with normal-conducting accelerating structures operating in the range of 70-100 MV/m. To reach multi-TeV collision energies in an acceptable site length and at affordable cost, the main linacs use normal conducting X-band accelerating structures; these achieve a high accelerating gradient of 100MV/m. For the first energy stage, a lower gradient of 72MV/m is the optimum to achieve the luminosity goal, which requires a larger beam current than at higher energies. In order to provide the necessary high peak power, the novel drive-beam scheme uses low-frequency high efficiency klystrons to efficiently generate long RF pulses and to store their energy in a long, high-current drive-beam pulse. This beam pulse is used to generate many short, even higher intensity pulses that are distributed alongside the main linac, where they release the stored energy in power extraction and transfer structures in the form of short RF power pulses, transferred via waveguides into the accelerating structures. This concept strongly reduces the cost and power consumption compared with powering the structures directly by klystrons, especially for stages 2 and 3, and is very scalable to higher energies.

The upgrade to higher energies will require lengthening the main linacs. For the RF power the upgrade to 1.5 TeV can be done by increasing the energy and pulse length of the primary drive-beam, while a second drive-beam complex must be added for the upgrade to 3 TeV. An alternative design for the 380 GeV stage has been studied, in which the main linac accelerating structures are directly powered by high efficiency klystrons. The further stages will also in this case be drive-beam based for the reasons mentioned above.

Power and energy efficiency studies have been integrated into the design from the very beginning. The design and parameter choices have been made to supply a certain luminosity at the minimum cost and power. These studies have covered accelerator structures and cavities, but also very importantly high efficiency RF power system with optimal system designs using high efficiency klystrons and modulators. These are also being prototyped.

It is expected that the CLIC - and ILC - power consumptive can be further consolidated and possibly reduced. In particular for stages 2 and 3 of CLIC many technical developments affecting the power have not been included in the current power estimates.

Sustainability studies in general, e.g. power/energy efficiency, using power predominantly in low cost periods as is possible for a linear collider, use of renewable energy sources, and energy/heat recovery where possible, will therefore be a priority for further studies for both LC projects. Such studies were already made with initial parameters for the CLIC Implementation Plan (see chapter 7 in [8]). Other studies include prototyping and use of permanent magnets as described below.

3. SUBSYSTEM AND COMPONENT DESIGN

The overall resource needs of a complete accelerator facility is given by the sum of the resources needed to produce, operate and finally dispose of all its subsystems and components. Optimisation of all these constituents with regard to sustainability is therefore a necessity, starting with those components that dominate resource consumption. Traditionally, this optimisation is performed regarding monetary costs, in particular capital costs for production of components, and operating costs, with an emphasis on electricity costs.

A direct quantification of the ecological footprint, be it greenhouse gas emissions during operation or production, or consumption of problematic materials, is currently performed only sporadically, mostly through translation of electricity consumption into equivalent CO₂ emissions. Nonetheless, intense R&D programs are under way with ambitious goals to reduce resource consumption, as illustrated by a few topical examples in the following.

1.1. Superconducting cavities for the ILC

The single biggest consumer of resources in the ILC are the Main Linacs, and within the Main Linac the construction and operation of the superconducting rf cavities. The performance of these cavities has been pushed ever further over the last decades, as illustrated in Fig. 2 [12]. The ILC baseline design assumes an operating gradient of 31.5MV/m, averaged over all installed Main Linac cavities. The immediate R&D goal is to raise this number by 10% to 35MV/m, and to 45MV/m for a potential 1TeV upgrade.

In parallel to the increase in maximum gradient, recent years have seen a lot of progress in improvements of the quality factor Q_0 that describe the losses in the cavity walls through new, improved surface (nitrogen doping and infusion) treatments. The R&D goal is to double the quality factor from 1 to $2 \cdot 10^{10}$. New heat treatments [13] indicate that it may be possible to achieve progress on all fronts: achieve higher gradients at higher quality factors with less use of problematic chemicals due to a reduction of electropolishing processes during production.

In addition, studies are underway and planned to replace bulk niobium with niobium or even Nb₃Sn coated copper cavities [14], reducing use of scarce materials and (in the case of Nb₃Sn) the prospect to raise the operating temperature from 2K to 4.5K, which would significantly reduce the cooling power needs.

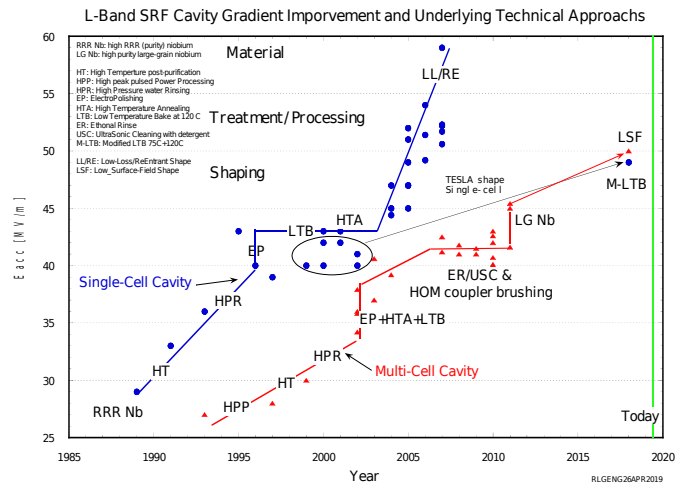


FIG. 1: Evolution of the accelerating gradient of superconducting cavities [24]

1.3. High-efficiency klystrons

The dominant contribution to the linear collider power consumption comes from the acceleration of the beams. The wall-plug to beam power efficiency is of paramount importance. The RF pulses are provided by modulator and klystrons systems. R&D on klystron efficiency have made very significant progress over the last decade, achieving efficiencies significantly above what was considered possible, and even limits, a decade ago. New klystron bunching technologies have been established and evaluated, and much improved computer codes and scaling procedures have been developed and bench marked [15]. A number of high efficiency klystrons has been designed according to these new ideas and/or making use of the new tools. For the linear colliders, efficiencies reaching 80% for the klystrons used for the CLIC drive-beam and ILC main beams are now being considered to be within reach.

1.4. Permanent magnets

Even at 1.5TeV centre-of-mass energy, resistive magnets constitute the second-largest consumer of electric power (after the rf equipment) at CLIC; in particular the drive-beam quadrupoles consume a lot of power. To alleviate this, the Zero-Power Tuneable Optics (ZEPTO) collaboration between CERN and STFC Daresbury Lab has been set up with the goal to provide permanent magnet dipoles and tuneable quadrupoles of the necessary field quality. Several prototype magnets (2 quadrupoles and a dipole) have been manufactured and tested for CLIC, and recently a ZEPTO dipole has been successfully installed in the Diamond Light Source [16].

For the ILC, permanent magnet designs for dipoles and corrector magnets are under consideration in particular for the damping rings [17]. To compensate variations in the magnetic field from temperature changes or ageing, the dipoles have a motor controlled trim rotor. To reduce cost and increase sustainability, the dipoles can be manufactured from ferrite material rather than rare earth based permanent magnets. Solutions for quadrupoles are also under investigation [18].

4. SITE DEVELOPMENT AND OPERATION

1.1. Green ILC program in Tohoku

For the ILC, a comprehensive initiative called the “Green ILC program” has been started in the Tohoku region of Japan where the preferred ILC site is located [19]. This program brings together academia, local government and the industry in the Tohoku ILC Development Center.

A based on a site power of 120MW, the yearly overall electricity consumption is estimated to be around 700GWh, which corresponds to 320kt CO₂ emissions based on an average CO₂ emission rate of 0.457kg CO₂/kWh as reported by the Tohoku electric power company [20, 21]. The Green ILC program aims to maximise the re-use of heat generated by the accelerator cooling infrastructure, and to directly offset the CO₂ emissions by collaboration with the local forestry industry. Extensive use of solar power and heat is also part of the plans.

Furthermore, the Green ILC initiative strives to develop modern forms of living environments for the scientists and workers that will come to Tohoku, with wood as the preferred, sustainable building material.

1.5. Operation of CLIC with electric power from regenerative sources

Given the flexibility on running and power consumption of a linear collider, it is interesting to consider how effectively the accelerator can be powered by renewable energies. First of all, it is likely the overall energy landscape in Europe will shift over the next decades towards renewables, secondly the investment costs of such power sources are decreasing so one can consider moving investments in energy production into the construction costs, hence lowering the operation costs. By installing a portfolio of different renewable generators (different technologies, like wind and photovoltaic (PV), or different types of installations, like photovoltaic modules orientated into different directions) it becomes possible to partly level out the individual fluctuations of single generators in the aggregated generation curve. Such a study was performed for CLIC in 2018 [22], with at that time a pessimistic power consumption of 200 MW, assuming that 1.2×10^7 s of operation would be needed annually.

The conclusions were that while it is possible to fully supply the annual electricity demand of the CLIC by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators, at a cost of slightly more than 10% of the CLIC 380 GeV cost), self-sufficiency during all times can not be reached. However, CLIC could run independently from public electricity supply 54% of the time with the portfolio simulated. About 1/3 of the generated PV and wind energy will be available to export to the public grid even after adjusting the load schedule of CLIC.

It is worth noting, however, that because of the correlation between electricity price and (national) generation from wind and PV, own local generators can generally not step in during times of high energy prize. Large storage systems are still too expensive to shift power

accordingly. Besides the direct investment in the generation technology, many aspects of standards, regulations, land-use, landscape-protection etc. would have to be considered. One alternative to own renewable power plants could be the participation in projects of other investors to build large renewable power plants. With a changing energy landscape and cost, reduced power estimates from CLIC (and ILC) and improvements in technology such solutions need to be studied for colliders expected to be operational in 2035-40.

5. SUMMARY, CONCLUSIONS AND OUTLOOK

To summarize, sustainability has become a prioritized goal in the design for future accelerators in high energy physics, in particular the future Higgs factories presently envisaged. Improving and optimising the overall system design, individual subsystems and components, and operational concepts reduces resource consumption during construction and operation, and thus is beneficial to the economic as well as the ecologic footprint. Carbon-neutral accelerator operation is a goal pursued in both projects presented here but requires further work.

Presently, the quantitative evaluation of the resources needed and the environmental impact is focused on electric power consumption and greenhouse gas emissions from electricity generation. A more comprehensive lifecycle impact assessment would entail a broader accounting of GHG emissions, in particular during construction, and cover further factors such as ecotoxicity of raw materials for a more targeted optimisation of sustainability.

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