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The next energy-frontier accelerator - a linear $e^+ e^-$ collider?

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Two options for a linear e+e- collider are presently under development, the ILC and CLIC. The energy reach of the two machines is different, which leads to two different technological choices. ILC is based on superconducting acceleration technology, the CLIC design uses a two-beam acceleration system with normal conducting copper cavities. Nevertheless considerable synergy between the two design groups has been developed. The paper will highlight the major differences a well as the status and the plans of both machines.

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1. Introduction

Physics requires to complement discoveries made with a hadron accelerator with experiments with leptons. Therefore the next major machine after LHC could be a lepton collider. In LEP, the e+ e- collider with the highest energy so far, at 209 GeV in the centre of mass system, the circulating particles lost 3.4% of their energy per turn due to the emission of synchrotron radiation. A powerful RF system provided a circumferential voltage of 3.6 GeV to keep the beam circulating, which required an RF power plant of 44 cw klystrons with a rated output power of >1 MW each. Since this energy loss scales with beam energy E and bending radius ρ as ${E^4}/{\rho}$ an energy substantially above LEP becomes impossible for electrons and positrons. Two possibilities exist to overcome this limitation:

a) Since the energy loss is proportional to ${1}/{m^4}$, where m is the particle mass, one can avoid excessive synchrotron radiation by using muons instead of electrons. Such colliders are extensively studied. A very comprehensive summary of ongoing work can be found in [1].

b) Avoid bending the particle trajectories by using linear colliders: Two opposing linear accelerators accelerate the particles to their final energy in one pass, with the collision point at their centre.

In 1999 ICFA issued a statement on linear colliders, confirming the " compelling and unique scientific opportunities at a linear electron-positron collider in the TeV range" [2].

Presently two different technical approaches towards linear colliders are being pursued by world-wide collaborations, the ILC (International Linear Collider) and CLIC (Compact Linear Collider). Their main difference is the energy reach, which leads to different technologies: The ILC aims at 0.5 TeV, upgradeable to 1 TeV, whereas CLIC pushes the energy frontier further to 3 TeV centre-of-mass energy.

The CERN Council in its special session held in Lisbon in 2006 recommended to continue to further develop the CLIC technology and also endorsed the development on ILC in "a well-coordinated European activity including CERN"[3].

This paper describes the main features of these two approaches. It is impossible to go into any details of the two projects within the space available here. Only basic relations and a few highlights can be shown. More information can be found about the ILC in [4] and in more detail in the ILC Reference Design report [5]. The information about CLIC is in [6,7]

2. Basic relation

The Luminosity L of a linear collider is given by

$$L = \frac{n_b * N^2 * f_{rep}}{A} * H_D$$

n_b is the number of bunches per train
N is the number of particles per bunch
f_{rep} is the bunch repetition frequency at the collision point
A is the beam cross section at the interaction point
H_D is the beam-beam enhancement factor

This basic relation can be rewritten in terms of beam energy E_{cm} and beam power P_{Beam}:

$$L = \frac{P_{Beam}}{4 * \pi * E_{cm}} * \frac{N}{\sigma_x * \sigma_y} * H_D$$

σ_x and σ_y are the horizontal and vertical beam dimensions at the interaction point.

The design of a linear collider is then an optimisation process where the beam power, which is related to the overall mains power consumption, the site length, the achievable beam parameters and cost have to be weighed against each other.

3 Acceleration

Since the total beam energy has to be reached in one pass, the accelerating gradient in the linac has to be as high as possible. In order to keep the power consumption small the RF to beam power efficiency has to be maximised.

In an accelerating cavity the Voltage U is given by

$$U = \sqrt{R/_Q * \omega * W}$$

$R/_Q$ is a structure parameter which depends only on the cavity geometry, ω is the RF frequency and W is the stored RF energy in the cavity.

W is given by

$$W = \frac{Q}{\omega} P$$

Q is the quality factor of the cavity and

P is the RF input power required to provide the necessary stored energy.

In order to achieve a given accelerating voltage in a cavity, it has to contain a certain stored RF energy W, which is linked to losses due to wall currents P.

3.1 Superconducting accelerating system

Superconducting cavities can have Q-values of the order of 10^{10}, Copper cavities typically of the order of 10^4.

Therefore superconducting cavities are one choice for efficient acceleration, because the losses due to wall currents are small compared to the power transmitted to the beam. However, these losses appear at cryogenic temperature where Niobium is superconducting. In addition the accelerating gradient achievable in superconducting cavities is intrinsically limited.

ILC is based on accelerating cavities made of solid Nb, operating at 2 K at a gradient of 31.5 MV/m. The low cavity dissipation allows to accelerate long bunch trains with many bunches, nevertheless the system has to be pulsed at 5 Hz.

The cavities (see fig.1) are relatively flexible and they deform under the influence of the strong electromagnetic fields. This has to be compensated during each pulse via a sophisticated RF low level and tuning system. Several large-scale superconducting accelerators have demonstrated the suitability of this technology and the achievable gradient has grown as the technology matured, such that the ILC gradient is now within reach.

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The acceleration frequency for ILC has been chosen to be 1.3 GHz. Individual klystron amplifiers can be used as power sources.

Fig.1: Solid Nb nine-cell cavity as foreseen for ILC

3.2 Normal conducting acceleration system

CLIC with its higher beam energy requires a higher accelerating gradient than is presently achievable with superconducting cavities, in order to keep the total accelerator length within reasonable limits. Very high RF power is needed to achieve high accelerating gradients in copper accelerating structures, therefore the duration of the pulse has to be short to keep the average RF power low.

CLIC is based on copper travelling wave accelerating structures, developed from “conventional” linac structures, which consist of a chain of coupled pill-box cells. However, the accelerating gradient is pushed to the very maximum.

A complicated optimisation process of cell geometry, structure length, cell impedance, e.t.c. has resulted in an RF frequency of 12 GHz and an accelerating gradient of 100 MV/m. The limits on gradient come from RF breakdown and RF pulse heating leading to fatigue. Since the bunches follow each other at short distance, wakefield control is very important. The figure of merit in this optimisation process – taking into account the constraints mentioned above - is efficiency, i.e. wall plug power for a given Luminosity and beam energy. A prototype accelerating structure is shown in fig 2.

Fig. 2: CLIC accelerating structure

High RF power is required to produce 100 MV/m: 275 MW per meter of accelerating structure, however only for short pulses of 240 ns at a repetition frequency of 50 Hz. It is hard to imagine that individual RF power sources could be used in this case. This led to the development of the two-beam concept, described below in chapter 6.

3.3. CLIC – ILC: basic features

The basic design features of ILC and CLIC are shown in table 1.

	ILC	CLIC
Centre of mass energy / Luminosity	500 GeV (upgradable to 1 TeV) / 2 * 10^{34}cm^{-2}s^{-1}	3 TeV / 2 * 10^{34}cm^{-2}s^{-1}
accelerating gradient	31.5 MV/m	100 MV/m
RF frequency	1.3 GHz	12 GHz
RF peak power per meter	0.37 MW/m, 1.6 ms, 5 Hz	275 MW/m, 240 ns, 50 Hz
RF average power	2.9 kW/m	3.7 kW/m
total length	31 km	48.4 km
total AC site power	230 MW	392 MW
Beam structure		
particles per bunch	20 * 10^9	3.7 * 10^9
number of bunches per pulse	2625 / pulse of 0.96 ms	312 /pulse of 156 ns
bunch spacing	396 ns	0.5 ns

Table 1: Basic parameters for ILC and CLIC.

The most important differences between the two machines are marked in red. It is interesting to note, that even though the peak RF power is quite different, the average RF power per length unit is very similar. The different bunch structure leads to differences in the detectors.

4. Getting the Luminosity

The beams have to be focused to very small dimensions at the interaction point. The generation of beams with low emittance and the preservation of emittance all the way up to the collision point is an important feature of linear colliders. The main parameters for ILC and CLIC at the interaction point are:

	ILC	CLIC
beam size horizontal / vertical:	640 nm / 5.7 nm	40 nm / 1 nm
normalised emittance $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$	10000 nm rad / 40 nm rad	660 nm rad / 20 nm rad

Both machines require powerful damping rings and a sophisticate final focus system to reach these values. Emittance preservation implies tight control of wakefields all along the linac as well as control of vibrations. In the case of CLIC, at 3 TeV, these tolerances are particularly severe, the final focus quadrupoles have to be stabilised to about 0.14 nm for frequencies above 4 Hz in the vertical and 2 nm in the horizontal plane. All quadrupoles in the linac have to be stabilized to 1 nm and 5 nm above 1 Hz in the vertical and the horizontal planes. For ILC with

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its bigger beam dimensions and the use of intra-train feedbacks, these tolerances are relaxed to about 10 nm.

5.1. ILC base-line design

The base-line layout of ILC is shown in fig. 3. It is based on a two-tunnel layout with one tunnel housing the main accelerator and the second one running parallel, the klystrons and other equipment.

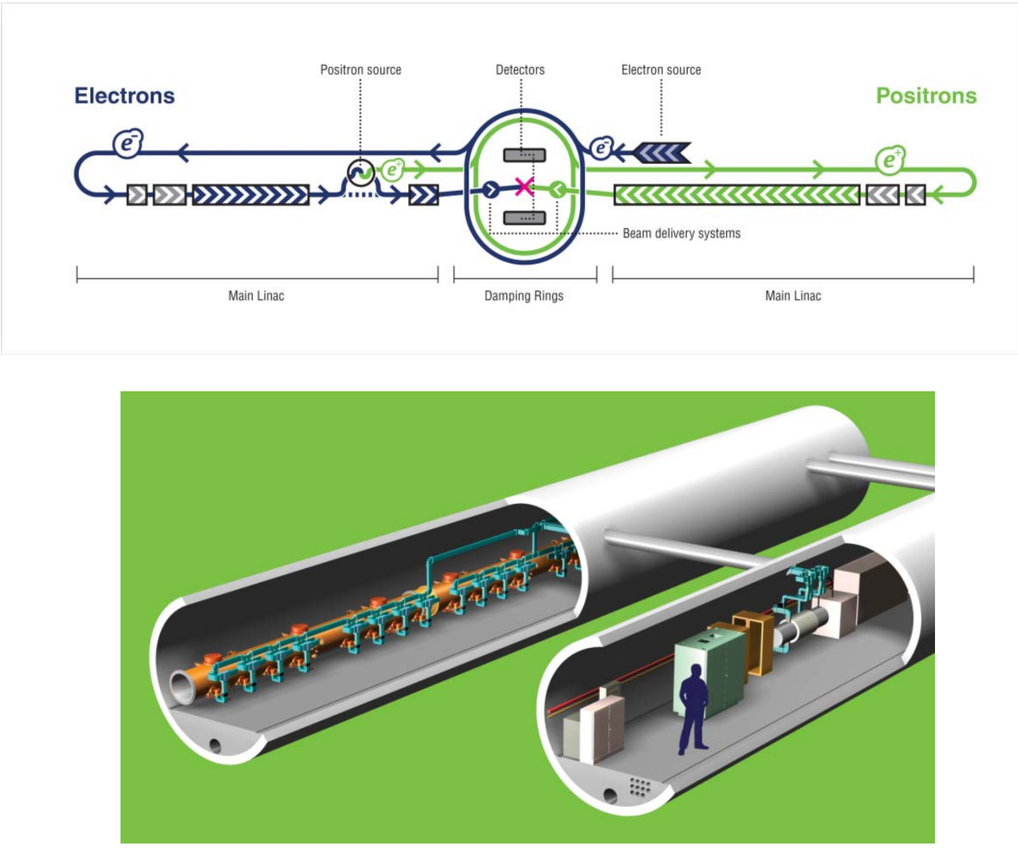

Fig. 3.: ILC base-line design (top)and at the bottom the two-tunnel layout with the main accelerator tunnel on the left, the klystron and service tunnel on the right.

Other alternatives are being evaluated.

The positron source uses a beam from the first part of the electron linac which is sent through a helical ondulator to produce photons, which in turn are converted to positrons in a rotating target

5.2. Accelerator R&D for ILC and status

Apart from beam dynamics studies and design of accelerator components, a major effort goes into the development of superconducting cavities, in order to reliably reach a gradient of 35 MV/m in vertical tests, such that an accelerating gradient of 31.5 MV/m can be safely achieved. This is done in a world-wide effort, test facilities are being built up, which report steady progress. The gradient has been demonstrated already, the main effort goes into increasing the yield of successful cavity production.

A number of test facilities are being used for accelerator R&D:

- FLASH at DESY for tests of cryomodules with beam,
- ATF2 at KEK and CesrTA at Cornell for testing final focus design, low emittance beam production, fast kicker developments and e-cloud mitigation.

A Reference Design Report has been published in 2007. Presently the project is in the Technical Design Phase. An interim report will be published in 2010, all documentation should be available to submit the project for approval in 2012.

6.1. CLIC base-line design

The CLIC scheme is based on normal conducting travelling wave accelerating structures, which require high peak RF power to generate the accelerating gradient of 100 MV/m. Individual RF power sources providing 275 MW peak power at 12 GHz per m of active length are barely possible. A two-beam scheme is being developed instead, where the power necessary for acceleration is transported to the accelerating structures through a secondary electron beam running parallel to the main beam. The power in this beam is converted to RF power in special RF structure, the PETS (Power Extraction and Transfer Structures). This is shown in the left part of fig. 4

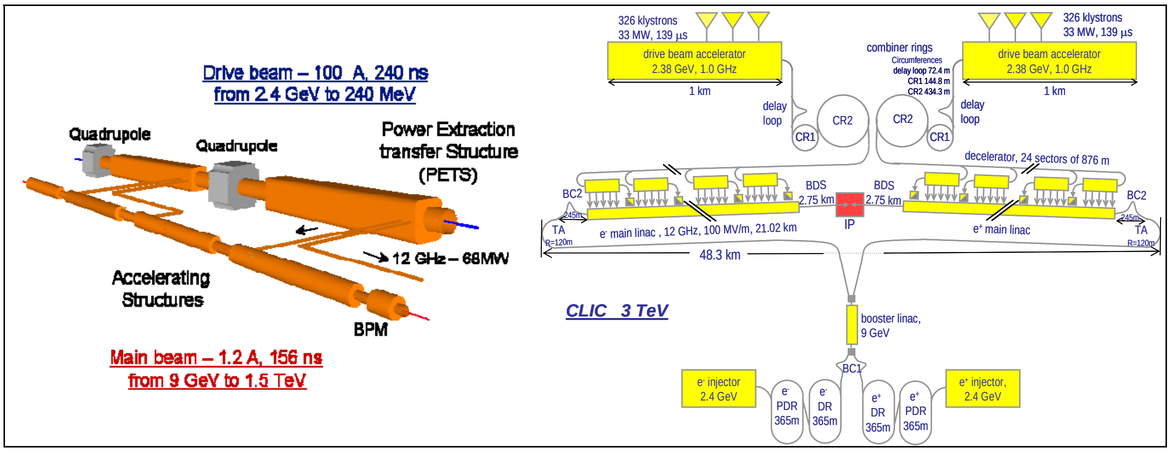

Fig. 4: CLIC two-beam scheme. The right picture shows the complete complex with the Drive Beam generation complex on top and the Main Beam generation at the bottom

The Drive Beam is generated in a 2.38 GeV linac from a 139 μs long bunch train with long bunch spacing of 1/500 MHz, which is then compressed by interleaving the bunches in a Delay Loop and two rings to 240 ns long sub-trains with a beam current of 100 A and a bunch repetition frequency of 12 GHz. The Drive Beam linac, which has to supply all power needed for the Main Beam acceleration, is based on an acceleration system with travelling wave structures, powered by 1 GHz klystrons. The full scheme is shown in the right part of fig. 4. This linac is highly efficient, because it is operated under full beam loading conditions, over 94% transfer efficiency from RF to beam power has already been demonstrated.

6.2. CLIC R&D and status

This two-beam scheme is being demonstrated in the CLIC Test Facility (CTF3) [8]. CTF3 consists of a linac representing the Drive Beam, two rings for bunch train compression and an experimental area where acceleration of a probe beam powered by the Drive Beam can be demonstrated, as shown in fig 5. Apart from one test beam line, this installation is now complete. Bunch combination has already been demonstrated by a factor of two in the Delay Loop and by a factor of four in the Combiner Ring. Since the conference a combination factor of eight could be demonstrated with operation of both rings together, giving a total current of 23 A so far.

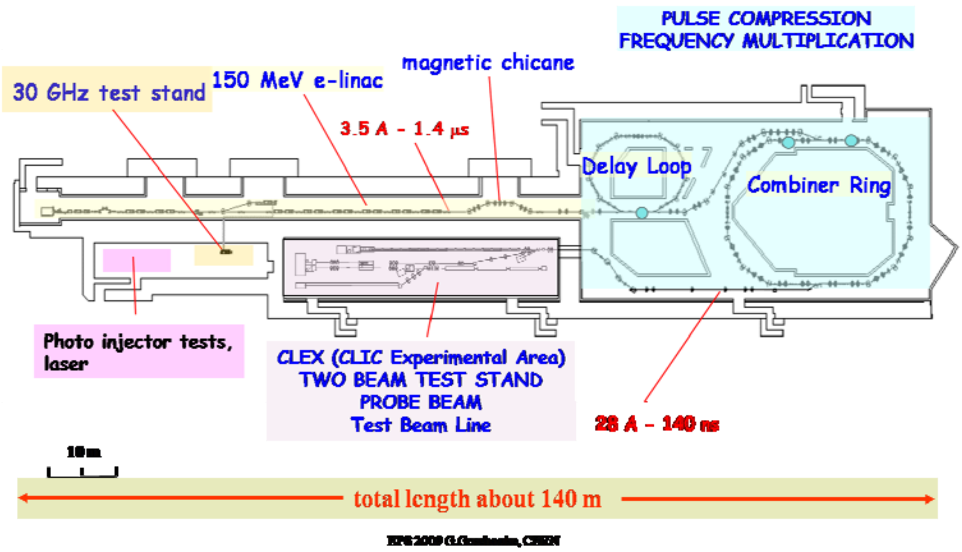

Fig. 5: CTF3 layout

A big effort goes into the development of accelerating and PETS structures. The accelerating gradient of 100 MV/m has already been demonstrated in three accelerating structures, however the Higher Order Mode damping features still need to be integrated.

CLIC will have two damping rings each for electrons and positrons. The final emittance is pushing the performance of existing synchrotron radiation facilities further, but a conceptual design is now available.

A design of the accelerator exists, a parameter list is available [7]. CLIC will issue a Conceptual Design Report by end 2010, a Technical Design Report is foreseen for 2015. Construction of the 500 GeV machine is expected to take seven years. Upgrade to the final energy will take 3 more years

Even though the design of CLIC is based on 3 TeV cm energy, parameters exist for 500 GeV as well, which could be the first project stage. The 500 GeV parameters are relaxed compared to the 3 TeV ones, in particular the emittances are closer to the present state of the art.

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7. Conclusions

Two approaches to linear colliders are presently being developed, ILC and CLIC. They have a different energy reach, which leads to a choice of different technologies. Nevertheless areas of common interest have been identified, which are explored in close collaboration:

- Detector and physics issues,
- Civil engineering and conventional facilities,
- Cost and schedule
- Beam delivery systems and machine-detector interface,
- Positron generation,
- Damping rings,
- Beam dynamics.

Both machines are being developed by international collaborations, the ILC design is managed by the GDE(Global Design Effort) with a distributed structure, CLIC is a collaboration of institutes (presently 33), which are linked together via formal collaboration agreements [9]. CERN acts as host laboratory, the collaboration is managed by the Collaboration Board.

The choice which machine to build will depend on physics requirements, but also on technical maturity at the moment of decision and cost.

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