Linear Collider

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Abstract

A linear collider is the next large project of particle physics following the commissioning of the LHC. By 2012 feedback can be expected from the LHC on the spectrum of *new physics* below 1 TeV. This information will be timely for a revision of the European Strategy for particle physics and the possible decision for a linear collider for which the ILC is the only contender that could promptly be realized. Similar strategic considerations are made in Japan so that currently two regions are exploring the implications of hosting the ILC. A multi-TeV collider would require considerable R&D, which is well under way for the CLIC project. The status of these two projects is described.

1 Introduction

Since a long time the key elements of the strategy of particle physics have been clearly laid out: following the commissioning of the *Large Hadron Collider* LHC a linear collider will be the next large project of particle physics. This strategy has most recently been formulated in 2006 in the European Strategy issued by the CERN Council [1, 2] when it assumed its role for coordination of the programmes in Europe. The outcome of that strategy process culminated in a list of recommendations. Explicitly, the first three recommendations read:

- The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance. A subsequent major luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.

- In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play a significant role in the study and development of a high-intensity neutrino facility.

- It is fundamental to complement the results of the LHC with measurements at a linear collider. In the energy range of 0.5 to 1 TeV, the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precision frontier; there should be a strong well-coordinated European activity, including CERN, through the Global Design Effort, for its design and technical preparation towards the construction decision, to be ready for a new assessment by Council around 2010.

At the same time there is considerable interest in Japan to host the ILC and correspondingly a similar plan for particle physics has been developed.

Following the magnet incident at the LHC start-up in 2008 these time lines will have to be somewhat revised. As the LHC turns on for physics production the machine performance will be better understood. The upgrade requirements will become clearer and so does the schedule that can be associated with this upgrade. Both the evolution of the luminosity at the LHC and of the centre of mass energy will have to be folded in to arrive at reasonable predictions for the upgrade needs of the LHC.

While the physics programme of a linear collider operating in the energy range up to 500 GeV [3, 4, 5, 6] has been fully worked out it will be helpful to receive guidance from the Large Hadron Collider: there is a good chance that the LHC may discover a light Higgs particle. Likewise will the spectrum of "low energy" SUSY particles – if realized in nature – define the homework for a linear collider. The physics potential at high energies above 1 TeV is largely uncertain; too little is known of the mass spectrum of new particles, their signatures and width and too large is the variety of options for firm predictions.

Given this uncertainty the technical development for the linear collider follows a dual approach: a strong emphasis on the R&D for a linear collider reaching well into the TeV region for which the *Compact Linear Collider* CLIC provides a proposal for technical realization and the preparation of the construction of the *International Linear Collider* ILC, initially targeted to operate at energies up to 500 GeV with an upgrade option up to 1 TeV, where a full physics case has been developed.

2 Brief Reminder of the Physics Case for a Linear Collider

The physics case for the linear collider has often been made and is summarized in [6]. The advantage lies in the simplicity of the initial state, the well-defined quantum numbers for the hard interaction and the well defined centre of mass energy of the hard interaction. As an often quoted example Figure 1 displays the recoil mass spectrum of the two muons from the decay $e^+e^- \rightarrow ZH$ with $Z \rightarrow \mu^+\mu^-$ for an assumed Higgs mass of 120 GeV and a centre of mass energy of 350 GeV. It is obvious that even for an invisibly decaying Higgs particle the mass can be well reconstructed if the detector provides the appropriate resolution. It is thus clear that the detector performance has to be fully optimized and that these detectors will be high precision instruments, in line with the theme of high precision for the layout of the collide proper.

3 Linear Colliders

It has long been recognized [7] that linear colliders provide an alternate way to circular colliding beam machines. They are more power efficient and hence more cost-effective at high energies where synchrotron radiation becomes prohibitive for circular machines. They are challenged to provide a respectable luminosity where beams of minute dimensions are required. The only high-energy e^+e^--collider built to date is the SLAC Linear Collider SLC, which operated at

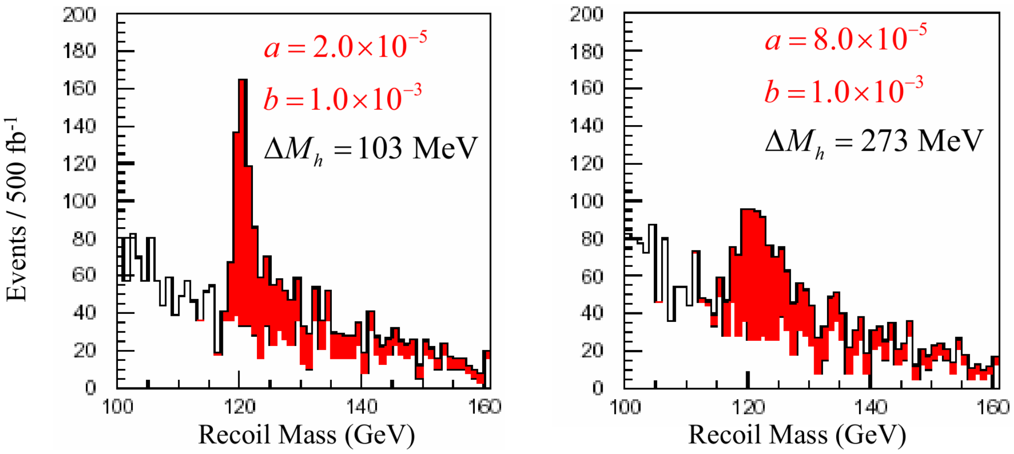

Figure 1: The Higgs boson recoil mass spectrum for two assumed resolutions for decays $e^+e^- \rightarrow ZH$, where the Z decays into 2 muons. The quantities a and b refer to the terms in the transverse momentum resolution $\sigma p_t/p_t = ap_t \bigoplus b/\sin\theta$ (from ref, [6]

the centre of mass energy around the Z-mass and provided highly polarized electrons. (With polarization of only one beam the case could be made that precise knowledge of yet another initial state quantity provides almost an order of magnitude more sensitivity in electroweak measurements.

Two technologies based on this radio-frequency cavities have been developed: a traveling wave accelerator with fully loaded structures operated in the *X-band* at 12 GHz and a standing wave accelerator using 1.3 GHz *L-band*-technology. The *X-band*-technology, originally explored for klystron operation [4, 5], has now become the baseline for the *Compact Linear Collider* design, which is the key linear collider project at CERN in the framework of the CLIC collaboration. The *L-band* technology based on superconducting RF structures constitutes the state of the art for a high-energy collider that could be built today.

Compact Linear Collider

The Compact Linear Collider (CLIC) is a linear collider design study that has emerged from acceleration ideas developed in the 80ies [8]. It uses high-frequency, high-gradient copper structures to accelerate the beam; the copper structures are excited by a high-current drive beam that runs parallel to the accelerator. The wakefields of the drive beam are transferred to the main beam. Following an optimization study [9] of the parameters the frequency has now been lowered to 12 GHz (from the original 30 GHz). The layout of the facility is shown in Figure 2.

The main e^+- and e^--beams are injected at 2.4 GeV into a predamping ring (PDR) and transferred to a subsequent damping ring (DR) to achieve the low emittance. A bunch compressor reduces the bunch length before the beam is accelerated to 9 GeV in a booster linac. These beams are transferred over roughly 21 km to the start of the respective linac section to be accelerated to 1.5 TeV in the actual linac. The RF power for the linac is extracted from the

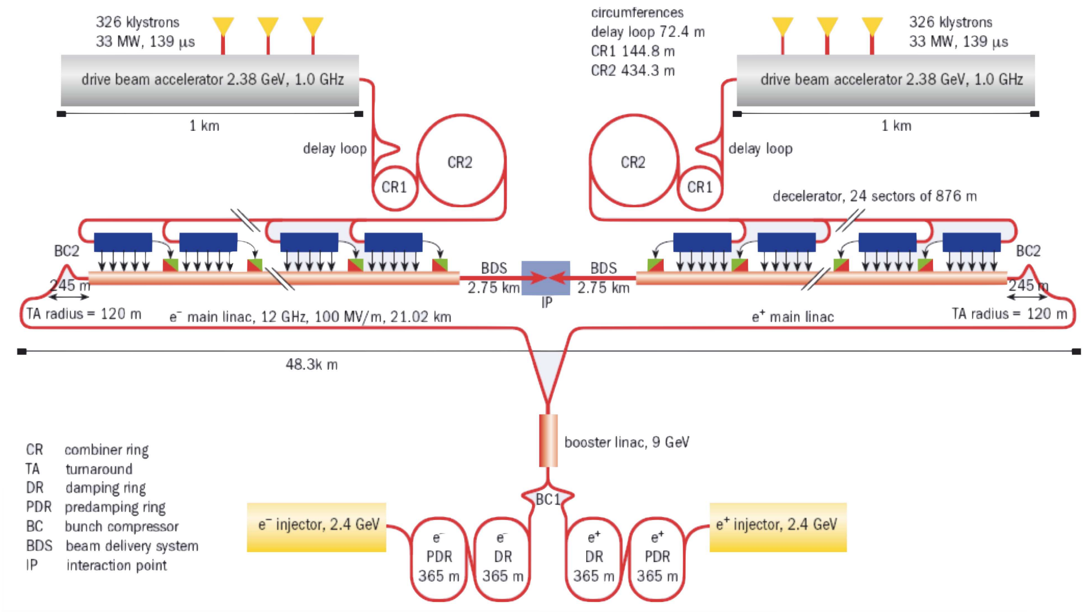

Figure 2: The layout of the Compact Linear Collider for operation at 3 TeV. The lower part shows the generation of the high-energy beam; the upper part describes the generation of drive beams.

drive beam.

The drive beams are generated in 1 km long conventional linacs operating at 1 GHz. Each of these high power linacs is equipped with 326 klystrons that accelerate a 139 μs pulse to 2.4 GeV. These linacs are highly efficient so that essentially no power is reflected under full beam loading. The 1 GHz bunch pattern is compressed to a 12 GHz train by using a delay loop and a two combiner rings that place subsequent bunches onto the adjacent empty bunch location and thus achieve a time compression by a factor two, three and four respectively. At the same time the current increases to 100 A. These trains are transferred to the respective acceleration section of $\sim$900 m length, where the drive beam power is extracted in the Power Extraction Structures (PETS), cf. Figure 3.

The wakefield is coupled into the accelerating structures of the main beam. Note that while it is the wakefield of the drive-beam that excites the RF in accelerating structure the principle should not be confused with the wakefield acceleration that uses the wakefield directly to accelerate particles, eg. in a plasma. Instead, the principle is better thought of as a very long klystron in which the RF power is delivered when and where it is needed. It is in fact this principle that results in the power efficiency of the two-beam acceleration.

Many aspects of the CLIC principle have been tested over the past decades [10]. The CTF3 test facility at CERN has demonstrated amongst others the successful time compression from 1 GHz to 12 GHz and the highly efficient power transfer from klystron to the drive beam. The beam has been extracted into the CLEX facility where the deceleration of the beam will be tested while the beam quality can be monitored. In addition the CLEX facility will enable tests of the power extraction onto a dedicated witness bunch.

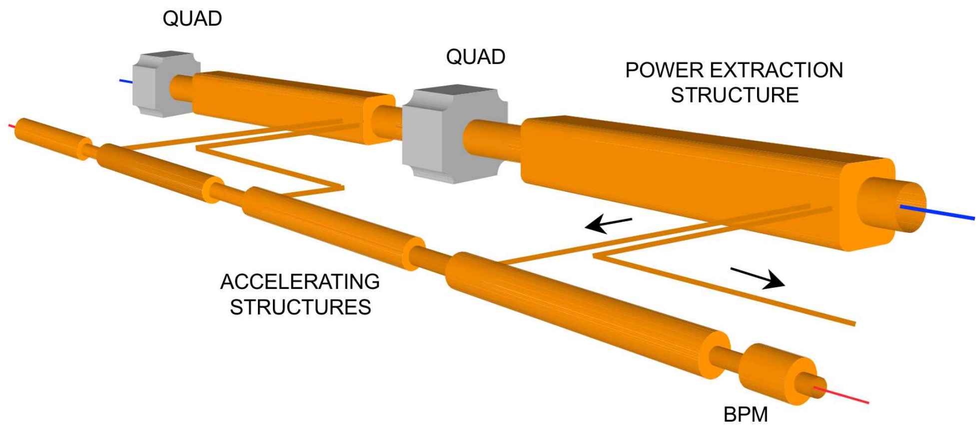

Figure 3: Principe of two-beam acceleration: as the high-current drive beam travels through the Power Extraction Structure the wakefield is coupled into the accelerating structures of the main beam.

The success of the CLIC concept hinges on several aspects that need to be demonstrated on a system level. At this time these challenges are the *high accelerating gradient* and the *beam stability*. CLIC is to operate at accelerating gradients of 100 MV/m. At these peak fields electric breakdowns become serious. Given the large number of accelerating structures the smallest possible breakdown rate is required. Figure 4 demonstrates proof of existence for a structure that yielded a breakdown rate below 10^{-6} after sufficient training of 1200 h. Note, however, that *Higher Order Modes* (HOM) were not damped in this structure and evidently no beam was traversing the structure.

The beam stability is tightly coupled to the stability of the entire accelerator structure. Given the high frequency of CLIC all dimensions are small; in particular the iris of the structure. A beam that propagates only slightly off-axis will be transversely deflected over its longitudinal dimensions. The CLIC structures are hence actively stabilized to maintain the required spatial accuracy.

The long-term optimistic schedule fro CLIC, only technically constraint, foresees to provide a Conceptual Design Report by the end of 2010. A Technical Design Report is to be issued by 2015, which would formally allow the project to proceed. It should be noted however, that a system test of the individual components will not have been possible by that time. In particular, the handling of the drive beam of 2.4 GeV, which is exhausted down to 10% of its energy over a length of ∼900 m will not have been demonstrated. In addition, the power transfer onto the main beam will not have been tested under operational conditions. The CLIC collaboration is developing concepts to circumvent these challenges. – The construction time for CLIC is canonically assumed to be 7 to 8 years.

In addition the viability of the entire concept hinges on the mandatory progress of the high gradient programme for the CLIC structures. To date only small scale tests have been carried out and the actual operational gradient under beam loading needs to be demonstrated.

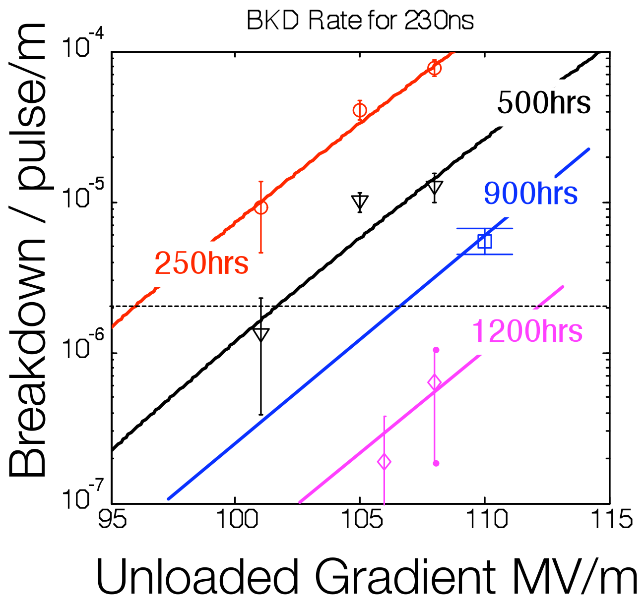

Figure 4: The breakdown rate of a unloaded 12 GHz CLIC structure after a considerable training time. After 1200 h the structure satisfies the breakdown requirement for gradients above 100 MV/m.

International Linear Collider

The International Linear Collider (ILC) is the technical solution to building an e^+e^--collider operating in the energy range from 100 GeV up to 500 GeV with an upgrade option to 1 TeV. It is based on superconducting RF technology which has been selected as the most suitable technology for such a machine following the deliberations of the ITRP in 2004 [11]. This decision led to the creation of the *Global Design Effort* (GDE) that brought together all experts and laboratories to design such a collider and eventually realize the machine. The GDE under the leadership of Prof.B. Barish is a virtual organization that prepares the machine independent of the site so that all regions are enabled to bid for the project.

The GDE has led to a reference design report (RDR) that was published in 2007 [12]. It includes a cost estimate of the ILC and forms the basis for further optimization. The layout resulting from the RDR is depicted in Figure 5.

The ILC extends over a length of ∼30 km and is laid out around a central campus that houses the beam sources and the damping ring and the interaction point of the two beams. Two detectors are foreseen at the interaction point. These detectors will be operated in a *push-pull* configuration[1], which is housed in the same experimental hall. The experimental hall also

[1]This configuration has been chosen over two separate beam delivery systems which seem more demanding to realize and yield effectively the same integrated luminosity. Note that the switch-over time needs to be small.

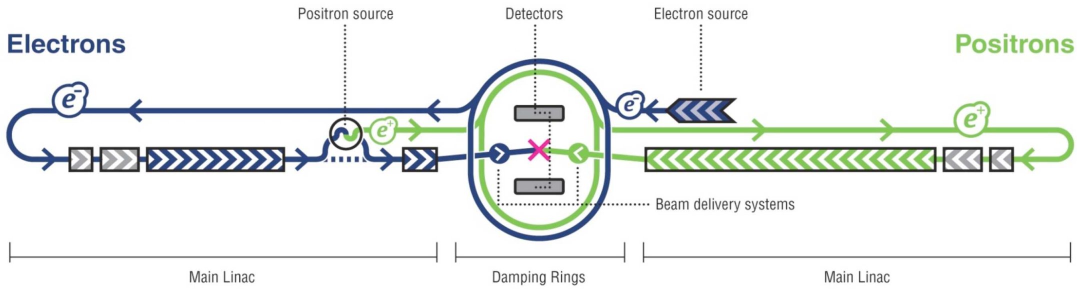

Figure 5: Schematic layout of the ILC according to the Reference Design Report. The whole complex stretches over length of 30 km

houses the final quadrupole triplet which is needed to focus the beam to the small dimensions at the interaction point.

Superconducting linacs are more efficient the longer the pulse train of bunches. Standing wave accelerators profit from the stored energy in the cavities of which only a small fraction is transferred to the individual bunch. The extracted energy is replenished in between bunches to maintain a constant accelerated field. Were it not for the overall cryogenic load such a collider would best be operated in continuous mode. To pick a compromise a train duration of 1 ms has been chosen for the ILC with a repetition rate of 5 Hz. This is also well matched to the power output of currently operating klystrons. At 1.3 GHz such a train is composed of ∼3000 bunches ($\dot{3}$MHz). The train hence has a length of 300 km.

The electron source provides highly polarized electrons which are accelerated to 5 GeV before they enter the damping ring with a circumference of 6 km. They are cooled to the final emittance within 200 ms. Since the bunches have a 6 ns separation in the damping ring a fast kicker is required to extract the particles and transfer them along the length of the linac where the enter a two stage bunch compressor that reduces the bunch length and accelerates the particles to 15 GeV at which point the electrons enter the main linac. The main linac accelerates the particles with a gradient of 31.5 MV/m and has a RF-fill factor of ∼0.7. At an energy of 150 GeV the electron traverse a helical undulator of ∼150 m length to produce polarized photons. These photons impinge on a thin rotating target to create e^+e^--pairs. The positrons are captured and accelerated to 5 GeV. They then enter their damping ring where they are cooled. A transfer line takes them to the beginning of the positron linac, where they proceed for acceleration analogous to the electrons.

A ∼5 km *final focus* section is required to squeeze the beams to the dimensions required for the collisions.

Superconducting RF-cavities have seen a dramatic technological development in the 90ies, when the accelerator gradient was pushed from 5 MV/m to 25 MV/m for niobium cavities whilst there was a similar decrease in cost. The technology was first applied at high gradients in the TESLA Test Facility at DESY, which subsequently turned into the FLASH facility for user operation as a Free Electron Laser. The Global Design Effort for the ILC made an early decision for a more ambitious average accelerating field of 31.5 MV/m. The technical limit for superconducting cavities at 1.3 GHz lies above 50 MV/m when the peak magnetic field exceeds

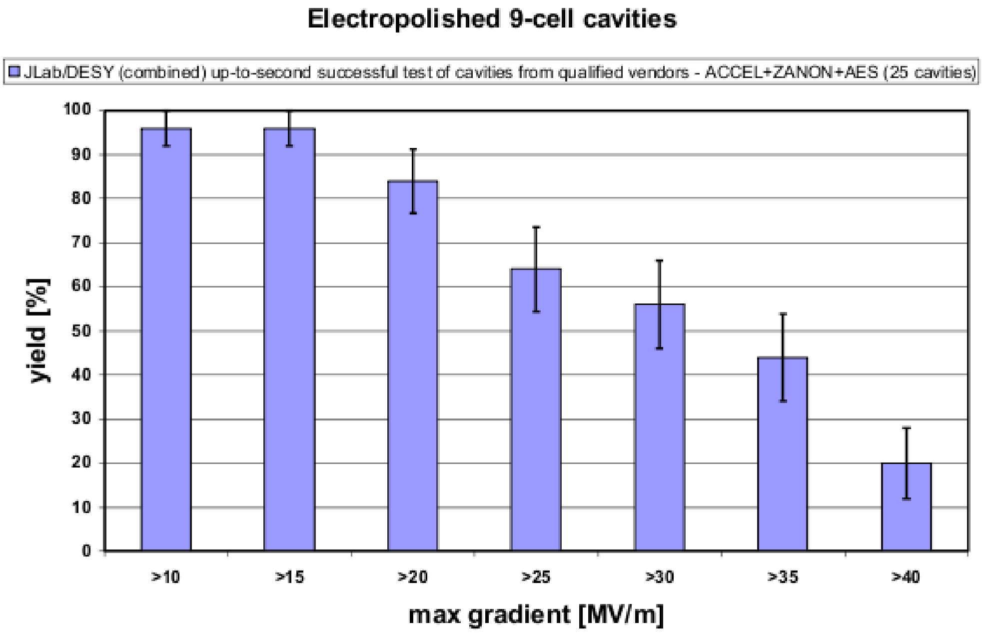

Figure 6: The production yield for cavities in the vertical test. The ILC requirement for this test is 35 MV/m. The cavities originate from two vendors.

the critical field for Nb and hence is far away from the envisaged operational field. Individual cavity cells (single resonators) have been manufactured that withstand fields of 50 MV/m. Hence there is no physics limitation for achieving the ambitious operational gradient. Instead the production technology has to be prepared for mass production. This is a field of particular R&D for the ILC.

The limitation results predominantly from two effects: *field emission* from impurities on the Nb surface and *quenches* that occur when local features in the Nb surface lead to field enhancement that exceeds the critical field. Once a quench is locally induced it spreads quickly and affects the entire bunch train. Such quenches are likely to occur near the equator of a resonator where the field is highest and the electro-beam welding affects the surface homogeneity. Big progress has been made in removing field emission as a primary source of breakdown by removing sulphur remnants from the electro-polishing in a dedicated rinsing cycle. Subsequent surface annealing at 800^{o}C improves the surface structure. The state of the art in this world-wide endeavour is shown in Figure 6. More than 40% of the cavities exceed a gradient of 35 MV/m in a so-called vertical test[2] and meet the acceptance criteria for the ILC. A 10% degradation for beam operation is allowed for so that an average gradient of 31.5 MV/m can be envisaged.

Quenches can typically be traced to features of the surface. They have typically a size of 10 μm to several 100 μm and can hence be identified using appropriate optical inspections.

[2]This low-power test is carried out with a provisional antenna inserted in place of the high-power coupler in actual beam operation.

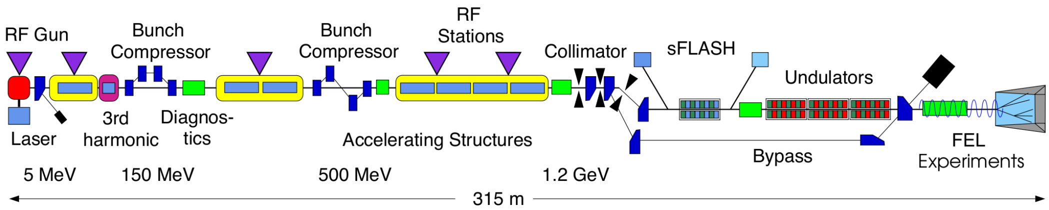

Figure 7: The first section of the FLASH linac. The RF-structures much resemble those of the ILC, where a cryomodule holds three 9-cell cavities.

	European XFEL	ILC	FLASH design	FLASH experiment
Bunch charge [nC]	1	3.2	1	3
# bunches	3250	2625	7200	2400
Pulse length [μs]	650	970	800	800
Current [mA]	5	9	9	9

Table 1: Comparison of operational parameters for the European XFEL, ILC and FLASH. The numbers shown for the FLASH experiment refer to the actual test that has been carried out.

Such tools are under development and are expected to provide the feedback to the cavity manufacturer for proper surface treatment, in particular during electro-beam welding. The ILC goal for cavity production yield is better than 50% for 2010 and better than 90% for 2012 for a gradient of 35 MV/m and above. The results are coming from all three regions: Asia, America and Europe. All regions invest heavily in the technology and infrastructure.

By now superconducting cavities have long been used at the FLASH facility which naturally much resembles the planned accelerator infrastructure for the ILC from the RF point of view. A layout of the injector section and the first acceleration stage is shown in Figure 7 together with the subsequent FEL undulator section. Even though in typical operation FLASH runs with a small number of bunches per train to respond to the wishes of the FEL users FLASH is also able to emulate the high power operation of the ILC: using long trains, high gradients and large number of bunches FLASH basically reproduces the envisaged operational environment for the ILC, cf. Table 1. This environment provides ample opportunity to study the performance of the superconducting accelerating structures in a real environment. It is also very demanding since e.g. the variation of maximum gradients and the gradient spread in FLASH are large. It is hence a demanding task to set up the so called *low level RF* to control the RF distribution that all cavities can perform maximally. The GDE is fortunate to have a test facility routinely operational at this early stage.

A veritable systems test for the ILC will be carried by the European XFEL project at DESY, which features a 1.2 km superconducting linac that serves the undulator beam lines. The construction of the the European XFEL is imminent. The ILC will profit from the understanding of the industrial production of the high-technology components and will gain valuable experience from the operation of the linac, which in effect constitutes a 5% prototype for the ILC.

While the superconducting infrastructure for the ILC is the largest single cost driver and hence warrants the concentrated effort there are other aspects of the project that are subject to optimization. The GDE is hence launching an assessment process that scrutinizes the assumptions of the RDR. As an example the underground tunnel layout of the ILC may offer potential for simplification and cost savings. The RDR assumes a two-tunnel main linac; one tunnel would be used to accelerate the beam whereas the other tunnel would accommodate the high power infrastructure which would remain accessible during operation. It may well be possible to obtain high availability of the ILC with even a single tunnel. Topological simplifications of the tunnel layout at the central campus may well be possible. The damping rings are large; progress in kicker technology allows for a 3 ns bunch spacing and consequently a 3 km ring could suffice. However, such a high-current positron ring may experience instabilities due to the electron cloud effect, which needs to be studied. The intensity requirements on the undulator based positron source are large and hence constitute a risk. − A corresponding research programme for risk mitigation and cost containment has thus been launched for the ILC. It profits from the availability of dedicated tests at facilities such as KEK, CesrTA and FLASH.

Results of this intense R&D programme will form the basis of the Technical Design Report (TDR) that will be released in 2012.

4 Conclusions

With the start of the LHC the exploration of the Terascale will begin. By 2012 considerable feedback will have been obtained on the existence of a low mass Higgs boson and the mass spectrum of particles from *new physics*. That input will bode well for a reassessment of the CERN Council strategy that is foreseen at the same time. The ILC will have completed its technical design phase with the publication of the Technical Design Report. It is expected that the TDR documents the construction of the machine to sufficient details so that there is minimal uncertainty in the estimated remaining engineering and cost. With this approach the ILC construction could begin soon after.

Should the community foresee immediately to concentrate on the multi-TeV energy range a linear collider will only be realized considerably later when the R&D for CLIC will have been successfully concluded. In an optimistic scenario all technical hurdles may have been overcome by the mid of the next decade. However, the demonstration of the technology at a large scale, which is no small endeavour itself, will not have been possible by that time.

Acknowledgments

I wish to thank the many colleagues from CLIC and the ILC in the preparation of the talk. N. Walker and J.P. Delahaye kindly provided most of the material that went into the presentation.

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Discussion

Cheng-Ju Lin (LBNL): What do you think are the deciding factor to choosing between ILC or CLIC?
Answer: Timing and physics interest: The ILC can be built now and will deliver e.g. on resolving the issue of electroweak symmetry breaking. Its energy reach can be extended to 1 TeV. If the interest were focussed on the multi-TeV region from the start CLIC is currently the most viable approach. Verification of its technology on a system scale will however consume a number of years.

The most complete and timely physics return would come from an early ILC implementation compatible with an upgrade option to multi-TeV using CLIC technology.