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特集　国際リニアコライダー（ILC）計画と新しい科学プロジェクトのあり方

International Linear Collider（ILC）－Overview

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Abstract

The International Linear Collider (ILC) is proposed as an energy frontier electron-positron colliding accelerator, started with a center-of-mass beam collision energy of 250 GeV, as "Higgs factory". The ILC accelerator design and the preparation for construction are discussed. The core technologies of Radio Frequency superconductivity and production and manipulation of extremely low emittance beams (nano-beam) are presented. The plan for the energy-staging at the center-of-mass energy starting with 250 GeV and future prospects are discussed. The ILC will allow the properties of the Higgs boson to be measured with unprecedented precision, and will provide possible discovery of new particles beyond the standard model with the energy extendability as a natural feature of the linear accelerator.

Introduction

The International Linear Collider (ILC) is an energy-frontier electron-positron collider based on two key technologies of superconducting radio-frequency (SRF) and nano-beam technologies. The center-of-mass energy (C.E.) will be in a range of 200–500 GeV, extendable to 1 TeV [1-3], which is a unique and great feature of the linear accelerator. ILC will provide the luminosity as high as 10^{34} $cm^{-2}\cdot s^{-1}$, based on the key technologies, and the polarized electron (potentially for positron) beam much enhances the physics significance and accuracy.

In view of the discovery of the Higgs boson with a mass of 125 GeV at CERN, the plan has recently been modified to start as a "Higgs factory" with a C.E. of 250 GeV. The total length of the accelerator complex is 21 km for this machine design. It will allow the properties of the Higgs boson to be measured with unprecedented precision, and the energy extendability enables to investigate new physics beyond the Standard Model, as it illustrated in Fig. 1.

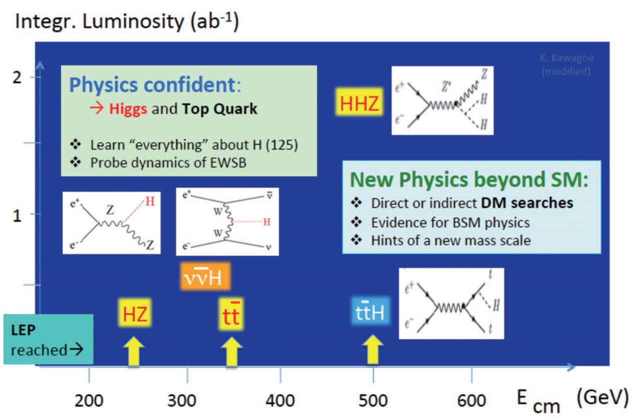

Figure 1: Physics scope with the ILC starting at 250 GeV.

The accelerator system is composed of i) a polarized electron and positron sources, ii) damping rings (DR) at 5 GeV, iii) beam transport followed by a two-stage bunch-compressors accelerating the beam up to 15 GeV, iv) 5.5 km main linacs accelerating the beam up to 125 GeV by using SRF cavities with an average gradient of 31.5 MV/m, and v) beam-delivery systems which bring the beams into collision with a 14 mrad crossing angle at a single interaction point. It will supply e^+e^- beam collisions to two detectors, operating alternately in "push-pull" configuration. The ILC accelerator parameters are summarized in Table 1, and the ILC accelerator configuration and layout is shown in Fig. 2.

SRF Technology for the ILC

The ILC accelerator design has been optimized with the SRF technology with the following advantages [2]:

Table 1: ILC accelerator parameters.

Collision Energy	≥250 GeV
Length	21 km
Luminosity	$\geq 1\times10^{34}$ $cm^{-2}\cdot s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA
SRF Cavity G. (av.)	31.5 MV/m
Q_0 (av.)	1×10^{10}

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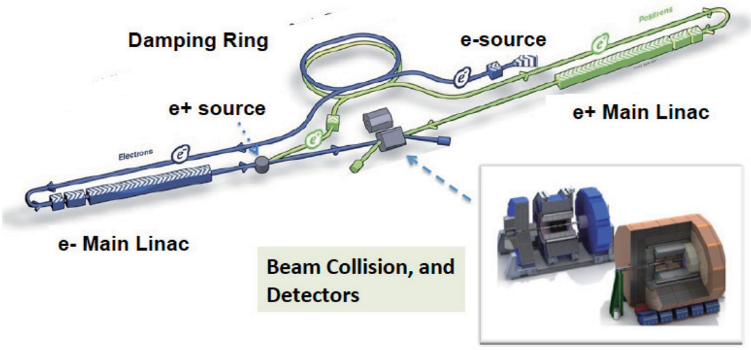


Figure 2: LC configuration and layout.

- Small RF surface resistance and large quality factor, Q, allowing a longer pulse-duration of a level of 1 ms with a higher duty operational factor in beam acceleration.
- Lower RF operational frequency of 1.3 GHz, leading to a larger beam-aperture of ~70 mm in diameter and larger acceptance for high intensity beam and high-luminosity.

The shape of a superconducting cavity is optimized for properties such as: (i) reduced excitation of higher-order harmonics by the beam; (ii) lower surface magnetic field to maximize the critical limit of the superconducting to normal-conducting phase transition; and (iii) lower surface electric field to suppress field emission. The large iris opening and elliptical shape result from optimization of these considerations. The ILC cavity design has been based on much experience from the TESLA and European XFEL programs, and the cavity and cryomodule configuraton is shown in Fig. 3 [4].

The ILC main linacs accelerate the beam from 15 GeV (after pre-acceleration in bunch compressors) to a maximum energy of 125 GeV. Beam acceleration in each linac is provided by approximately 3,700 superconducting nine-cell niobium cavities with a unit length of 1.27 m operating at 2 K, assembled into 425 cryomodules. The average design accelerating gradient of the cavities is 31.5 MV/m, for 125 GeV operation in each linac, with a corresponding quality factor Q_0 of 1×10^{10}. A random cavity-to-cavity gradient spread of ±20% is tolerated to accommodate expected mass-production variations. If the newly established R&D program for increasing the gradient is successful, it will be possible to increase the operating gradient to 35 MV/m, reducing the linac length by about 10%, with associated cost saving.

The extensive worldwide production experience both in laboratories and in industry now gives confidence that these

(a)

(b)

Figure 3: SRF beam-accelerating structure: (a) 9-cell cavity and (b) the cavity string in a cryomodule.

requirements can be achieved. For an average of 31.5 MV/m operation with the nominal beam current of 5.8 mA, the optimal matched loaded-Q (Q_L) is 5.4×10^6. This corresponds to a cavity fill-time of 0.92 ms, added to the nominal beam pulse width of 0.73 ms, gives a total RF pulse length of 1.65 ms in the baseline design. The cavity package includes the cavity mechanical tuner integrated into the titanium helium vessel of the cavity, and an adjustable high-power coupler. In addition to a slow mechanical tuner (used for initial tuning after cool-down and slow drift compensation), a fast piezo-driven tuner is provided to dynamically adjust the frequency variation due to the cavity deformation, caused by the RF pulse, known as "Lorentz-force detuning". The RF power is provided by 10 MW multi-beam klystrons (MBK). A string of 39 cavities is powered by a single 10 MW klystron, as shown in Fig. 4.

Cooling of the SRF main linac is provided by large cryogenics plants, each of which has an equivalent cooling power of ~20 kW at 4.5 K. The plants are located at each 5 km along the linacs, with each plant cooling 2.5 km of continuous linac. To simplify the liquid-helium transport, the main linacs follow the Earth's average curvature for the cavity operation at 2 K (required to reduce RF heating (BCS losses)), the SRF cavities are immersed in a saturated He-II bath. Shields cooled with helium gas intercept thermal radiation and provide a heat sink for conduction at 5–8 K and at 40–80 K. Each cryomodule has an estimated 2 K static cryogenic heat load of 1.3 W while the 2 K dynamic heat load is approximately 9.8 W.

Over the last 30 years, significant progress has been made and the cavity gradient performance has been significantly improved. Figure 5 (a) shows the gradient improvement with both single-cell and multi-cell cavities [5]. Various efforts of mechanical assembly and surface treatment contributed to this significant progress, as well as important efforts for the invention and deployment of tools to identify and repair quench-causing effects. These processes have been needed to achieve both the high-gradient goal and to demonstrate a production yield of 90% worldwide to be ready for a large-scale manufacturing required for ILC. This goal has been met in the ILC technical design phase: a yield of 94% for cavity production above 28 MV/m (as a lower threshold for 35 MV/m ±20%) and an average gradient of 37.1 MV/m has been achieved as shown in Fig. 5 (b) [1]. The yield thus corresponds to 94% for a cavity ensemble with an average gradient above 35 MV/m and complies with the allowable gradient-spread specification of ±20%. The yield for cavities with gradient ≥35 MV/m is 75%.

Larger statistics on the yield has been obtained from the European XFEL cavity production program. A half of 800 cavities fabricated by industry have been surface-processed with the same recipe as that of the ILC SRF cavities, and the results may well represent the state of the technology as shown in Fig. 6 [6, 7]. The accelerating field gradient has reached a 90% level of the ILC requirements. It should be also noted that there has been progress in the averaged field gradient achieved after the 8-cavity-string assembly into the cryomodule. The gradient degradation happening in the early stage of the construction has been successfully mitigated, after much effort on very careful assembly and keeping the cleanest possible working environment [8]. In the United State, the Linear Coherent Light Source II (LCLS-II) at SLAC, Stanford, is under construction, and the SRF beam acceleration facility will be soon realized [9].

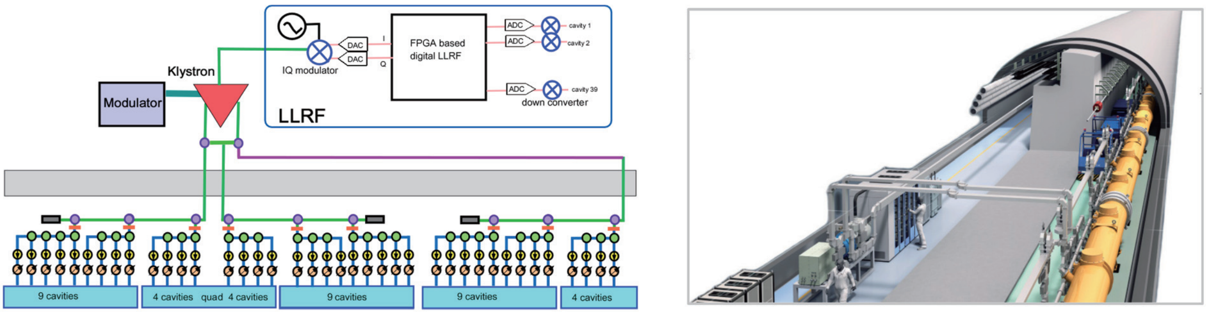
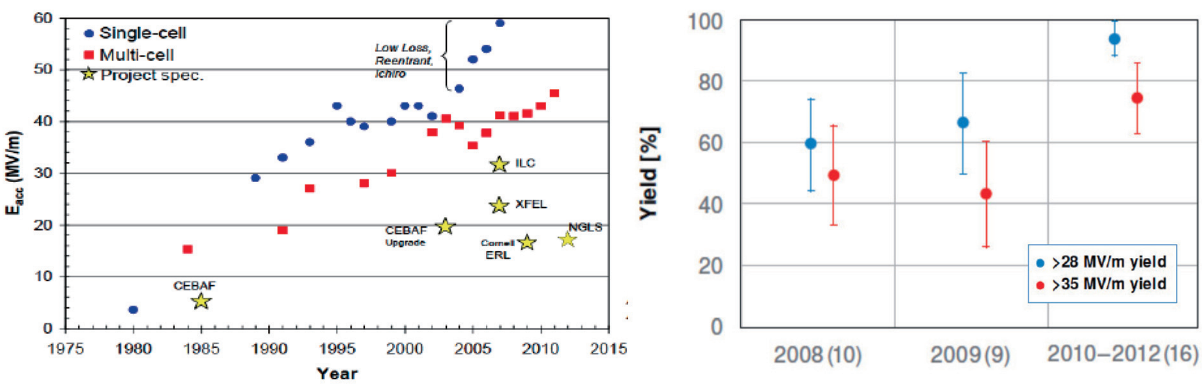


Figure 4: A string of 39 cavities in 4.5 cryomodule powered by a 10 MW klystron, and the RF power transferred and distributed by using wave guides.



(a) (b)

Figure 5: (a) SRF L-band cavity-gradient progress and requirements from various projects, and (b) progress in the gradient yield at G >28 MV/m and >35 MV/m during a period of the GDE phase in 2007–2012.

SRF beam test facilities have been required for major technical demonstrations to evaluate the SRF cavity and the beam acceleration performances. The Free Electron Laser in Hamburg (FLASH) as a soft X-ray free-electron laser facility [10] and the so called “9 mA program” has successfully demonstrated the beam acceleration parameters required for the ILC [2, 11]. The superconducting linac facility at Fermilab has demonstrated an averaged field gradient above 31.5 MV/m, in the 2nd cryomodule assembly consisting of eight 9-cell cavities [12] and also realized the beam acceleration up to 250 MV with confirming the acceleration gradient achieved. S1-Global program hosted at KEK has demonstrated 8 SRF cavities, fabricated in different regions and assembled to a string in a cryomodule, and tested [13]. KEK is preparing to demonstrate the SRF beam acceleration at the superconducting RF test facility (STF) [14]. The ILC SRF accelerator technology has been sufficiently progressed with worldwide efforts and prepared for the ILC project realization. Figure 7 shows from (a) photo from S1-Global experiment and (b) the STF CM string for the beam test preparation.

Nano-Beam Technology for the ILC

The challenge of colliding nanometer-sized beams at the beam interaction point are three distinct issues of i) creating small emittance beams, ii) preserving the emittance during beam acceleration and transport, and iii) focusing the beams to nanometers for colliding them. The Accelerator Test Facility (ATF) hosted at KEK is providing a prototype accelerator complex consisting of an electron linac, a damping ring, a beam extraction system, and the final focus beam transport line ATF2, as shown in Fig. 8 [15].

The damping ring is to deal with the first issue (i) and has succeeded to reach the low emittance satisfying the ILC requirements [16]. The ATF program has been extended to demonstrate the third issue (iii) to study the final focusing of the beam to nanometers. A primary goal is to establish the ILC final focus method with the same optics and with comparable beam-line tolerances, and to reach a final-focus beam size of 37 nm at an ATF2 beam energy of 1.3 GeV, corresponding to

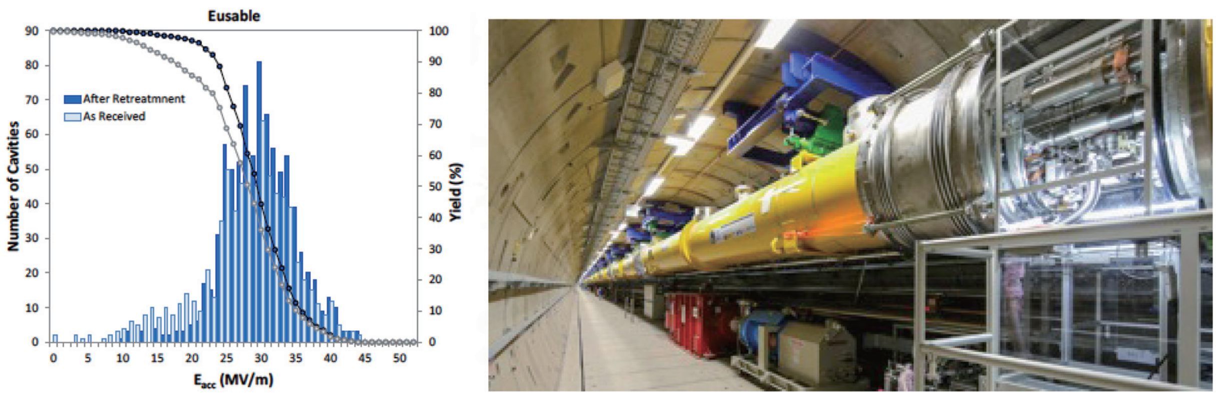


Figure 6: Accelerating Gradient achieved in European XFEL, and SRF CMs installed in European XFEL.

(a) (b)

Figure 7: S1-Global Cavity-string tests held at KEK and recent SRF test facility at KEK for the beam acceleration test expected in JFY2018.

5.9 nm at the ILC beam energy of 250 GeV. ATF2 achieved a vertical beam size of 55 nm in 2013, and achieved 41 nm, in 2016, nearly approaching to the primary goal as shown in Fig. 9 [17-20].

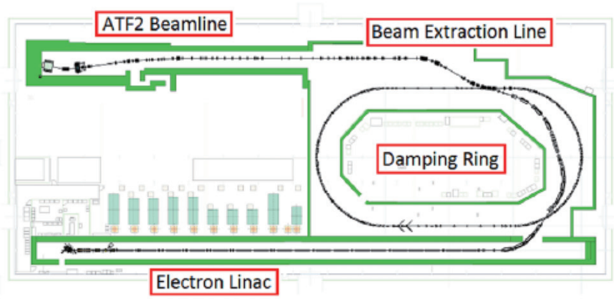
The next important goal is to develop the position stabilization at the beam collision point, with in a few nanometer by using a bunch train feedback scheme. It should be noted that measuring transverse beam sizes of tens of nanometers at the IP requires specialized beam instrumentation, in particular a beam-size monitor, and it has been realized by using laser interferometry technology (IPBSM, referred to as a Shintake monitor [21]).

Status and Prospect

The ILC is based on two key technologies of superconducting RF and nano-beam technologies, with a high level of maturity due to more than 20 years of global collaboration, as described in the ILC Technical Design Report published by the ILC Global Design Effort in 2013. Superconducting RF technology has been much matured through industrialization efforts for the European XFEL accelerator construction. The nano-beam technology required has advanced with the global ATF collaboration, and the final focus beam size have been nearly demonstrated to reach the ILC R&D goal. These progress are summarized in Table 2.

In preparation for the ILC construction, the SRF technology will now be developed further for cost effective fabrication and mass-production. A recent breakthrough in surface treatment, so-called “nitrogen infusion” developed at Fermilab [22] should be further demonstrated with sufficient statics, and it may contribute to high-Q and high-G performance resulting in the cost effective cavity fabrication. For nano-beam technology, beam position stabilization for final focusing will be further R&D goal. Further engineering design and R&D works for positron source and beam dump are to be carried out in the preparation phase for the ILC [23].

The Technical Design Report (TDR) of the ILC mainly concentrates on a baseline machine of 500 GeV center-of-mass with detailed cost and manpower estimates consistent with this option. However, the discovery of a Higgs boson with a mass of 125 GeV opens up the possibility of reducing cost by starting at a center-of-mass energy of 250 GeV with the possibility of future upgrades to 500 GeV or even 1 TeV should the physics case be compelling [24, 25]. The options for the 250 GeV design



Parameters		ILC-TDR	ATF2
Beam Energy	[GeV]	250	1.3
L* (FFQ-IP dist.)	[m]	4	1
V. β function at IP	[mm]	0.48	0.1
V. emittance	[pm]	0.07	0.1
V. beam size at IP (achieved)	[nm]	5.9	37 (41)

Figure 8: ATF accelerator layout and main parameters compared with the ILC parameters.

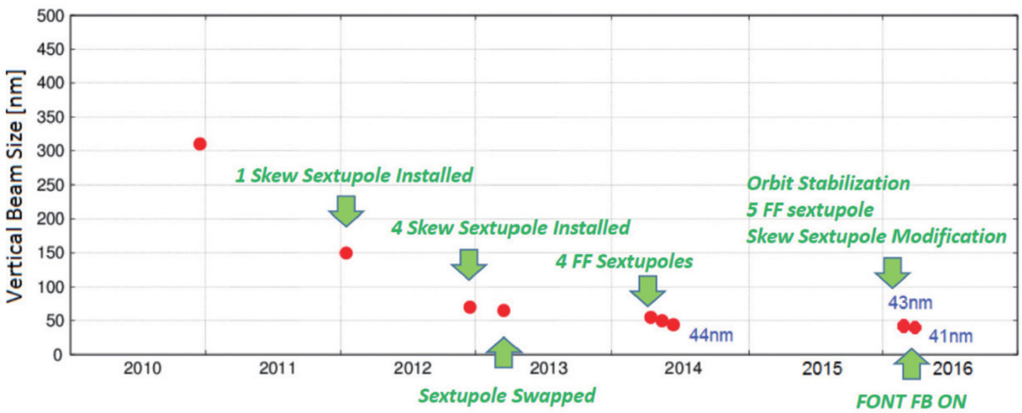


Figure 9: Progress in the final-focus beam size at ATF-2.

provides "Higgs factory". The scientific program that the machine is described in the physics report [25].

A first stage 250 GeV machine would imply the installation of approximately half of the linac of the 500 GeV baseline machine. There are various possible scenarios for the civil construction and conventional facilities, as shown in Fig. 10, and are summarized as follows:

- Option A: Only the tunnel for the 250 GeV machine is constructed and equipped. Increasing the machine energy would then require extensive additional civil engineering at a later date.
- Option B: The tunnel length is extended to allow the energy to be increased to 350 GeV (the top quark threshold) at a later date. Only the downstream part is filled with linac.
- Option C: The complete tunnel and access shafts for the 500 GeV machine is constructed in the beginning and only the downstream part is filled with linac. The remaining tunnel will be left in a raw state (no dividing wall, cooling or ventilation) in order to save money in the first stage. Upgrading the energy to 500 GeV then requires finishing the tunnel and installing extra cavities.

The first scenario (Option A) represents the lowest cost for the initial phase. The second and third obviously require extra investment in the initial stage but open up the possibility of increasing the center-of-mass energy without major tunneling work. The main parameters, including luminosity, are initially assumed to be the same as those specified for the 500 GeV baseline scaled to 250 GeV. This means that the electron and positron sources, damping rings and bunch compressors remain unchanged from the baseline. However, an improved luminosity performance is being considered. The beam delivery systems could be further optimized for low energy but the

Table 2: Technical parameters demonstrated to prepare for the ILC realization.

Characteristics	Parameter	Unit	Demonstrated with global effort
SRF			
Av. accelerating gradient in CM	31.5 (±20%)	MV/m	DESY, FNAL
Cavity Q_0	10^{10}		DESY, FNAL
Cavity qualification gradient	35 (±20%)	MV/m	DESY, FNAL, JLab, Cornell, KEK
Beam current	5.8	mA	DESY, KEK
Number of bunches per pulse	1,312		DESY
Beam pulse length	730	ms	DESY, KEK
RF pulse length (incl. fill time)	1.65	ms	DESY, KEK, FNAL
Pulse repetition rate	5	Hz	DESY, KEK
Nano-beam			
ILC-FF beam size (y) KEK-ATF-FF equiv. beam size (y)	5.9 37 (reaching 41)	nm nm	ATF collaboration

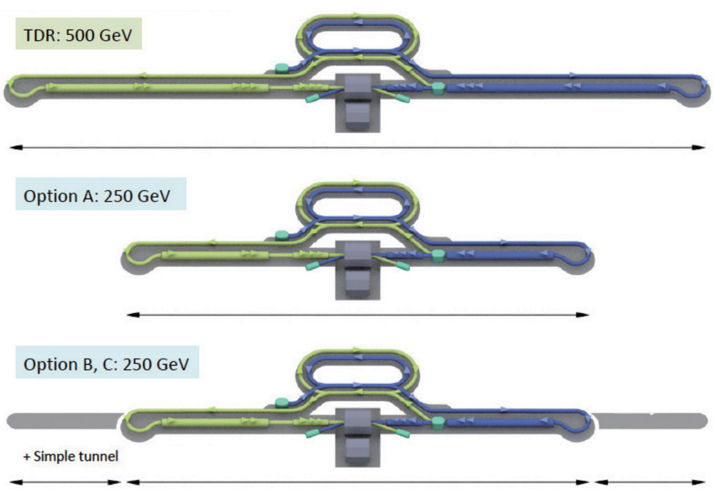


Figure 10: Illustrated schemes of the ILC 250 GeV staging scenarios.

overall geometry is still assumed to be consistent with a 1 TeV upgrade eventually.

For positron production, 5 Hz is still assumed but the lower energy of the electron beam (125 GeV instead of 150 GeV in the baseline) makes it harder to produce the required polarized positron flux. To compensate for the lower energy, the undulator length must be increased by about 60% in order to preserve the photon flux to the convertor target. A more straightforward way of preserving the positron flux would be to use a conventional positron source which would require an additional 3 GeV linac. This option would mean that partial polarization of the positrons would not be possible. The impact on the scientific potential of the machine must be addressed. First indications are that the cost of the two options is very similar.

It is estimated that the reduction in center-of-mass energy to 250 GeV with no improvement in cavity gradient compared with the TDR will reduce the cost to about 65% of the TDR value (only the linac cost is reduced, the cost of the damping rings and ancillary systems is unchanged). Recent developments on superconducting radio frequency technology and improved design of components gives good prospects of further reducing the cost down to 60% after a few years of R&D.

Conclusions

Many years of development of RF superconductivity has resulted in a mature technology that is being used in the Xray Free Electron Laser (XFEL) at DESY, Hamburg as well as the Linear Coherent Light Source II (LCLS-II) at SLAC, Stanford and is ready to be used at the ILC. The discovery of the Higgs boson at the relatively low mass of 125 GeV opens up the option of building a powerful "Higgs factory" with a guaranteed rich physics output and with the possibility to upgrade in energy at a later stage. This approach has been supported by the International Committee for Future Accelerators (ICFA) as well as the international scientific community.

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