STATUS OF THE INTERNATIONAL LINEAR COLLIDER

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Abstract

The International Linear Collider (ILC) is the next-generation electron-positron collider. Since the publication of the Reference Design Report, the project is now in the middle of the Technical Design Phase. The present paper will describe the process of the design improvements, status of the R&D effort, and the plans for the future

INTRODUCTION

The International Linear Collider (ILC) is the next-generation electron-positron collider to be build by international effort. The design and development works are being coordinated by the Global Design Effort (GDE) which was established in 2005. The Reference Design Report (RDR)[1] was published in 2007. The layout of the whole complex described in RDR is shown in the plot on the left in Figure 3. The center-of-mass energy for the first stage is set to 500GeV. (The energy for the actual construction will be decided later, according to the physics scenario taking into account possible future inputs such as from LHC.)

The next major milestone is the Technical Design Report (TDR) to be completed by the end of 2012. The period till then is divided into two phases, TDP1 (Technical Design Phase) and TDP2. We are now at the end of TDP1.

R&D ISSUES AND STATUS

R&D on the technology of superconducting acceleration, which is the key issue for ILC, is divided into four fields:

- S0: Development of high gradient cavities
- S1: Development of a system of cryomodule containing several (8 or 9 in ILC) cavities and power sources
- S2: String test of a few cryomodules with full current beam
- Industrialization

Cavity

The essential component of the linac is the high-gradient superconducting cavity. It is the most important among the single cost drivers. The specification in the RDR is: accelerating gradient in the vertical test > 35MV/m (quality factor Q_0>0.8x1010). As the production yield of such cavities, the R&D target is set to >50% in the TDP1 and >90% in the TDP2. In order to evaluate the yield on a firm basis with uniform and well-controlled database, Cavity Global Database Team was formed last year. The `production yield' is defined as the number of cavities accepted by the criterion divided by the number of cavities produced (rather than the number of surface processing). From recent experiences the following criterion seems to be adequate:

1) Those cavities which exceeded 35MV/m in the first vertical experiment are accepted.
2) Those below 35MV/m are processed again and, if they exceed 35MV/m, they are accepted.
3) Otherwise rejected. (i.e., only up to second pass)

Only the cavities from `established vendors' should be included. The cavities for R&D (such as large grain cavities) should be excluded in the statistics for the moment.

According to the above rule the production yield of the cavities over the last few years is estimated to be 44%. However, improved HLRF (high level RF) system can accept a large spread in the cavity gradient. It is thought to be more practical to accept cavities below 35MV/m if the average gradient of the accepted cavities exceeds 35MV. For example if we accept cavities in the range 27.9-41.8MV/m (+/- 20%), the present yield becomes 64%. (See Figure.1) Thus, the target yield 50% in TDP1 is considered to be almost reached.

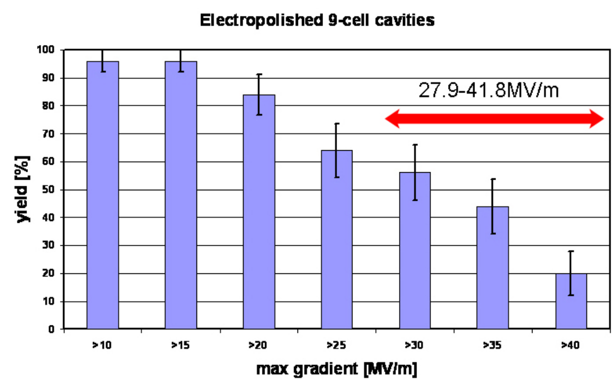

Figure 1: Recent results of cavity production yield vs. gradient. The yield over 35MV/m is about 44% but, if one includes those in the range shown by the arrow, the yield will be 64%. (Only cavities from `established vendors are included.)

The most important progress in the cavity R&D is the technology of locating and removing the defects. Several techniques of finding the location of cavity defects have been developed. They include:

- Pass-band mode measurement, which reveals which cell, among the 9 cells, is responsible.
- Temperature map by many sensors attached to the cavities during vertical test, which shows the location of heating.
- Optical inspection camera, which finds the location and show the shape of the defects.

In many cases these techniques agree each other. A technology of making a replica of the defect and measuring the shape and size accurately has been developed. This enables a detailed computer simulation of the local field enhancement factor [2] and comparison with the vertical test results. It turned out that the cavities whose gradients are limited below 20-25MV/m are most likely to have large surface defects of a few 100μm.

Further progress is the local repair technique of cavities having such defects. A device to locally grind the inner surface has been developed at KEK [3] and showed improvement of the gradient for several cavities.

S1-Global

RDR adopts the average operating gradient > 31.5MV/m (Q_0>1x1010), which allows 10% reduction from the vertical experiment. In order to confirm this gradient a project called `S1-Global' is going on [4]. It also has the purpose to demonstrate the so-called `Plug-Compatibility', i.e., a system assembled from components designed with slightly different specification. 8 cavities, 2 from FNAL, 2 from DESY and 4 from KEK, have been transported to KEK. The average gradient in the vertical tests of these cavities are about 30.5MV/m. These cavities are assembled and installed into two cryostats, one from INFN the other from KEK. Assembling works have been finished in May and the cooling down of the whole system will start in early June. All the tests will be completed by the end of this year.

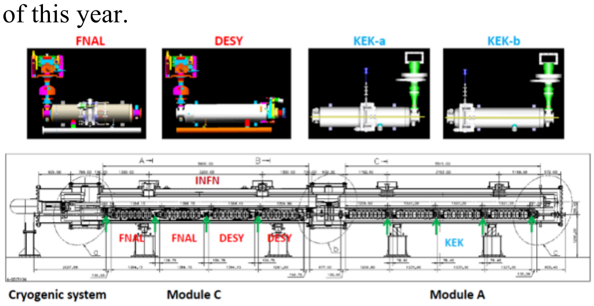

Figure 2. Configuration of the S1-Global.

S2

String tests of cryomodules with a high current beam have been performed at the facility FLASH at DESY. In the latest experiment in September last year a long-time operation (>10 hours) was successfully done at the beam current 3mA (ILC specification 9mA) with the pulse length ~800μs. 6mA could be achieved, though a short time near the end of the experiment period. In a typical experiment the energy uniformity of ~0.5% (peak-to-peak) along a pulse was achieved. These parameters nearly satisfy the ILC specification.

S2 experiments are also planned at FNAL and KEK. At FNAL the first module (consisting of components fabricated at DESY) has been assembled and the first cooling down will start soon. The second module, which uses US cavities, will be built this year. Further modules are being planned as synergy with Project-X. At KEK the fabrication of the first module together with the RF gun and capture cavities has started last year. It will be completed by the end of 2012.

Industrialization

Success in S0/S1/S2 does not immediately mean readiness for construction. ILC requires about 16,000 cavities to be produced in about 4 years, which corresponds to ~7 cavities per day in each of the 3 regions (Asia, Europe, Americas). This number exceeds the present capacity of any company in the world. For the construction of ILC we must consider mass-production, quality control, and cost reduction. Considering the possible organization style of ILC it is reasonable that each region should have the technology and production capability and it is desirable to have more than one vendor in each region. In this conference there is a special session for industry on Wednesday (WEIRA) where these problems will be discussed. In addition prior to the conference a satellite meeting [5] was held which was devoted to the industrialization of cavity production.

Damping Ring Issues

The most critical R&D issues on the damping rings are the electron-cloud instabilities and the fast injection/extraction kicker. These are studies mainly in the facilities CESR-TA and KEK-ATF.

Electron-cloud instability is one of the highest risk factor of the ILC. This is important not only for ILC but also many other rings such as LHC and B-factories. The 3 year study plan at CESR started in 2008. It allows measurements of the evolution of electron clouds under various environments, including different chambers (chamber coatings, clearing electrons, grooved chambers) and different magnetic fields (drift space, dipole, quadrupole, wiggler). To this end the CESR ring must be re-configured to install various devices and to obtain emittance as small as possible (BPM upgrade, beam size monitor, fast feedback, solenoid windings, etc). The reconfiguration works have been completed by summer last year. Since the parameters of CESR ring are not identical to those of ILC damping rings, extrapolation by computer simulation is essential. The vertical geometric emittance ~20pm has been reached and the comparison of various instability mitigation methods is in progress. The simulation technique has been greatly improved. A working group meeting is scheduled in coming October. An extension of the project for about 2 years is being proposed. See [6] for the recent status.

Another important issue on the damping rings is the fast kicker with the rise/fall time 3-6 ns. A stripline kicker using a fast pulser has been developed at KEK-ATF by international collaboration [7]. The first extraction test succeeded in October last year. By March this year the system has been extended to kick up to 30 bunches (interval 5.6ns). It turned out the pulse-to-pulse stability of the kick angle was ~$4x10^{-4}$, which is better than the ILC requirement $7x10^{-4}$. However, there is still a problem of timing jitter. The next experiment is scheduled in June. When sufficient stability is confirmed, this kicker will be permanently installed in the ATF and be used for the beam feedback experiment in the ATF2 (second goal of ATF2).

Beam Delivery System

One of the main issues of the BDS (Beam Delivery System) is the beam focusing down to a few nanometer. The beam extraction line of KEK-ATF has been extended for the project ATF2, which is a miniature of the ILC Final Focus System. The beamline construction was completed by the end of 2008. Since then experiments are being done for the first goal of ATF2, namely focusing the beam to ~37nm. Tuning works of the beamline and the beam size monitor have been done and, by the time of this conference, the beam size as small as 300nm has been confirmed [8]. The plan is to reach the goal by the end of this year. After achieving the first goal, the second goal, i.e., the beam centroid stability down to a few nanometer by using a feedback system will be pursued.

DESIGN IMPROVEMENTS

The RDR quotes the estimation of the construction cost 6.62 billion ILC unit (1 ILC init = 1US$ in 2007 = 0.83 Euros = 117 Yen) plus the explicit labour 14000 person-years, which is comparable to the large-scale science projects such as LHC and ITER. For the realization of such projects the technical maturity is obviously the most important point. However, what is not less important is the cost issue. It must be affordable and its estimation must be robust. In the process of the design study of RDR we have made intensive efforts for cost reduction. In fact the RDR value is nearly 30% lower than the first internal estimation. Nonetheless, we feel the result is still very high. Moreover, we have to anticipate possible cost increase in particular in the high-tech components for which our experience is not abundant. For example the cost estimation of the cryomodule may contain some uncertainty, and the assumed accelerating gradient might be slightly too high. We have to prepare for such possible cost increase so that at least the cost does not exceed that in RDR (cost containment). Since last year we considered design improvements which lead to significant cost reduction with minimizing the risk and keeping the physics capability as much as possible. Possible design changes are listed in the followings. They were combined in the name of `SB2009' (Strawman Baseline). The expected cost reduction is around 13% if all the items are adopted as baseline.

Single Tunnel

In the RDR the linac components are accommodated in two tunnels running in parallel, one containing the power source (modulators, 10MW klystrons, etc.) and the other the cryomodules. It has been intensively discussed if all components can be accommodated in a single tunnel so that the cost of one tunnel can be saved. Detailed simulation study on the availability of the total system was performed and it turned out the simple single tunnel layout (same components as in RDR packed into one tunnel) will cause significantly longer machine downtime. However, this can be improved nearly to the level of RDR by introducing appropriate RF distribution system. Two possible systems have been proposed.

- KCS (Klystron cluster system): The microwave sources are housed in the power stations on the surface ground at every 2km. Each station accommodates about 30 klystrons (10MW MBK) and modulators. The combined microwave output (~300MW) is transported to underground tunnel by over-moded waveguides (diameter 48cm) and distributed to individual unit (3 cryomodules) by coaxial tap-offs (the longest distance of microwave transportation is about 1km).
- DRFS (Distributed RF System): One unit of ~750kW MA (modulating anode) klystron drives 2 cavities (about 8000 klystrons are needed in total). In this scheme all the linac components are housed underground. One unit is much simpler and compact compared with RDR and KCS.

Choice of these two depends on further technical study as well as on the chosen site. Horizontal access slopes, as long as kilometre, are being considered rather than vertical shafts for the Asian sample site, which is in mountainous area. In such case KCS is not very attractive due to the power loss in the long waveguides.

Either of these schemes requires R&D. The major issues are the high-power handling for the KCS and the maintainability and cost for the DRFS. The high-power components for KCS, such as the large-diameter waveguide, coaxial tap-off and other auxiliary parts are being developed at SLAC. High power test using a resonant line (or ring) is being planned. For the DRFS the MA klystron is being developed at KEK. The two units of the prototype will be tested at S1-Global. Later models will be installed in the capture section of STF2 (drives 2 cavities) in 2011 and in the main module in a larger scale in 2012. The development of permanent magnet version will be done in parallel.

Reduced Beam Power

If one reduces the number of bunches in a pulse to half (from 2640 bunches in RDR to 1320) with the fixed pulse length (~1ms), the beam current in the linac would become half (from 9mA to 4.5mA). This allows to make the power source (klystrons and modulators) half, thus leading to a significant cost reduction. The upgrade to the RDR value can be done by adding the power source in a later stage.

Half Size Damping Rings

The damping rings for the ILC are very large, compared with damping rings for normal conducting colliders such as CLIC, in order to accommodate large number of bunches. If the number of bunches is halved as mentioned in the previous subsection, then the circumference of the damping rings can also be halved (bunch interval unchanged) at essentially the same risk of electron-cloud instability and the fast kicker. This also give rise to a significant cost saving. A choice still remains whether a space for one more ring is to be reserved in the tunnel for future upgrade to full number of bunches.

Single Stage Bunch Compressor

In the RDR the bunch compressor is designed as a two stage compressor such that it has the capability to compress the bunch to 200μm while the nominal parameter set defines the linac bunch length 300μm. This might be useful when a smaller value of the disruption parameter at the collision point becomes desirable in actual operation. However, some cost saving is achieved by adopting a single stage compressor though this may exclude the possibility of shorter bunches below 300μm.

Tighter Focusing

If the number of bunches is halved, this naturally makes the luminosity half. A tighter focusing (smaller beta function) at the collision point would be ineffective due to the hour-glass effect if the bunch length cannot be shorter than 300μm. This can be remedied by adopting the so-called `travelling focus'. However, a tight focusing with a long bunch would make the luminosity sensitive to the offset errors of the electron and positron bunches. Accordingly the requirement to the feedback system would become severer.

Undulator Scheme

The positron beam is generated by the undulator scheme using the high-energy electron beam. RDR places the undulator at the 150GeV point of the electron linac. In this case the electron beam is either accelerated or decelerated after 150GeV point to adjust the beam energy at the collision point. This scheme has an advantage that the positron production is independent of the collision energy. It turned out, however, it requires another machine protection system before the undulator in addition to the one at the linac end. Moreover, the electron linac up to 150GeV point must always be operated nearly at the full gradient even in the commissioning stage in order to produce sufficient number of positrons. In order to overcome these problems a new design where the undulator is located at the end of the electron linac is being considered. In this case the problem is the low efficiency of positron production when the beam energy is below 150GeV (center-of-mass energy below 300GeV). The production rate is about half at 125GeV.

The flux concentrator is assumed as the capture system of produced positrons in RDR, but SB2009 adopts more conventional QWT (Quarter Wave Transformer). This demands a longer undulator due to the lower capture efficiency, which makes the load on the target higher by factor of ~1.6. SB2009 also eliminates the `keep alive source' and instead add an auxiliary conventional source which shares the target with the main (undulator) positron production system.

Compact Layout of the Central Region

The central region includes various facilities such as the damping rings, the electron source, BDS and many different transport lines. In SB2009 the layout of these facilities has been modified so that the central region tunnelling and civil engineering are simplified. The result is shown in Figure 3. The notable changes are

- Shift the damping rings (to the right in Figure 3)
- House the electron source and 5GeV injector linac in the same tunnel as the BDS for positron
- Move and undulator and positron booster linac to the end of the electron linac

By combining all these modification together with the single-tunnel, the total tunnel length was reduced by 27km (40%).

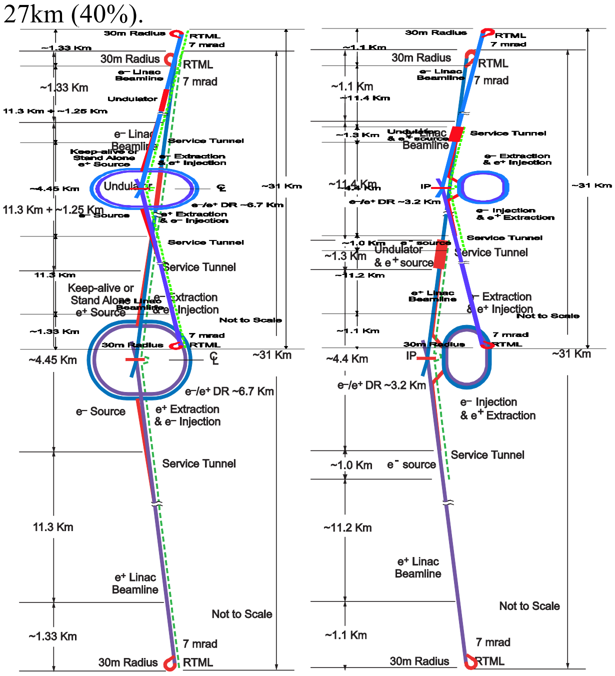

Figure 3. Layout of RDR (left) and SB2009 (right).

Impact on the Luminosity

As described above the reduction of the luminosity due to the reduced number of bunches is compensated for by the adoption of a tighter focusing with the travelling focus scheme. However, it turned out that the travelling focus scheme is not effective at low energies because the small beta function makes the radiation angle large, in particular at lower energies due to the larger geometric emittance, causing more background to the detector. Moreover, the number of positrons would be less at low energies due to the location of the undulator. Accordingly, the luminosity at the center-of-mass energy 250GeV would be less than that of RDR by a factor of 3 to 4. This raised a strong objection to SB2009 from physicists.

In the joint LCWS (Linear Collider Workshop) and GDE meeting at Beijing in March 2010, new schemes were proposed to recover the luminosity at low energies.

Since the required total power for low energies is lower than at full energy (500GeV), one can raise the machine repetition rate to raise the luminosity. (For example, from 5Hz at 500GeV to 10Hz at 250GeV.) An obvious obstacle is the damping time of the damping rings, i.e., the injected beam would have to be damped in 100ms rather than 200ms. It turned out fortunately that the damping wigglers in the damping rings can be reinforced to meet this requirement. All the machine components are being revisited now if there is any other problem in raising the repetition rate. Presumably, 10Hz is too high due to the lower efficiency of klystrons at lower output power, but 8Hz seems to be feasible.

Another possible improvement of luminosity can come from redesign of the final focus quadrupoles for low energies in order to avoid the background problem. If the optics in the final focus system is fixed, the field of the magnets can be lowered at low energies. This makes it possible to reduce the magnet length at least if we replace the magnets for low energy experiments. Detailed studies are still needed.

Future Steps of Re-baseline

We originally planned to revise the baseline design by mid 2010 in order to have sufficient time to complete the design work for the TDR by the end of 2012. However, the luminosity problem should still be revisited. Also, as the AAP (Accelerator Review Panel) pointed out in the review meeting at Oxford in Jan 2010, there are still several R&D items needed before adopting SB2009 or its modification as the new baseline. Thus, we are planning to adopt the items in SB2009 one by one (rather than SB2009 as a whole) by early 2011. The major items to be revisited for re-baseline are

a) Accelerating gradient (This is not an SB2009 item but should be revisited for TDR)
b) Single tunnel (with HLRF options)
c) Reduction of number of bunches
d) Undulator scheme

We are planning to hold two workshops dedicated to these problems, one in September this year at KEK and the other in January 2011 at SLAC.

OTHER ISSUES

Collaboration with CLIC

CLIC (CERN Linear Collider) is another electron-positron linear collider project aiming at higher energies up to around 3TeV. Although the basic acceleration technology (normal-conducting two-beam acceleration) is completely different from ILC, there are many components which share the technology with ILC. The collaboration of the two big projects, ILC and CLIC, is desirable in view of the synergies and saving resources. Formal collaboration started in late 2007. By now several groups have been formed:

Positron source
Damping ring
Beam delivery system
Cost estimation
Conventional facility

In addition, `General Issues' group was formed recently for the discussion to identify the common issues regarding siting, technical issues and project implementation plan, and to identify the points of comparison between the two approaches to linear collider. The above groups are formed for accelerator issues but detector groups are also creating a collaboration group. The next GDE meeting scheduled in October in Geneva will be the first ILC-CLIC joint meeting.

Governance

To realize ILC political issues are also important in addition to the technical development. Discussion on the possible organization has launched among the management levels of ICFA, ILCSC, GDE and physics group. There are already a few groups in the world thinking of the governance problem and they are going to collaborate to reach a general consensus. There are several models of large organization such as CERN, ITER, Euro-XFEL, etc. ILC shares similar problems with these organizations but also has its own speciality. The budget model including the in-kind contribution and the common fund will be one of the most important issues. The site selection procedure is also being discussed. A general consensus should be reached by the time of completion of TDR.

BEYOND TDR

TDR is not the end of the technical works. There will still remain several technical issues after completion of TDR in 2012 such as

- Possible remaining R&D issues including RF distribution (KCS and DRFS) and positron source (flux concentrator, etc)
- System tests, most importantly the string test S2
- Engineering design
- Industrialization for cost reduction and mass-production

And of course the project implementation plan including governance and siting will become more and more important.

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