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ILC Reference Design Report – Accelerator Executive Summary

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The International Linear Collider (ILC) is a 200-500 GeV center-of-mass high-luminosity linear electron-positron collider, based on 1.3 GHz superconducting radio-frequency (SCRF) accelerating cavities. The use of the SCRF technology was recommended by the International Technology Recommendation Panel (ITRP) in August 2004 [1], and shortly thereafter endorsed by the International Committee for Future Accelerators (ICFA). In an unprecedented milestone in high-energy physics, the many institutes around the world involved in linear collider R&D united in a common effort to produce a global design for the ILC. In November 2004, the 1st International Linear Collider Workshop was held at KEK, Tsukuba, Japan. The workshop was attended by some 200 accelerator physicists from around the world, and paved the way for the 2nd ILC Workshop in August 2005, held at Snowmass, Colorado, USA, where the ILC Global Design Effort (GDE) was officially formed. The GDE membership reflects the global nature of the collaboration, with accelerator experts from all three regions (Americas, Asia and Europe). The first major goal of the GDE was to define the basic parameters and layout of the machine – the Baseline Configuration. This was achieved at the first GDE meeting held at INFN, Frascati, Italy in December 2005 with the creation of the Baseline Configuration Document (BCD). During the next 14 months, the BCD was used as the basis for the detailed design work and value estimate (as described in section 1.6) culminating in the completion of the second major milestone, the publication of the draft ILC Reference Design Report (RDR).

The technical design and cost estimate for the ILC is based on two decades of world-wide Linear Collider R&D, beginning with the construction and operation of the SLAC Linear Collider (SLC). The SLC is acknowledged as a proof-of-principle machine for the linear collider concept. The ILC SCRF linac technology was pioneered by the TESLA collaboration*, culminating in a proposal for a 500 GeV center-of-mass linear collider in 2001 [2]. The concurrent (competing) design work on a normal conducting collider (NLC with X-band [3] and GLC with X- or C-Band [4]), has advanced the design concepts for the ILC injectors, Damping Rings (DR) and Beam Delivery System (BDS), as well as addressing overall operations, machine protection and availability issues. The X- and C-band R&D has led to concepts for the RF power source that may eventually produce either cost and/or performance benefits. Finally, the European XFEL [5] to be constructed at DESY, Hamburg, Germany, will make use of the TESLA linac technology, and represents a significant on-going R&D effort which remains of great benefit for the ILC.

The current ILC baseline assumes an accelerating gradient of 31.5 MV/m to achieve a centre-of-mass energy of 500 GeV. The high luminosity requires the use of high power and small emittance beams. The choice of 1.3 GHz SCRF is well suited to the requirements, primarily because the very low power loss in the SCRF cavity walls allows the use of long RF pulses, relaxing the requirements on the peak-power generation, and ultimately leading to high wall-plug to beam transfer efficiency.

* Now known as the TESLA Technology Collaboration (TTC); see http://tesla.desy.de.

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The primary cost drivers are the SCRF Main Linac technology and the Conventional Facilities (including civil engineering). The choice of gradient is a key cost and performance parameter, since it dictates the length of the linacs, while the cavity *quality factor* (Q_0) relates to the required cryogenic cooling power. The achievement of 31.5 MV/m as the baseline average operational accelerating gradient – requiring a minimum performance of 35 MV/m during cavity mass-production acceptance testing – represents the primary challenge to the global ILC R&D

With the completion of the RDR, the GDE will shortly begin an engineering design study, closely coupled with a prioritized R&D program. The goal is to produce an Engineering Design Report (EDR) demonstrating readiness for construction by 2010, followed by start of construction in 2012. A seven-year construction phase is currently assumed, allowing operations to begin in 2019. This is consistent with a technically driven schedule for this international project.

Figure 1: A TESLA nine-cell 1.3 GHz superconducting niobium cavity.

1 Superconducting RF

The primary cost driver for the ILC is the superconducting RF technology used for the Main Linacs, bunch compressors and injector linacs. In 1992, the TESLA Collaboration began R&D on 1.3 GHz technology with a goal of reducing the cost per MeV by a factor of 20 over the then state-of-the-art SCRF installation (CEBAF). This was achieved by increasing the operating accelerating gradient by a factor of five from ~5 MV/m to ~25 MV/m, and reducing the cost per meter of the complete accelerating module by a factor of four for large-scale production.

The TESLA cavity R&D was based on extensive existing experience from CEBAF (TJNAF), CERN, Cornell University, KEK, Saclay and Wuppertal. The basic element of the technology is a nine-cell 1.3 GHz niobium cavity, shown in Figure 1. Approximately 160 of these cavities have been fabricated by industry as part of the on-going R&D program at DESY; some 17,000 will be needed for the ILC.

A single cavity is approximately 1 m long. The cavities must be operated at 2 K to achieve their performance. Eight cavities are mounted together in a *string* and assembled into a common low-temperature cryostat or *cryomodule* (Figure 2), the design of which is already in the third generation. Ten cryomodules have been produced to-date, five of which are currently installed in the in the VUV free-electron laser (FLASH) † at DESY, where they are routinely operated. DESY is currently preparing

† Originally known as the TESLA Test Facility (TTF).

for the construction of the European XFEL facility, which will have a ~20 GeV superconducting linac containing 116 cryomodules.

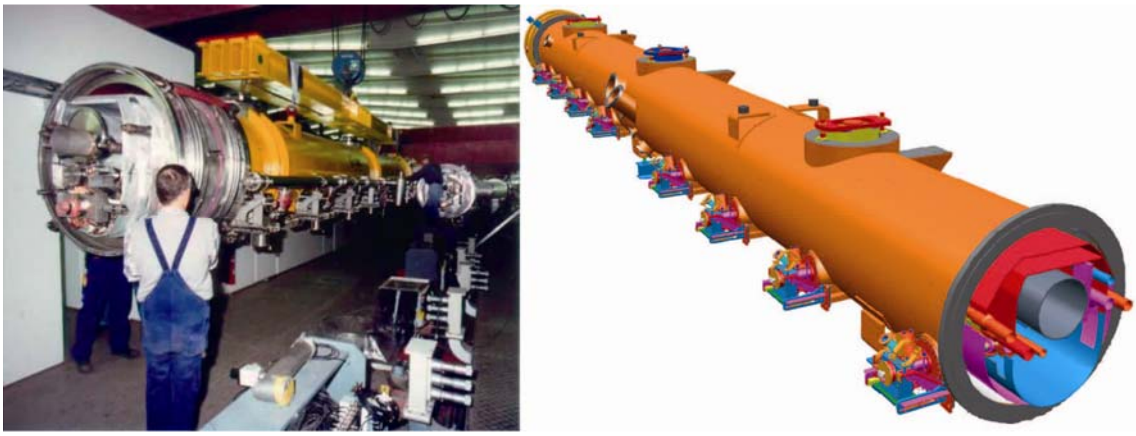

Figure 2: SCRF Cryomodules. Left: an 8 cavity TESLA cryomodule is installed into the FLASH linac at DESY. Right: design for the 4th generation ILC prototype cryomodule, due to be constructed at Fermilab National Laboratory.

The ILC community has set an aggressive goal of routinely achieving[‡] 35 MV/m in nine-cell cavities, with a minimum production yield of 80%. Several cavities have already achieved these and higher gradients (see Figure 3), demonstrating proof of principle. Records of over 50 MV/m have been achieved in single-cell cavities at KEK and Cornell [7]. However, achieving the desired production yield at the mass-production levels (~17,000 cavities) required for nine-cell cavities remains a challenge.

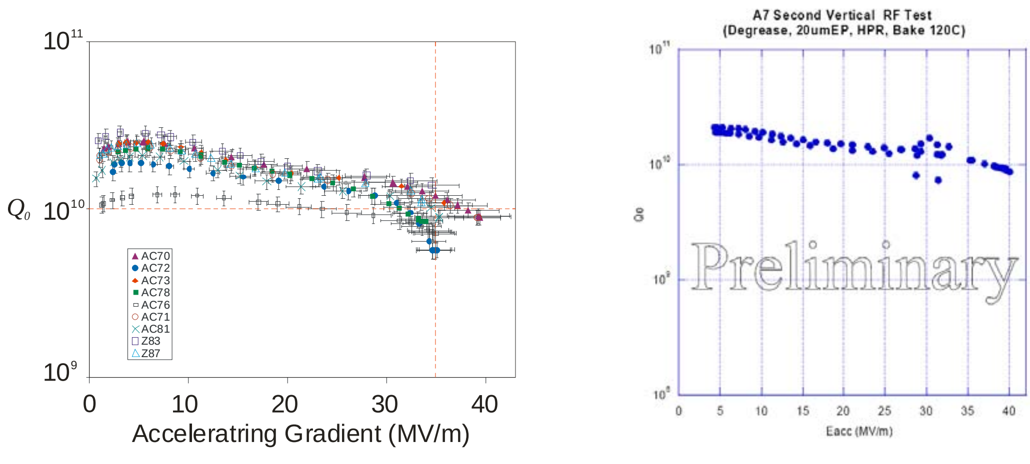

Figure 3: High-performance nine-cell cavities. Left: Examples of DESY nine-cell cavities achieving ≥35 MV/m. Right: Recent result from JLAB of nine-cell cavity achieving ~40 MV/m.

‡ Acceptance test.

Figure 4: Clean room environments are mandatory. Left: the assembly of eight nine-cell TESLA cavities into a cryomodule string at DESY. Right: an ICHIRO nine-cell cavity is prepared for initial tests at the Superconducting RF Test Facility (STF) at KEK.

The key to high-gradient performance is the ultra-clean and defect-free inner surface of the cavity. Both cavity preparation and assembly into cavity strings for the cryomodules must be performed in clean-room environments (Figure 4). The best cavities have been achieved using *electropolishing*, a common industry practice which was first developed for use with superconducting cavities by CERN and KEK. Over the last few years, research at Cornell, DESY, KEK and TJNAF has led to an agreed standard procedure for cavity preparation, depicted in Figure 5. The focus of the R&D is now to optimize the process to guarantee the required yield. The ILC SCRF community has developed an internationally agreed-upon plan to address the priority issues.

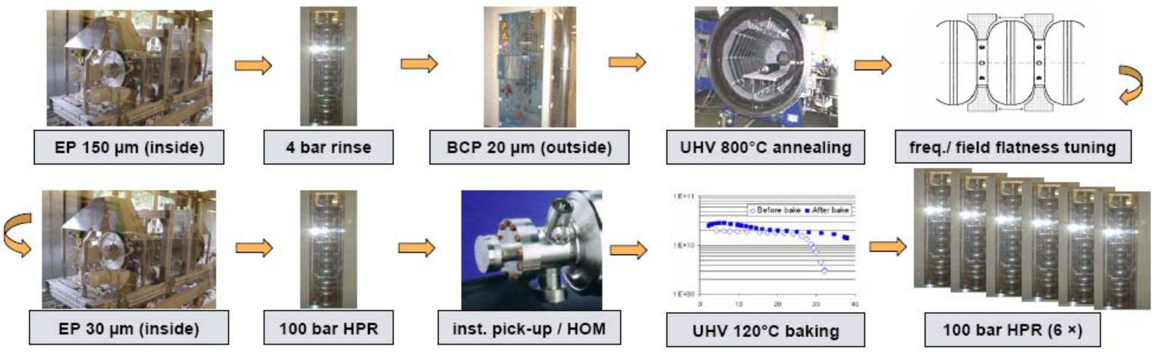

Figure 5: Birth of a nine-cell cavity: basic steps in surface treatment needed to achieve high-performance superconducting cavities.
(EP = electropolishing; HPR = high-pressure rinsing.)

The high-gradient SCRF R&D required for ILC is expected to ramp-up world-wide over the next years. The U.S. is currently investing in new infrastructure for nine-cell cavity preparation and string and cryomodule assembly. These efforts are centered at Fermilab (ILC Test Accelerator, or ILCTA), together with ANL, Cornell University, SLAC and TJNAF. In Japan, KEK continues to ramp up its Superconducting RF Test Facility (STF). In Europe, the focus of R&D at DESY has shifted to industrial preparation for construction of the XFEL. There is continued R&D to support the high-gradient program, as well as other critical ILC-related R&D such as high-power RF couplers (LAL, Orsay, France) and cavity tuners (CEA Saclay, France; INFN Milan, Italy).

The quest for high-gradient and affordable SCRF technology for high-energy physics has revolutionized accelerator applications. In addition to the European XFEL, many linac-based projects utilizing SCRF technology are being developed, including 4th-generation light sources such as single-pass FELs and energy-recovery linacs, and the Spallation Neutron Source (SNS) in Oak Ridge, Tennessee. For the large majority of new accelerator-based projects, SCRF has become the technology of choice.

2 The ILC Baseline Design

The overall system design has been chosen to realize the physics requirements with a maximum CM energy of 500 GeV and a peak luminosity of 2×10^{34} cm^{-2}s^{-1}. Figure 6 shows a schematic view of the overall layout of the ILC, indicating the location of the major sub-systems:

- A polarized electron source based on a photocathode DC gun.
- An undulator-based positron source, driven by a 150 GeV electron beam.
- 5 GeV electron and positron damping rings (DR) with a circumference of 6.7 km, housed in a common tunnel at the center of the ILC complex.
- Beam transport from the damping rings to the main linacs, followed by a two-stage bunch compressor system prior to injection into the main linac.
- Two 11 km long main linacs, utilizing 1.3 GHz SCRF cavities, operating at an average gradient of 31.5 MV/m, with an RF pulse length of 1.6 ms.
- A 4.5 km long Beam Delivery System (BDS), which brings the two beams into collision with a 14 mrad crossing angle, at a single interaction point which can be shared by two detectors.

The total foot-print is ~31 km. The electron source, the damping rings, and the positron auxiliary (‘keep-alive’) source are centrally located around the interaction region (IR). The plane of the damping rings is elevated by ~10 m above that of the BDS to avoid interference.

To upgrade the machine to E_{cms} =1 TeV, the linacs and the beam transport lines from the damping rings would be extended by another ~11 km each. Certain components in the beam delivery system would also need to be replaced.

2.1 *Beam Parameters*

The nominal beam parameter set in Table 1, corresponding to the design luminosity of 2×10^{34} cm^{-2}s^{-1} at E_{cms} = 500 GeV, has been chosen to meet known accelerator physics and technology challenges throughout the whole accelerator complex. Examples of such challenges are:

- beam instability and kicker hardware constraints in the damping rings;
- beam current, beam power, and pulse length limitations in the main linacs;
- emittance preservation requirements, in the main linacs and the beam delivery system;
- background control and kink instability issues in the interaction region.

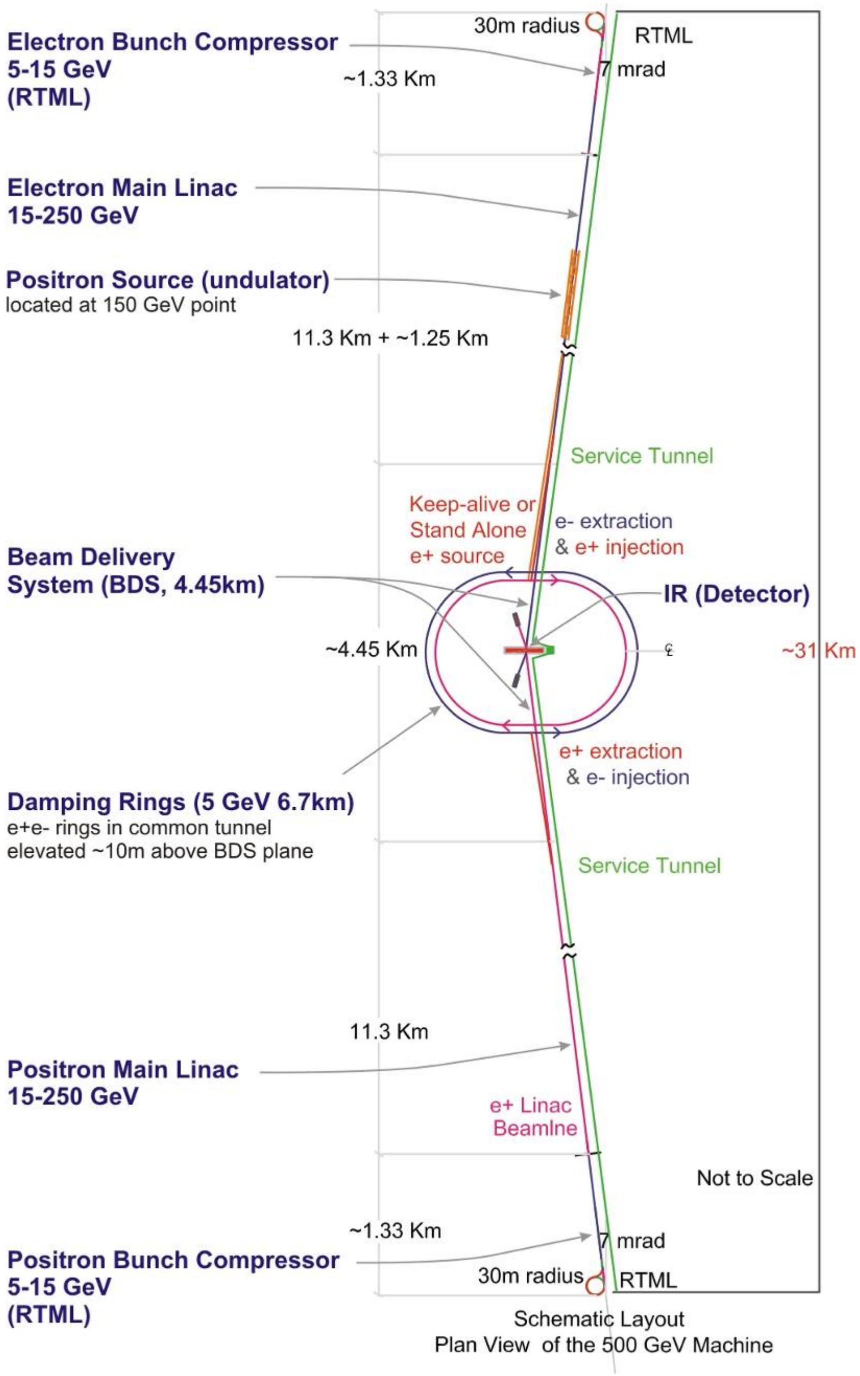

Figure 6: Schematic layout of the ILC complex for 500 GeV CM

Nearly all high-energy physics accelerators have shown unanticipated difficulties in reaching their design luminosity. The ILC design specifies that each subsystem support a range of beam parameters. The resulting flexibility in operating parameters will allow identified problems in one area to be compensated for in another. The nominal IP beam parameters and design ranges are presented in Table

Table 1: Basic design parameters for the ILC

Center-of-mass energy range	200–500	GeV
Peak luminosity[1]	2×10^{34}	$cm^{-2}s^{-1}$
Beam current	9.0	mA
Pulse rate	5.0	Hz
Pulse length (beam)	~1	ms
Accelerating gradient[a]	31.5	MV/m
RF pulse length	1.6	ms
Beam power (per beam)[a]	10.8	MW
Total AC Power consumption[a]	230	MW

a) at 500 GeV center-of-mass energy

Table 2: Nominal and design range of beam parameters at the IP. The min. and max. columns do not represent consistent sets of parameters, but only indicate the span of the design range for each parameter. (Nominal vertical emittance assumes a 100% emittance dilution budget from the damping ring to the IP.)

	min.	***nominal***	***max.***	
Bunch population	1	2	2	$\times10^{10}$
Number of bunches	1260	2670	5340	
Linac bunch interval	180	369	500	ns
RMS bunch length at IP	200	300	500	μm
Normalized horizontal emittance at IP	10	10	12	mm·mrad
Normalized vertical emittance at IP	0.02	0.04	0.08	mm·mrad
Horizontal beta function at IP	10	20	20	mm
Vertical beta function at IP	0.2	0.4	0.6	mm
RMS horizontal beam size at IP	474	640	640	nm
RMS vertical beam size at IP	3.5	5.7	9.9	nm
Vertical disruption parameter	14	19.4	26.1	
Fractional RMS energy loss to beamstrahlung	1.7	2.4	5.5	%

2.2 *Electron Source*

Functional requirements

The ILC polarized electron source must:

- generate the required bunch train of polarized electrons (>80% polarization)
- capture and accelerate the beam to 5 GeV;
- transport the beam to the electron damping ring with minimal beam loss, and perform an energy compression and spin rotation prior to injection.

System Description

The polarized electron source is located on the positron linac side of the damping rings. The beam is produced by a laser illuminating a photocathode in a DC gun. Two independent laser and gun systems provide redundancy. Normal-conducting structures are used for bunching and pre-acceleration to 76 MeV, after which the beam is accelerated to 5 GeV in a superconducting linac. Before injection into the damping ring, superconducting solenoids rotate the spin vector into the vertical, and a separate superconducting RF structure is used for energy compression. The layout of the polarized electron source is shown in Figure 7.

Challenges

The SLC polarized electron source already meets the requirements for polarization, charge and lifetime. The primary challenge for the ILC electron source is the ~1 ms long bunch train, which demands a laser system beyond that used at any existing accelerator.

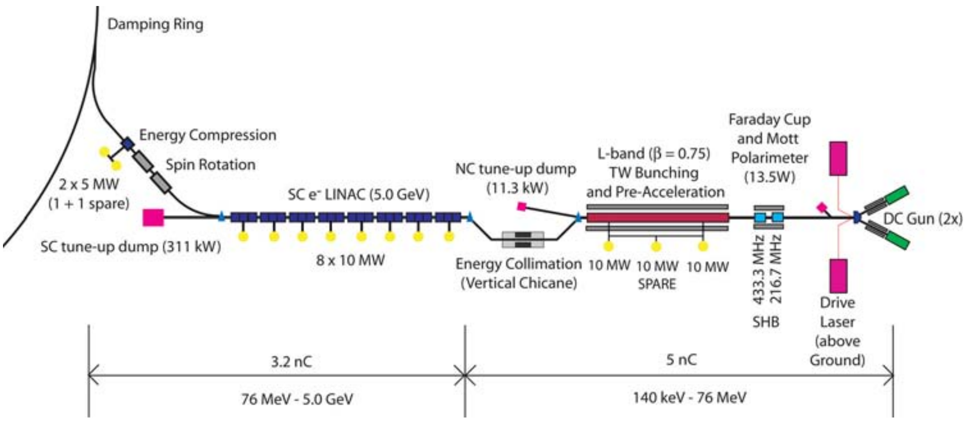

Figure 7: Schematic View of the Polarized Electron Source

2.3 *Positron Source*

Functional requirements

The positron source must perform several critical functions:

- generate a high-power multi-MeV photon production drive beam in a suitably short-period, high *K*-value helical undulator;
- produce the needed positron bunches in a metal target that can reliably deal with the beam power and induced radioactivity;
- capture and accelerate the beam to 5 GeV;
- transport the beam to the positron damping ring with minimal beam loss, and perform an energy compression and spin rotation prior to injection.

System Description

The major elements of the ILC positron source are shown in Figure 8. The source uses photoproduction to generate positrons. After acceleration to 150 GeV, the electron beam is diverted into an offset beamline, transported through a 150-meter helical undulator, and returned to the electron linac. The high-energy (~10 MeV) photons from the undulator are directed onto a rotating 0.4 radiation-length Ti-alloy target ~500 meters downstream, producing a beam of electron and positron pairs. This beam is then matched using an optical-matching device into a normal conducting (NC) L-band RF and solenoidal-focusing capture system and accelerated to 125 MeV. The electrons and remaining photons are separated from the positrons and dumped. The positrons are accelerated to 400 MeV in a NC L-band linac with solenoidal focusing. The beam is transported ~5 km through the rest of the electron main linac tunnel, brought to the central injector complex, and accelerated to 5 GeV using superconducting L-band RF. Before injection into the damping ring, superconducting solenoids rotate the spin vector into the vertical, and a separate superconducting RF structure is used for energy compression.

The baseline design is for unpolarized positrons, although the beam has a polarization of 30%, and beamline space has been reserved for an eventual upgrade to 60% polarization.

To allow commissioning and tuning of the positron systems while the high-energy electron beam is not available, a low-intensity auxiliary (or “keep-alive”) positron source is provided. This is a conventional positron source, which uses a 500 MeV electron beam impinging on a heavy-metal target to produce ~10% of the nominal positron beam. The keep-alive and primary sources use the same linac to accelerate from 400 MeV to 5 GeV.

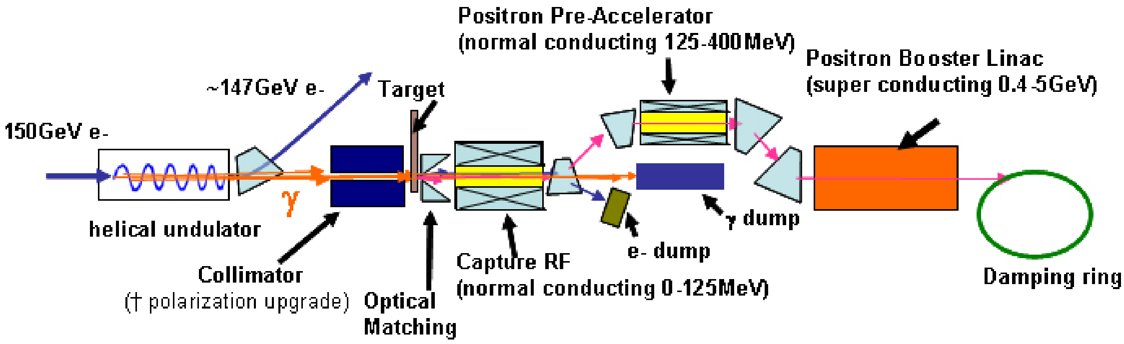

Figure 8: Overall Layout of the Positron Source.

The most challenging elements of the positron source are:

- the 150 m long superconducting helical undulator, which has a period of 1.15 cm and a *K*-value of 0.92, and a 6 mm inner diameter vacuum chamber;
- the Ti-alloy target, which is a cylindrical wheel 1.4 cm thick and 1 m in diameter, which must rotate at 100 m/s in vacuum to limit damage by the photon beam;
- the normal-conducting RF system which captures the positron beam, which must sustain high accelerator gradients during millisecond-long pulses in a strong magnetic field, while providing adequate cooling in spite of high RF and particle-loss heating.

The target and capture sections are also high-radiation areas which present remote handing challenges.

2.4 *Damping Rings*

Functional requirements

The damping rings must perform four critical functions:

- accept e^- and e^+ beams with large transverse and longitudinal emittances and damp to the low emittance beam required for luminosity production (by five orders of magnitude for the positron vertical emittance), within the 200 ms between machine pulses.
- inject and extract individual bunches without affecting the emittance or stability of the remaining stored bunches;
- damp incoming beam jitter (transverse and longitudinal) and provide highly stable beams for downstream systems;
- delay bunches from the source to allow feed-forward systems to compensate for pulse-to-pulse variations in parameters such as the bunch charge.

System Description

The ILC damping rings include one electron and one positron ring, each 6.7 km long, operating at a beam energy of 5 GeV. The two rings are housed in a single tunnel near the center of the site, with one ring positioned directly above the other. The plane of the DR tunnel is located ~10 m higher than that of the beam delivery system. This elevation difference gives adequate shielding to allow operation of the injector system while other systems are open to human access.

The damping ring lattice is divided into six arcs and six straight sections. The arcs are composed of TME cells; the straight sections use a FODO lattice. Four of the straight sections contain the RF systems and the superconducting wigglers. The remaining two sections are used for beam injection and extraction. Except for the wigglers, all of the magnets in the ring, are normal-conducting. Approximately 200 m of superferric wigglers are used in each damping ring. The wigglers are 2.5 m long devices, operating at 4.5K, with a peak field of 1.67 T.

The superconducting RF system is operated CW at 650 MHz, and provides 24 MV. The frequency is chosen to be half the linac RF frequency to easily accommodate different bunch patterns. The single-cell cavities operate at 4.5 K and are housed in eighteen 3.5 m long cryomodules. Although a number of 500 MHz CW RF systems are currently in operation, development work is required for this 650 MHz system, both for cavities and power sources.

The momentum compaction of the lattice is relatively large, which helps to maintain single bunch stability, but requires a relatively high RF voltage to achieve the design RMS bunch length (9 mm). The dynamic aperture of the lattice is sufficient to allow the large emittance injected beam to be captured with minimal loss.

Challenges

The principal challenges in the damping ring are:

- Control of the electron cloud effect in the positron damping ring. This effect, which can cause instability, tune spread, and emittance growth, has been seen in a number of other rings and is relatively well understood. Simulations indicate that it can be controlled by proper surface treatment of the vacuum chamber to suppress secondary emission, and by the use of solenoids and clearing electrodes to suppress the buildup of the cloud.

- Control of the fast ion instability in the electron damping ring. This effect can be controlled by limiting the pressure in the electron damping ring to below 1 nTorr, and by the use of short gaps in the ring fill pattern.
- Developing a very fast rise and fall time kicker for single bunch injection and extraction in the ring. For the most demanding region of the beam parameter range, the bunch spacing in the damping ring is ~3 ns, and the kicker must have a rise plus fall time no more than twice this. Short stripline kicker structures can achieve this, but the drive pulser technology still needs development.

2.5 *Ring to Main Linac (RTML)*

Functional requirements

The RTML must perform several critical functions for each beam:

- transport the beam from the damping ring to the upstream end of the linac;
- collimate the beam halo generated in the damping ring;
- rotate the polarization from the vertical to any arbitrary angle required at the IP;
- compress the long Damping Ring bunch length by a factor of 30~45 to provide the short bunches required by the Main Linac and the IP;

System Description

The layout of the RTML is identical for both electrons and positrons, and is shown in Figure 9. The RTML consists of the following subsystems:

- ~15 km long 5 GeV transport line;
- betatron and energy collimation systems;
- 180° turn-around, which enables feed-forward beam stabilization;
- spin rotator to orient the beam polarization to the desired direction;
- 2-stage bunch compressor to compress the beam bunch length from several millimeters to a few hundred microns as required at the IP.

The bunch compressor includes acceleration from 5 GeV to 13-15 GeV in order to limit the increase in fractional energy spread associated with bunch compression.

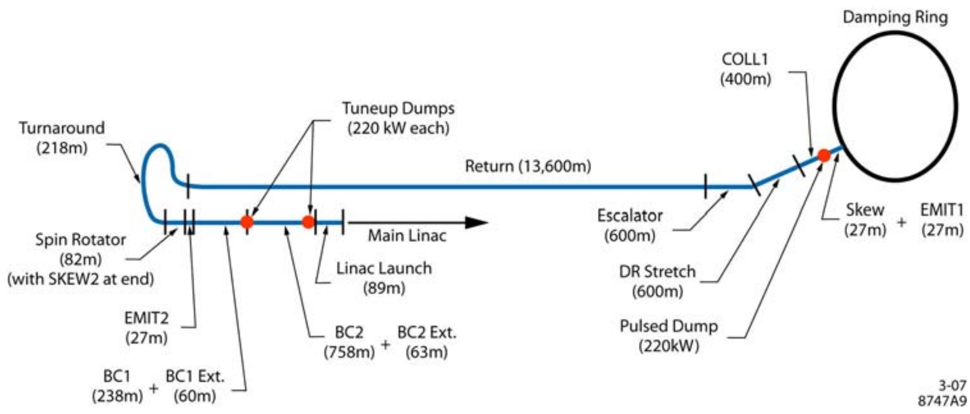

Figure 9: Schematic of the RTML

Challenges

The principal challenges in the RTML are:

- Control of emittance growth due to static misalignments, resulting in dispersion and coupling. Simulations indicate that the baseline design for beam-based alignment can limit the emittance growth to tolerable levels.
- Suppression of phase and amplitude jitter in the bunch compressor RF, which can lead to timing errors at the IP. RMS phase jitter of 0.24° between the electron and positron RF systems results in a 2% loss of luminosity. Feedback loops in the bunch compressor low-level RF system should be able to limit the phase jitter to this level.

2.6 *Main Linacs*

Functional requirements

The two main linacs accelerate the electron and positron beams from their injected energy of 15 GeV to the final beam energy of 250 GeV, over a combined length of 23 km. The main linacs must:

- accelerate the beam while preserving the small bunch emittances, which requires precise orbit control based on data from high resolution beam position monitors, and also requires control of higher-order modes in the accelerating cavities;
- maintain the beam energy spread within the design requirement of ~0.1% at the IP;
- not introduce significant transverse or longitudinal jitter, which could cause the beams to miss at the collision point.

System Description

The ILC Main Linacs accelerate the beam from 15 GeV to a maximum energy of 250 GeV at an average accelerating gradient of 31.5 MV/m. The linacs are composed of RF units, each of which are formed by three contiguous SCRF cryomodules containing

26 nine-cell cavities. The layout of one unit is illustrated in Figure 10. The positron linac contains 278 RF units, and the electron linac has 282 RF units§.

Each RF unit has a stand-alone RF source, which includes a conventional pulse-transformer type high-voltage (120 kV) modulator, a 10 MW multi-beam klystron, and a waveguide system that distributes the RF power to the cavities (see Figure 10). It also includes the low-level RF (LLRF) system to regulate the cavity field levels, interlock systems to protect the source components, and the power supplies and support electronics associated with the operation of the source.

The cryomodule design is a modification of the Type-3 version developed and used at DESY. Within the cryomodules, a 300 mm diameter helium gas return pipe serves as a strongback to support the cavities and other beam line components. The middle cryomodule in each RF unit contains a quad package that includes a superconducting quadrupole magnet at the center, a cavity BPM, and superconducting horizontal and vertical corrector magnets. The quadrupoles establish the main linac magnetic lattice, which is a weak focusing FODO optics with an average beta function of ~80 m. All cryomodules are 12.652 m long, so the active length to actual length ratio in a nine-cavity cryomodule is 73.8%. Every cryomodule also contains a 300 mm long high-order mode beam absorber assembly that removes energy through the 40-80 K cooling system from beam-induced higher-order modes above the cavity cutoff frequency.

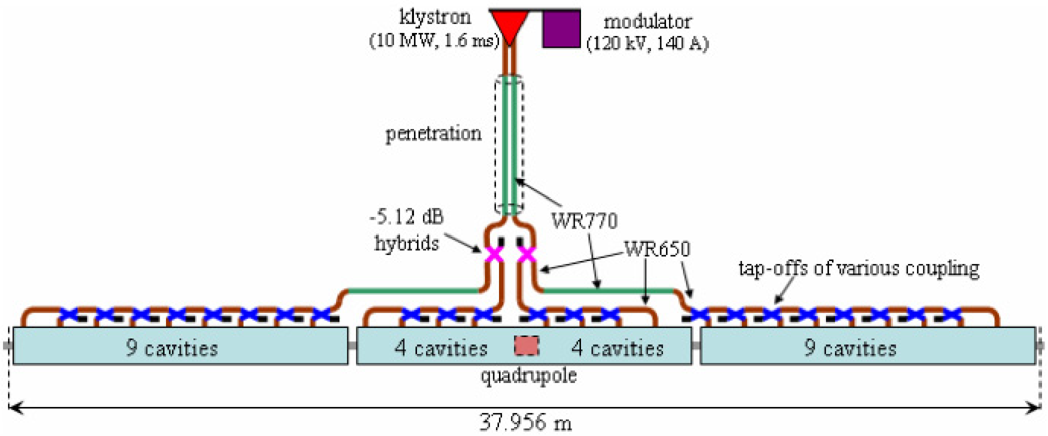

Figure 10: RF unit layout.

To operate the cavities at 2 K, they are immersed in a saturated He II bath, and helium gas-cooled shields intercept thermal radiation and thermal conduction at 5-8 K and at 40-80 K. The estimated static and dynamic cryogenic heat loads per RF unit at 2 K are 5.1 W and 29 W, respectively. Liquid helium for the main linacs and the RTML is supplied from 10 large cryogenic plants, each of which has an installed equivalent cooling power of ~20 kW at 4.5 K. The main linacs follow the average Earth's curvature to simplify the liquid helium transport.

§ Approximate 3 GeV of extra energy is required in the electron linac to compensate for positron production.

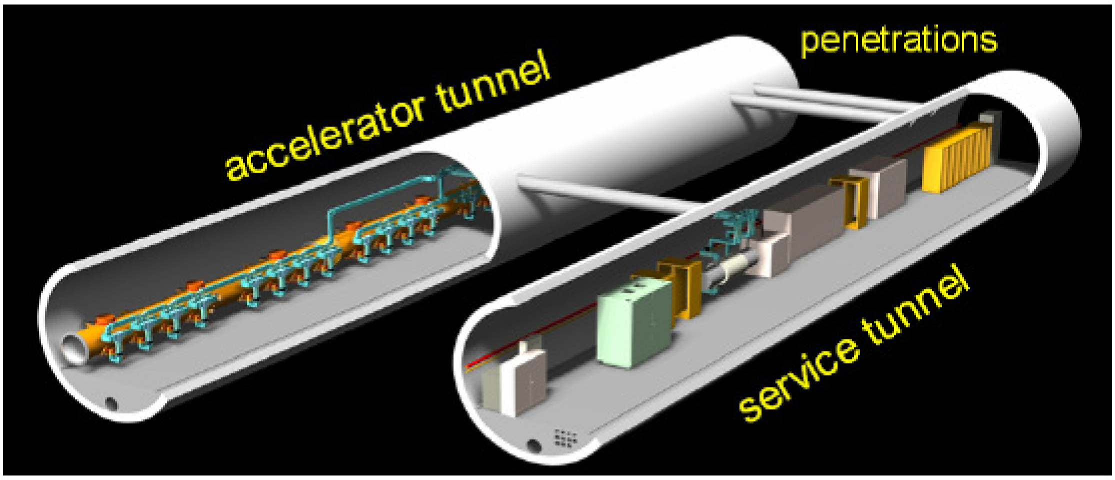

Figure 11: Cutaway view of the linac dual-tunnel configuration.

The Main Linac components are housed in two tunnels, an accelerator tunnel and a service tunnel, each of which has an interior diameter of 4.5 meters. To facilitate maintenance and limit radiation exposure, the RF source is housed mainly in the service tunnel as illustrated in Figure 11.

The tunnels are typically hundreds of meters underground and are connected to the surface through vertical shafts[**]. Each of the main linacs includes three shafts, roughly 5 km apart as dictated by the cryogenic system. The upstream shafts in each linac have diameters of 14 m to accommodate lowering cryomodules horizontally, and the downstream shaft in each linac is 9 m in diameter, which is the minimum size required to accommodate tunnel boring machines. At the base of each shaft is a 14,100 cubic meter cavern for staging installation and housing utilities and parts of the cryoplant, most of which are located on the surface.

Challenges

The principal challenges in the main linac are:

- Realizing the design average accelerating gradient of 31.5 MV/m. This operating gradient is higher than that typically achievable today and assumes further progress will be made during the next few years in the aggressive program that is being pursued to improve cavity performance.
- Control of emittance growth due to static misalignments, resulting in dispersion and coupling. Beam-based alignment techniques should be able to limit the single-bunch emittance growth. Long-range multibunch effects are mitigated via HOM damping ports on the cavities, HOM absorbers at the quadrupoles, and HOM detuning. Coupling from mode-rotation HOMs is limited by splitting the horizontal and vertical betatron tunes.
- Control of the beam energy spread. The LLRF system monitors the vector sum of the fields in the 26 cavities of each RF unit and makes adjustments to flatten the energy gain along the bunch train and maintain the beam-to-RF phase constant. Experience from FLASH and simulations indicate that the baseline system should perform to specifications.

[**] Except for the Asian sample site: see Section 1.4.

2.7 *Beam Delivery System*

Functional requirements

The ILC Beam Delivery System (BDS) is responsible for transporting the e^+e^- beams from the exit of the high energy linacs, focusing them to the sizes required to meet the ILC luminosity goals, bringing them into collision, and then transporting the spent beams to the main beam dumps. In addition, the BDS must perform several other critical functions:

- measure the linac beam and match it into the final focus;
- protect the beamline and detector against mis-steered beams from the main linacs;
- remove any large amplitude particles (beam-halo) from the linac to minimize background in the detectors;
- measure and monitor the key physics parameters such as energy and polarization before and after the collisions.

System Description

The layout of the beam delivery system is shown in Figure 12. There is a single collision point with a 14 mrad total crossing angle. The 14 mrad geometry provides space for separate extraction lines but requires crab cavities to rotate the bunches in the horizontal plane for effective head-on collisions. There are two detectors in a common interaction region (IR) hall in a so-called "push-pull" configuration. The detectors are pre-assembled on the surface and then lowered into the IR hall when the hall is ready for occupancy.

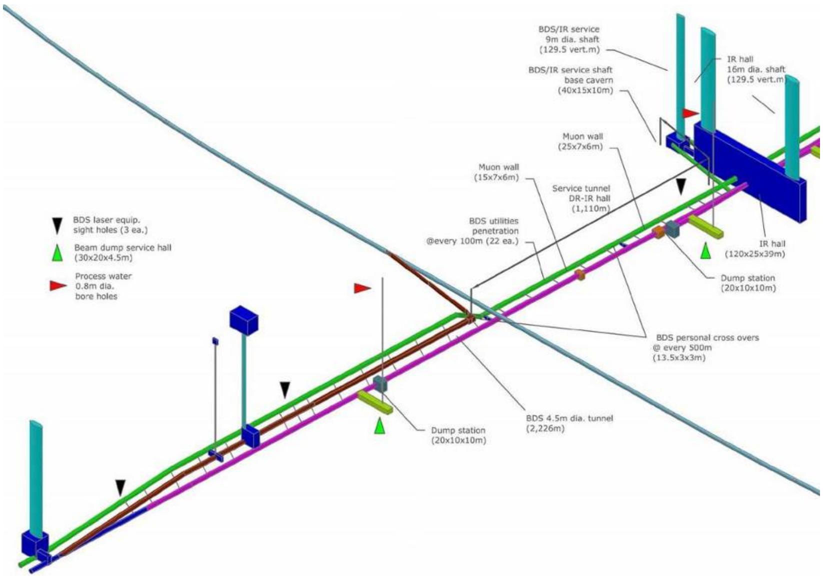

Figure 12: BDS layout, beam and service tunnels (shown in magenta and green), shafts, experimental hall. The line crossing the BDS beamline at right angles is the damping ring, located 10 m above the BDS tunnels.

The BDS is designed for 500 GeV center-of-mass energy but can be upgraded to 1 TeV with additional magnets.

The main subsystems of the beam delivery, starting from the exit of the main linacs, are:

- A section containing post-linac emittance measurement and matching (correction) sections, trajectory feedback, polarimetry and energy diagnostics.
- A fast pulsed extraction system used to extract beams in case of a fault, or to dump the beam when not needed at the IP.
- A collimation section which removes beam halo particles that would otherwise generate unacceptable background in the detector, and also contains magnetized iron shielding to deflect muons.
- The final focus (FF) which uses strong compact superconducting quadrupoles to focus the beam at the IP, with sextupoles providing local chromaticity correction.
- The interaction region, containing the experimental detectors. The final focus quadrupoles closest to the IP are integrated into the detector to facilitate detector “push-pull”.
- The extraction line, which has a large enough bandwidth to cleanly transport the heavily disrupted beam to a high-powered water-cooled dump. The extraction line also contains important polarization and energy diagnostics.

Challenges

The principal challenges in the beam delivery system are:

- Tight tolerances on magnet motion (down to tens of nanometers), which make the use of fast beam-based feedbacks systems mandatory, and may well require mechanical stabilization of critical components (e.g. final doublets).
- Uncorrelated relative phase jitter between the crab cavity systems, which must be limited to the level of tens of femtoseconds.
- Control of emittance growth due to static misalignments, which requires beam-based alignment and tuning techniques similar to the RTML.
- Control of backgrounds at the IP via careful tuning and optimization of the collimation systems and the use of the tail-folding octupoles.
- Clean extraction of the high-powered disrupted beam to the dump. Simulations indicate that the current design is adequate over the full range of beam parameters.

3 Sample Sites

CFS (Conventional Facilities and Siting) is responsible for civil engineering, power distribution, water cooling and air conditioning systems. The value estimate (see Section 5 below) for the CFS is approximately 38% of the total estimated project value.

In the absence of a single agreed-upon location for the ILC, a sample site in each region was developed. Each site was designed to support the ILC baseline design described in Section 1.3. Although many of the basic requirements are identical, differences in geology, topography and local standards and regulations lead to different construction approaches, resulting in a slight variance in value estimates across the three regions. Although many aspects of the CFS (and indeed machine design) will ultimately depend on the specific host site chosen, the approach taken here is considered sufficient for the current design phase, while giving a good indication of the influence of site-specific issues on the project as a whole.

All three sites satisfied a matrix of criteria agreed upon by the regional CFS groups early in the RDR process, including the mandatory requirement that all sites can support the extension to the 1 TeV center-of-mass machine.

The three sample sites have the following characteristics:

- The Americas sample site lies in Northern Illinois near the existing Fermilab. The site provides a range of locations to position the ILC in a north-south orientation. The site chosen has approximately one-quarter of the machine on the Fermilab site. The surface is primarily flat. The long tunnels are bored in a contiguous dolomite rock strata (‘Galena Platteville’), at a typical depth of 30-100 m below the surface.
- The Asian site has been chosen from several possible ILC candidate sites in Japan. The sample site has a uniform terrain located along a mountain range, with a tunnel depth ranging from 40 m to 600 m. The chosen geology is uniform granite highly suited to modern tunneling methods. One specific difference for the Asian site is the use of long sloping access tunnels instead of vertical shafts, the exception being the experimental hall at the Interaction Region, which is accessed via two 112 m deep vertical shafts. The sloping access tunnels take advantage of the mountainous location of the sample site.
- The European site is located at CERN, Geneva, Switzerland, and runs parallel to the Jura mountain range, close to the CERN site. The majority of the machine is located in the ‘Molasse’ (a local impermeable sedimentary rock), at a typical depth of 370 m.

The elevations of the three sample sites are shown in Figure 13. The tunnels for all three sites would be predominantly constructed using Tunnel Boring Machines (TBM), at typical rates of 20–30 m per day. The Molasse of the European site near CERN requires a reinforced concrete lining for the entire tunnel length. The Asian site (granite) requires rock bolts and a 5 cm ‘shotcrete’ lining. The US site is expected to require a concrete lining for only approximately 20% of its length, with rock-bolts being sufficient for permanent structural support.

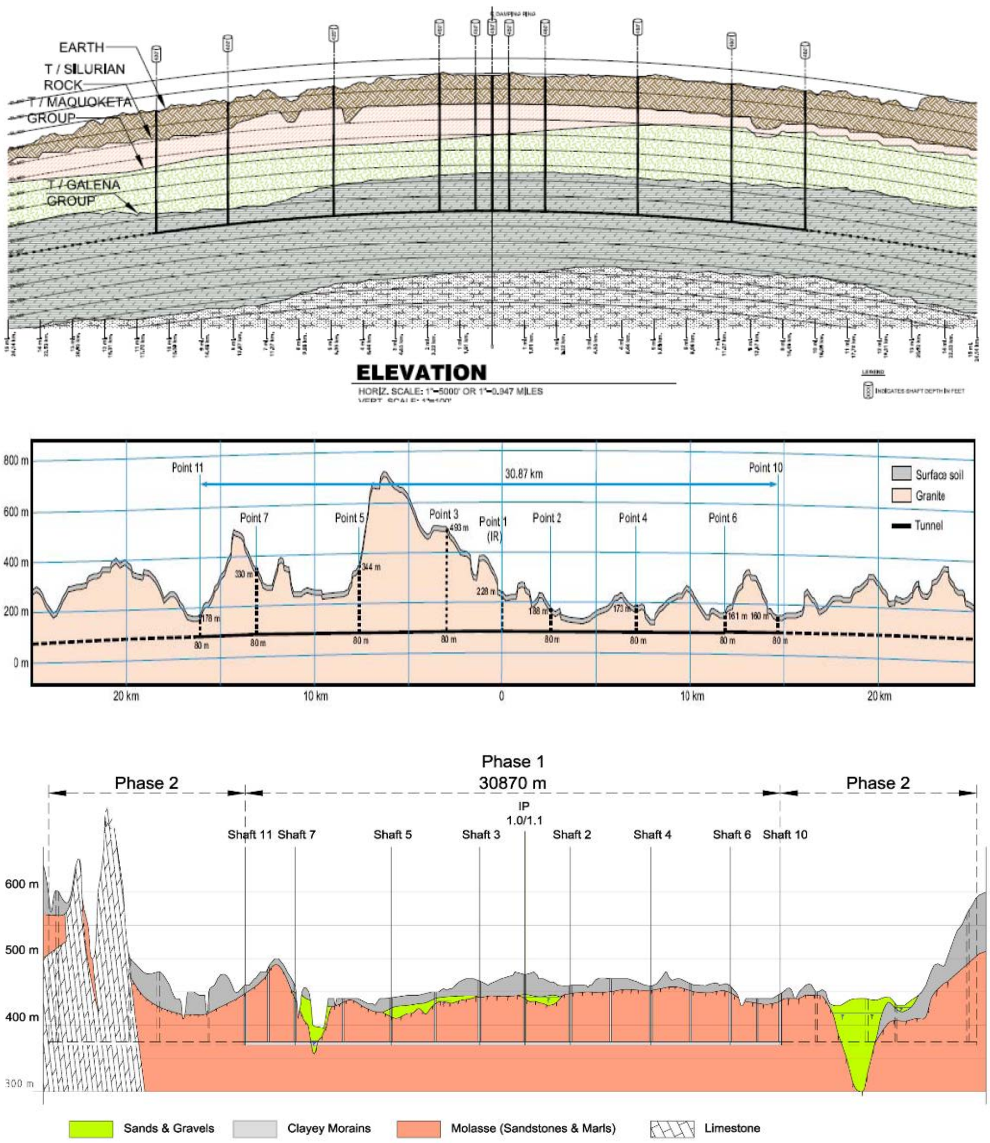

Figure 13: Geology and tunnel profiles for the three regional sites, showing the location of the major access shafts (tunnels for the Asian site). Top: the Americas site close to Fermilab. Middle: the Asian site. Bottom: the European site close to CERN.

A second European sample site near DESY, Hamburg, Germany, has also been developed. This site is significantly different from the three reported sites, both in geology and depth (~25 m deep), and requires further study.

In addition, the Joint Institute for Nuclear Research has submitted a proposal to site the ILC in the neighborhood of Dubna, Russian Federation.

The three sites reported in detail here are all ‘deep-tunnel’ solutions. The DESY and Dubna sites are examples of ‘shallow’ sites. A more complete study of shallow sites – shallow tunnel or cut-and-cover – will be made in the future as part of the Engineering and Design phase.

4 Value Estimate

A preliminary cost analysis has been performed for the ILC Reference Design. A primary goal of the estimate was to allow cost-to-performance optimization in the Reference Design, before entering into the engineering design phase. Over the past year, the component costs were estimated, various options compared and the design evolved through about ten significant cost-driven changes, resulting in a cost reduction of about 25%, while still maintaining the physics performance goals.

The ILC cost estimates have been performed using a "value" costing system, which provides basic agreed-to value costs for components in ILC Units[††], and an estimate of the *explicit* labor (in person hours) that is required to support the project. The estimates are based on making world-wide tenders in major industrialized nations, using the lowest reasonable price for the required quality. There are three classes of costs:

- site-specific costs, where a separate estimate was made in each of the three regions;
- conventional costs for items where there is global capability – here a single cost was determined;
- costs for specialized high-tech components (e.g. the SCRF linac technology), where industrial studies and engineering estimates were used.

The total estimated value for the shared ILC costs for the Reference Design is 4.87 Billion (ILC Units). An important outcome of the value costing has been to provide a sound basis for determining the relative value of the various components or work packages. This will enable equitable division of the commitments of the world-wide collaboration.

In addition, the site specific costs, which are related to the direct costs to provide the infrastructure required to site the machine, are estimated to be 1.78 Billion (ILC Units). These costs include the underground civil facilities, water and electricity distribution and buildings directly supporting ILC operations and construction on the surface. The costs were determined to be almost identical for the Americas, Asian, and European sample sites. It should be noted that the actual site-specific costs will depend on where the machine is constructed, and the facilities that already exist at that location.

Finally, the explicit labor required to support the construction project is estimated at 22 million person-hours; this includes administration and project management, installation and testing. This labor may be provided in different ways, with some being contracted and some coming from existing labor in collaborating institutions.

The ILC Reference Design cost estimates and the tools that have been developed will play a crucial role in the engineering design effort, both in terms of studying options for reducing costs or improving performance, and in guiding value engineering studies, as well as supporting the continued development of a prioritized R&D program.

The total estimated value cost for the ILC, defined by the Reference Design, including shared value costs, site specific costs and explicit labor, is comparable to other recent major international projects, e.g. ITER, and the CERN LHC when the cost of pre-existing facilities are taken into account. The GDE is confident that the overall scale of the project has been reliably estimated and that cost growth can be contained in the engineering phase, leading to a final project cost consistent with that determined at this early stage in the design.

[††] For this value estimate, 1 ILC Unit = 1 US 2007$ (= 0.83 Euro = 117 Yen).

5 R&D and the Engineering Design Phase

For the last year, the focus of the core GDE activity has been on producing the RDR and value estimate. In parallel, ILC R&D programs around the world have been ramping up to face the considerable challenges ahead. The GDE Global R&D Board – a group of twelve GDE members from the three regions – has evaluated existing programs, and has convened task forces of relevant experts to produce an internationally agreed-upon prioritized R&D plan for the critical items. The highest-priority task force (S0/S1) addresses the SCRF accelerating gradient:

- S0: high-gradient cavity – aiming to achieve 35 MV/m nine-cell cavity performance with an 80% production yield.
- S1: high-gradient cryomodule – the development of one or more high-gradient ILC cryomodules with an average operational gradient of 31.5 MV/m.

The S0/S1 task force has already produced focused and comprehensive R&D plans. Other task forces (S2: test linac; S3: Damping Ring; S4: Beam Delivery System, *etc.*) are in the process of either completing their reports, or just beginning their work.

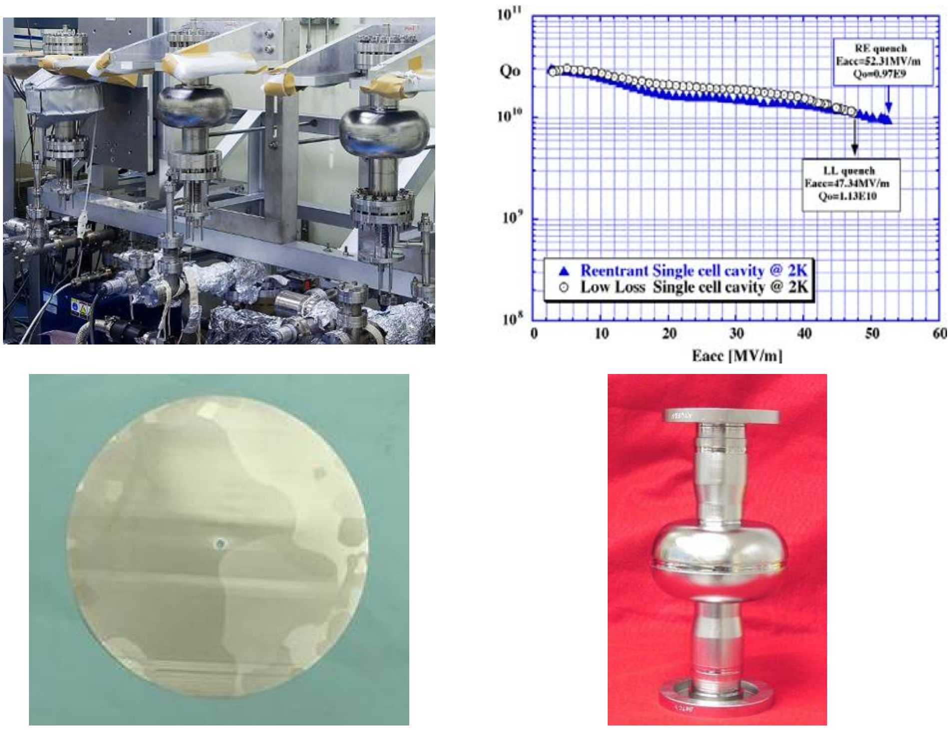

Figure 14: Cutting-edge SCRF R&D. top-left: ICHIRO single-cells being prepared for testing at KEK. Top right: world-record performance from novel shape single-cells (ICHIRO and Cornell's reentrant cavity). Bottom left: large-grain niobium disk (JLAB). Bottom-right: single-cell cavity produced from large-grain niobium material (JLAB).

For the cost- and performance-critical SCRF, the primary focus of S0/S1 remains the baseline choice, the relatively mature TESLA nine-cell elliptical cavity. However, additional research into alternative cavity shapes and materials continues in parallel. One promising technique is the use of 'large-grain' niobium [8], as opposed to the small-grain material that has been used in the past (Figure 14). Use of large grain material may remove the need for electropolishing, since the same surface finish can potentially be achieved with Buffered Chemical Polishing (BCP) – a possible cost saving. Several single-cells have achieved gradients in excess of 35 MV/m (without electropolishing) and more recent nine-cell cavity tests have shown very promising results.

Various new and promising cavity shapes are also being investigated, primarily at KEK and Cornell. While the basic nine-cell form remains, the exact shape of the 'cells' is modified to reduce the peak magnetic field at the niobium surface. In principle these new shapes can achieve higher gradients, or higher *quality factors* (Q_0). Single-cells at KEK (ICHIRO) and Cornell (reentrant) have achieved the highest gradients to date (~50 MV/m, see Figure 14). R&D towards making high-performance nine-cell cavities using these designs continues as future possible alternatives to the ILC baseline cavity.

Beyond the cavity itself, R&D on several alternative designs that promise potentially cost and/or performance benefit alternatives is also formally supported by the GDE. Some key examples are alternative RF power source components, of which the Marx modulator is currently the most promising. In addition, R&D on the critical technologies will continue through the EDR. Topics include items such as the damping ring kickers and electron-cloud mitigation techniques, the positron target and undulator, the final magnets around the interaction region, and global issues that require very high availability such as the control system, the low-level RF, and the magnet power supplies.

While investment into the critical R&D remains a priority, a significant ramping-up of global engineering resources will now be required to produce an engineered technical design by 2010. An important aspect of this work will be the refinement and control of the published estimate by value engineering. The EDR phase will also require a restructuring of the GDE to support the increased scope. A more traditional project structure will be adopted based on the definition of a discrete set of Work Packages. The responsibility for achieving the milestones and deliverables of each Work Package will be assigned to either a single institute, or consortium of institutes, under the overall coordination of a central project management team. The Work Packages need to be carefully constructed to accommodate both the direct needs of the Engineering Design phase, while at the same time reflecting the global nature of the project. An important goal of the current planning is to integrate the engineering design and fundamental R&D efforts, since these two aspects of the project are clearly not independent. The goal is to have the new project structure ready to start the EDR in place by mid 2007.

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