

# SUMMARY OF THE ILC R&D AND DESIGN

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## Abstract

The International Linear Collider (ILC) is a linear electron-positron collider based on 1.3 GHz superconducting radio-frequency (SCRF) accelerating technology. It is designed to reach 200-500 GeV (extendable to 1TeV) centre-of-mass energy with high luminosity. In this paper, I review the work of the Global Design Effort (GDE), which was set up by ICFA in 2005 to coordinate the development of this technology and to produce a TeV scale accelerator design through a worldwide international collaboration. This work proceeded in two phases, first the development of a reference design, which was produced in 2008 and presented a feasible design and identified many high-risk challenges that required R&D. We have subsequently focused on these during the Technical Design Phase.

We have achieved a significant increase in the achievable gradient of SCRF cavities through a much better understanding of the factors that affect it. This improved understanding has permitted the industrialisation of the superconducting RF technology to more than one company in all three regions, achieving the TDP goal of 90% of industrially produced cavities reaching an accelerating gradient of 31.5MV/m. Other important R&D milestones have included the detailed understanding of the effects of, and effective mitigation strategies for, the “electron-cloud” effects that deteriorate the quality of the positron beam in the ILC damping rings, and demonstrations of the final focus requirements through the ATF-2 program at KEK.

The culmination of the R&D demonstrations and the development of the Technical Design Report (TDR) will complete the mandate of the GDE, and the next stages toward a project will proceed through the newly established Linear Collider Collaboration that will integrate the ILC and CLIC programs, as well as physics and detector developments.

## INTRODUCTION

The International Linear Collider (ILC) is a high-luminosity linear electron-positron collider based on 1.3 GHz superconducting radio-frequency (SCRF) accelerating technology. Its centre-of-mass-energy range is 200–500 GeV (extendable to 1TeV). The main elements feeding the main linacs include:

- a polarised electron source based on a photocathode DC gun;
- a polarised positron source in which positrons are obtained from electron-positron pairs by converting high-energy photons produced by passing the high-energy main electron beam through an undulator;
- 5 GeV electron and positron damping rings (DR) with a circumference of 3.2 km, housed in a common tunnel;

- 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 main linacs, utilising 1.3 GHz SCRF cavities operating at an average gradient of 31.5 MV/m, with a pulse length of 1.6 ms;

- two beam-delivery systems, each 2.2 km long, which bring the beams into collision with a 14 mrad crossing angle, at a single interaction point which can be occupied by two detectors in a so-called “push-pull” configuration.

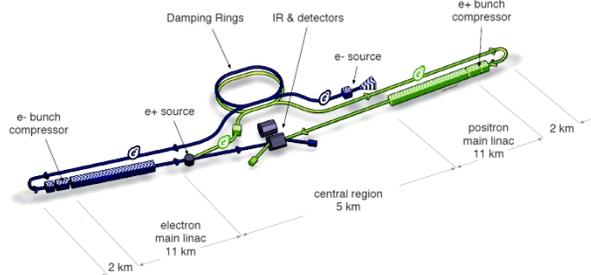


Figure 1: Schematic layout of the ILC.

The total footprint of the ILC complex is  $\sim 31$  km long. The electron source, positron source (including an independent low-powered auxiliary source), and the electron and positron damping rings are centrally located around the interaction region (IR) in the Central Region. The damping-ring complex is displaced laterally to avoid interference with the detector hall. The electron and positron sources themselves are housed in the same (main accelerator) tunnels as the beam-delivery systems, which reduces the overall cost and size of the central-region underground construction.

## MACHINE PARAMETERS

The baseline operational range for the ILC ranges from centre-of-mass energies from 250 to 1000 GeV, have been optimised with respect to cost, physics performance and risk and have been either directly demonstrated, or represent justifiable extrapolations from the current state of the art (see Table 1). The relatively conservative operating points result from constraints imposed by the various accelerator sub-systems. For example, the bunch charge, bunch spacing and the total number of bunches in the damping rings are limited by various instability thresholds (most notably the electron cloud in the positron ring), realistic rise-times for the injection and extraction kickers, and the desire to minimise the circumference of the rings.

Similarly, the maximum length of the beam pulse is constrained to  $\sim 1.6$  ms, which has been routinely achieved in the available 1.3 GHz 10MW multi-beam

Table 1: Summary table of the 250–500 GeV baseline and luminosity and energy upgrade parameters. Also included is a possible 1st stage 250 GeV parameter set (half the original main linac length)

			Baseline 500 GeV Machine			1st Stage	L Upgrade	$E_{CM}$ Upgrade	
			250	350	500	250	500	A 1000	B 1000
Centre-of-mass energy	$E_{CM}$	GeV	250	350	500	250	500		
Collision rate	$f_{rep}$	Hz	5	5	5	5	5	4	4
Electron linac rate	$f_{linac}$	Hz	10	5	5	10	5	4	4
Number of bunches	$n_b$		1312	1312	1312	1312	2625	2450	2450
Bunch population	$N$	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	$\Delta t_b$	ns	554	554	554	554	366	366	366
Pulse current	$I_{beam}$	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	$G_n$	MV m <sup>-1</sup>	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	$P_{beam}$	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	$P_{AC}$	MW	122	121	163	129	204	300	300
RMS bunch length	$\sigma_z$	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	$P_-$	%	80	80	80	80	80	80	80
Positron polarisation	$P_+$	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	$\mu\text{m}$	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	$\beta_x^*$	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	$\beta_y^*$	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	$\sigma_x^*$	nm	729.0	683.5	474	729	474	481	335
IP RMS vertical beam size	$\sigma_y^*$	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	$L$	$\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	$\delta_{BS}$		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	$N_{pairs}$	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	$E_{pairs}$	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

klystrons and modulators. The beam current is further constrained by the need to minimise the number of klystrons (peak power) and higher-order modes (cryogenic load and beam dynamics). Dynamic cryogenic load (refrigeration) is also a cost driver, which limits the repetition rate of the machine.

The electron and positron sources constrain the achievable beam current and total charge: For the laser-driven photocathode polarized electron source, the limits are set by the laser; for the undulator-based positron source, the limits are set by the power deposition in the photon target.

The beam pulse length is further constrained by the achievable performance of the warm RF capture sections (both sources). Finally, at the interaction point, single-bunch parameters are limited by the strong beam-beam effects and requirements on both the beam-beam backgrounds and beam stability.

## SCRF MAIN LINAC

The ILC Main Linacs accelerate the beam from 15 GeV (after acceleration in the upstream bunch compressors) to a maximum energy of 250 GeV. Beam acceleration in each linac is provided by approximately 7,400 1 m-long superconducting nine-cell niobium cavities operating at 2K, assembled into  $\sim 850$  cryomodules. The average accelerating gradient of the cavities is 31.5MV/m (for 500 GeV centre-of-mass beam energy), with a corresponding quality factor  $Q_0 > 10^{10}$ .

A random cavity-to-cavity gradient spread of  $\pm 20\%$  is tolerated to accommodate expected mass production variations in the maximum achievable gradient. The choice of these key parameters is the result of over a decade of extensive R&D. The GDE recognised the need to establish expertise in this technology in all three regions of the world and established the high-gradient programme as its highest priority during the Technical Design Phase. As a result, extensive worldwide experience both in the labs and in industry now gives high confidence that these requirements can be routinely achieved.



Figure 2: 1m long, nine-cell 1.3 GHz superconducting niobium cavity.

For an average of 31.5MV/m operation with the nominal beam current of 5.8mA, the optimal matched  $Q_L$  is  $\sim 5.4 \times 10^6$ . This corresponds to a cavity fill time of 925  $\mu\text{s}$ , which, added to the nominal beam pulse width of 727  $\mu\text{s}$ , gives a total RF pulse length of 1.65 ms.

The cavity package includes the cavity mechanical tuner, which is integrated into the titanium helium vessel

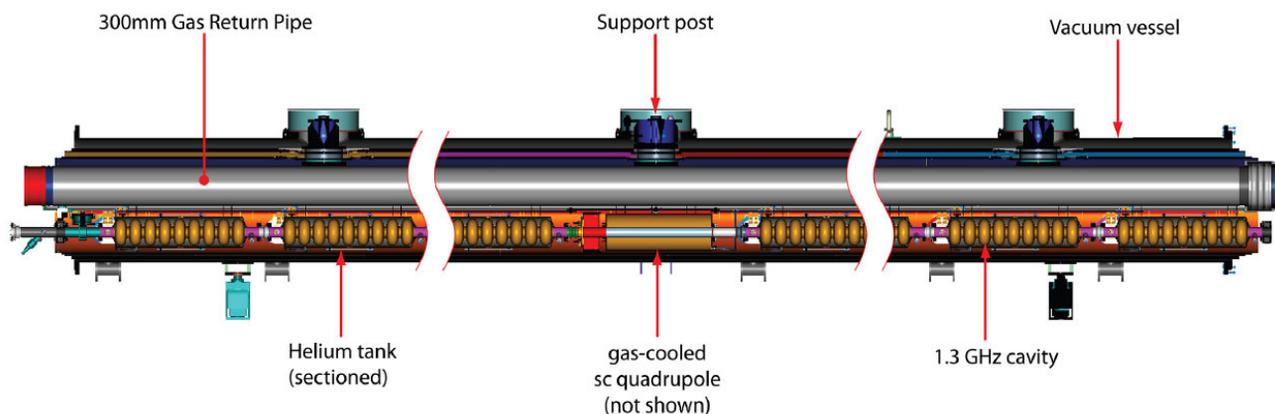


Figure 3: Longitudinal cross section of a Type B ILC cryomodule.

of the cavity, and an adjustable high-power coupler. In addition to a slow mechanical tuner (used for tuning and initial slow drift compensation), a fast piezo-driven tuner is also included to compensate dynamically for the mechanical deformation of the cavity caused by the RF pulse, known as “Lorentz-force detuning”

The cryomodules (Fig. 3) that make up the Main Linacs are 12.65m long. There are two types: a Type A module with nine 1.3 GHz nine-cell cavities and Type B with eight nine-cell cavities and one superconducting quadrupole package located at the centre of the module.

The ILC cryomodule design is a modification of the Type-3 version developed and used at DESY in the FLASH accelerator as well as the 100 cryomodules currently being produced by industry for the European X-Ray FEL (XFEL), also based at DESY. A 300 mm-diameter helium-gas return pipe serves as the primary support for the nine cavities and other beamline components in the Type A module. For Type B, the central cavity package is replaced by a superconducting quadrupole package that includes the quadrupole itself, a cavity BPM, and superconducting horizontal- and vertical-corrector dipole magnets. The quadrupoles establish the magnetic lattice for the Main Linac, which is a weak-focusing FODO optics with an average beta function of ~ 80m. Every cryomodule also contains a 300 mm-long assembly that removes energy from beam-induced higher-order modes above the cavity cut-off frequency through the 40–80K cooling system.

To operate the cavities at 2K, they are immersed in a saturated He-II bath. Shields cooled with Helium gas intercept thermal radiation and provide a heat sink for conduction at 5–8K and at 40–80K. Each cryomodule has an estimated 2K static cryogenic heat load of 1.3W while the 2K dynamic heat load is approximately 9.8W. Liquid helium for the main linacs and the bunch compressor RF is supplied from a total of 10-12 large cryogenic plants, each of which has an installed equivalent cooling power of ~ 20 kW at 4.5K. The plants are located in pairs separated by 5 km along the linacs, with each plant cooling ~ 2.5 km of continuous linac. The main linacs

follow the Earth’s average curvature to simplify the liquid-helium transport and tunnel construction.

The RF power is provided by 10MW multi-beam klystrons (MBK) each driven by a 120 kV Marx modulator. The 10MW MBK has achieved the ILC specifications and is now a well-established technology with several vendors worldwide. The 120 kV Marx-modulator prototypes have achieved the required specifications and are now undergoing design optimisation for transfer to industrial vendors.

Two alternative methods of transporting the RF microwave power to the accelerating structures are considered in the baseline. The first is a Distributed Klystron Scheme (DKS), where each klystron drives 39 cavities; the klystrons and modulators are distributed along the entire length of the SCRF linacs, in the same tunnel but shielded from the accelerator itself, which allows personnel access to make repairs as necessary while beam is on. The second is a novel Klystron Cluster Scheme (KCS), where all the klystrons are located in ‘clusters’ in surface buildings located periodically along the linacs. The power from a single cluster of 19 klystrons (~ 190MW) is combined into an over-moded waveguide, which then transports the power down into the tunnel and along an approximately 1 km section of linac. A Coaxial Tap-Off extracts ~ 6.7MW of power to a local power-distribution system feeding three cryomodules containing 26 cavities.

The advantages of KCS are primarily that most of the heat load is on the surface, where it can be more cost-effectively removed, at the same time as reducing the required underground volume. The disadvantages are the need for additional surface buildings and shafts (one every 2 km of linac). and additional losses in the long waveguide distribution systems. In addition significant R&D is still required compared to the mature and tested distributed system. Nonetheless, the estimated cost savings associated with KCS make it an attractive solution for flatter terrains with sufficient space for the required surface infrastructure. For more mountainous terrains or sites where surface access is at a premium,

DKS is the preferred solution.

For both KCS and DKS, the in-tunnel power-distribution system to the cavities themselves is essentially identical. A key requirement is the ability to tune both the phase and forward power to each cavity remotely, in order to support the allowed  $\pm 20\%$  gradient spread among the cavities, thus maximising the accelerating gradient.

## OTHER ACCELERATOR SUBSYSTEMS

### Electron Source

The polarised electron source shares the central region accelerator tunnel with the positron Beam Delivery System. The beam is produced by a laser illuminating a strained GaAs photocathode in a DC gun, providing the necessary bunch train with 90% polarisation. 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 Type- A superconducting RF cryomodule is used for energy compression.

### Positron Source

The major elements of the ILC positron source are shown in Fig. 3 and Fig. 4. After acceleration in the main linac, the primary electron beam is transported through a 147m superconducting helical undulator that generates photons with maximum energies from  $\sim 10$  MeV up to  $\sim 30$  MeV depending on the electron beam energy. The electron beam is then separated from the photon beam and displaced horizontally by 1.5m using a low-emittance-preserving chicane. The photons from the undulator are directed onto a rotating 0.4 radiation-length Ti-alloy target  $\sim 500$ m downstream, producing a beam of electron-positron pairs. This beam is then matched using an optical-matching device (a pulsed flux concentrator) 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. Similar to the electron beam, the positron beam is then accelerated to 5 GeV in a superconducting linac which uses modified Main Linac cryomodules, the spin is rotated into the vertical, and the energy spread compressed before injection into the positron damping ring.

The target and capture sections are high-radiation areas which will require shielding and remote handling facilities.

The baseline design provides a polarisation of 30%. Space for a  $\sim 220$ m undulator has been reserved for an eventual upgrade to 60% polarisation, which would also require a photon collimator upstream of the target.

A low-intensity auxiliary positron source supports commissioning and tuning of the positron and downstream systems when the high-energy electron beam is not available. This is effectively a conventional positron source, which uses a 500 MeV NC linac to provide an electron beam that is directed onto the photon target, providing a few percent of the nominal positron current.

To accommodate the 10 Hz operation required to produce the required number of positrons at centre-of-mass energies below 300 GeV, a separate pulsed extraction line is required immediately after the undulator, to transport the 150 GeV electron pulse for positron-production to the high-powered tune-up dump, located downstream in the Beam Delivery System.

### Positron Source

The ILC damping rings must accept  $e^-$  and  $e^+$  beams with large transverse and longitudinal emittances and damp them to the low emittances required for luminosity production. The specification for the extracted normalised vertical emittance of 20 nm represents a reduction of five orders of magnitude for the positron bunch. This reduction must be achieved within the 200 ms between machine pulses (100 ms for 10-Hz mode). In addition, the  $\sim 1$  ms beam pulse must be compressed on injection by roughly a factor of 90 to fit into the ring circumference of

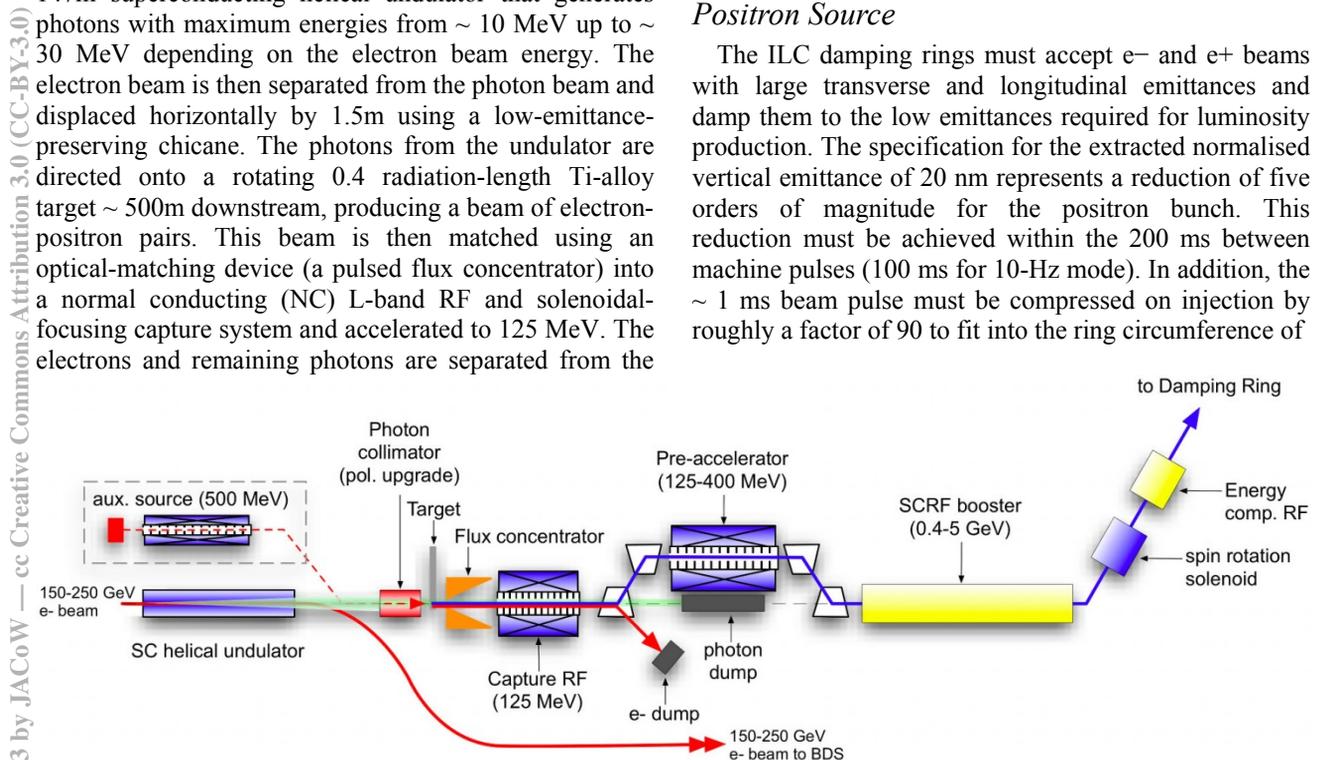


Figure 4: Overall Layout of the Positron Source, located at the end of the electron Main Linac.

3.2 km; a corresponding decompression is required on extraction. For the baseline parameters, the bunch spacing within trains is approximately 8 ns, which determines the rise and fall time of the injection and extraction kicker systems. (For the luminosity upgrade this number reduces to  $\sim 4$  ns.) Individual bunch injection and extraction is accomplished in the horizontal plane using a total of 42 fast kickers switching 10 kV pulses with rise/fall times of  $\sim 3$  ns.

One electron and one positron ring are included in the baseline, operating at a beam energy of 5 GeV. Both rings are housed in a single tunnel with one ring positioned directly above the other. The damping ring complex is located in the central region, horizontally offset from the interaction region by approximately 100m to avoid the detector hall. The damping rings are connected to the electron and positron main accelerators by transfer lines.

The damping-ring lattice follows a race-track design. The two arc sections are constructed from 75 Theoretical Minimum Emittance (TME) cells. One of the two 712 m-long straight sections accommodates the RF cavities, damping wigglers, and a variable path length to accommodate changes in phase (phase trombone), while the other contains the injection and extraction systems, and a circumference-adjustment chicane.

Damping is accomplished by approximately 113m of superferric wigglers (54 units  $\times$  2.1m) in each damping ring. The wigglers operate at 4.5 K, with a peak-field requirement of 2.16 T.

The superconducting RF system is operated in continuous-wave (CW) mode at 650MHz, and provides a maximum of 20MV for each ring, required for the positron ring in 10 Hz mode (nominal 5 Hz operation requires 14MV for both electron and positron). The frequency is chosen to be half the linac RF frequency to maximise the flexibility for different bunch patterns. The single-cell cavities operate at 4.5K and are housed in twelve 3.5m-long cryomodules. The RF section of the lattice can accommodate up to 16 cavities, of which 12 are assumed to be installed for the baseline.

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 (6mm). The dynamic aperture of the lattice is sufficient to allow the large-emittance injected beam to be captured with minimal loss.

Mitigation of the fast ion instability in the electron damping ring is achieved by limiting the pressure in the ring to below 1 nTorr and by the use of short gaps in the ring fill pattern and a fast transverse feedback system, similar to those used in B-factories.

The performance of the damping rings was noted as one of the biggest challenges facing the post-RDR R&D programme. In particular, intensive studies were carried out on the electron-cloud effect, in which electrons emitted from the vacuum-pipe walls by synchrotron-radiation photons are attracted to the positron beam, resulting in a perturbing electromagnetic field that increases the beam emittance. These studies have resulted

in mitigation methods that have been included in a major redesign of the vacuum systems for the baseline damping rings.

### *Ring to Main Linac (RTML)*

The electron and positron Ring to Main Linac (RTML) systems are the longest continuous beamlines in the ILC. The layout of the RTML is identical for both electrons and positrons. The RTML consists of five subsystems, representing the various functions that it must perform: a  $\sim 15$  km long 5 GeV transport line; betatron and energy collimation systems; a  $180^\circ$  turn-around, which enables feed-forward beam stabilisation; spin rotators to orient the beam polarisation to the desired direction; and a two-stage bunch compressor to compress the beam bunch length from several millimetres to a few hundred microns, as required at the IP.

The two-stage bunch compressor includes acceleration from 5 GeV to 15 GeV in order to keep the increase in relative energy spread associated with bunch compression small. The acceleration is provided by sections of SCRF main-linac technology. A primary challenge for the RTML systems is the preservation of the damped emittance extracted from the damping rings; the combination of the long uncompressed bunch from the damping ring and large energy spread (after compression) make the tuning and tolerances particularly demanding. However, tuning techniques developed through detailed simulations have demonstrated acceptable emittance growth.

In addition to the beam-dynamics challenges, acceptable jitter in bunch arrival time at the IP requires an RMS phase jitter of  $\sim 0.24^\circ$  between the electron and positron bunch-compressor RF systems. Beam-based feedback systems integrated into the bunch-compressor low-level RF system should be able to limit the phase jitter to this level.

## CONCLUSIONS AND REMARKS

The ILC design presented here proceeded in two stages, first, a conceptual or reference design completed in 2008 and a technical design (TDR) scheduled to be completed in June 2013. This paper presents highlights and main features of the technical design that will be presented in detail in the ILC TDR, as well as the demonstrations and advances achieved in the ILC R&D program.

## ACKNOWLEDGMENTS

The work presented here is the product of the ILC Global Design Effort, a collaboration consisting of the combined work of hundreds of accelerator scientists from around the world. Funds and resources have been contributed from the major particle physics laboratories around the world.

## REFERENCES

- [1] The ILC Technical Design Report (to be published) <http://www.linearcollider.org>.