THE INTERNATIONAL LINEAR COLLIDER

Gateway to the Quantum Universe

international linear collider

PASSPORT

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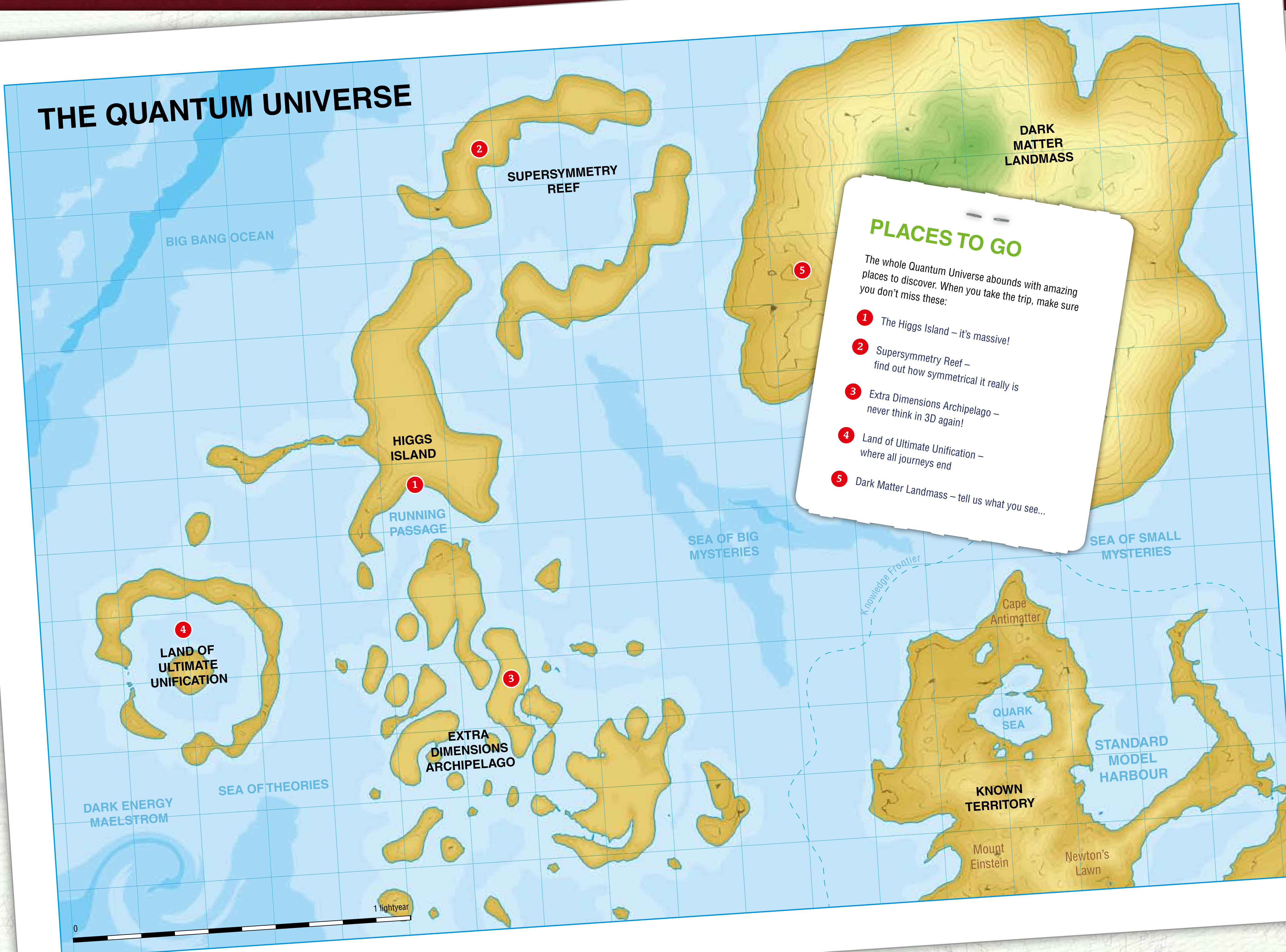

PLACES TO GO

The whole Quantum Universe abounds with amazing places to discover. When you take the trip, make sure you don't miss these:

1. The Higgs Island – it's massive!
2. Supersymmetry Reef – find out how symmetrical it really is
3. Extra Dimensions Archipelago – never think in 3D again!
4. Land of Ultimate Unification – where all journeys end
5. Dark Matter Landmass – tell us what you see...

01 INTRODUCTION

What is the International Linear Collider?

You are about to witness a scientific revolution. The *International Linear Collider* (ILC), a proposed new particle accelerator, promises to radically change our understanding of the universe – revealing the origin of mass, uncurling hidden dimensions of space, and even explaining the mystery of dark matter. Advanced superconducting technology will accelerate and collide particles to incredibly high energies down tunnels that span more than 30 kilometres in length. State-of-the-art detectors will record the collisions at the centre of the machine, opening a new gateway into the Quantum Universe, an unexplored territory where the very small answers questions about the very large. From young graduate students to university professors, more than a thousand scientists worldwide are collaborating today to design and build the particle accelerator of tomorrow.

THE INTERNATIONAL LINEAR COLLIDER – GATEWAY TO THE QUANTUM UNIVERSE COMMITTEE

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ABOUT THIS REPORT:

The global ILC community, a group of more than 1,000 physicists and engineers dedicated to making this next-generation machine a reality, has published its *Reference Design Report.* The four-volume report specifies in great detail the physics goals, technical challenges, R&D achievements, and general characteristics of the planned accelerator. This document, *The International Linear Collider – Gateway to the Quantum Universe,* translates the technical and detailed content of the *Reference Design Report* and explains why and how we will build the next big machine for particle physics.

Note to reader: following the guidelines of the United Nations Editorial Manual, this report has adopted British English language and style.


ilc
Check-in

EXECUTIVE SUMMARY

Particle physicists are on a quest to answer profound questions about the universe by studying fundamental laws of nature: What are the building blocks of matter, and how do they fit together to shape the world? Are there more dimensions than the three known to our everyday senses? Are all the forces of nature aspects of a single unified whole? Where does matter come from? What is the nature of the dark matter that binds galaxies together? These are currently mysteries.

Our current and past particle accelerators have revealed the realm and behaviour of elementary particles down to very small distances. We now know the constituent particles of ordinary matter and that there are four fundamental forces of nature.

We are now ready to take the next steps and embark on a journey of discovery. We aim to solve the outstanding mysteries using the next generation of advanced particle accelerators. These will take us into the new energy region needed to explore smaller and more fundamental phenomena. It is named the 'Terascale' after the trillions of volts of energy needed to access it.

What does Quantum Universe mean?

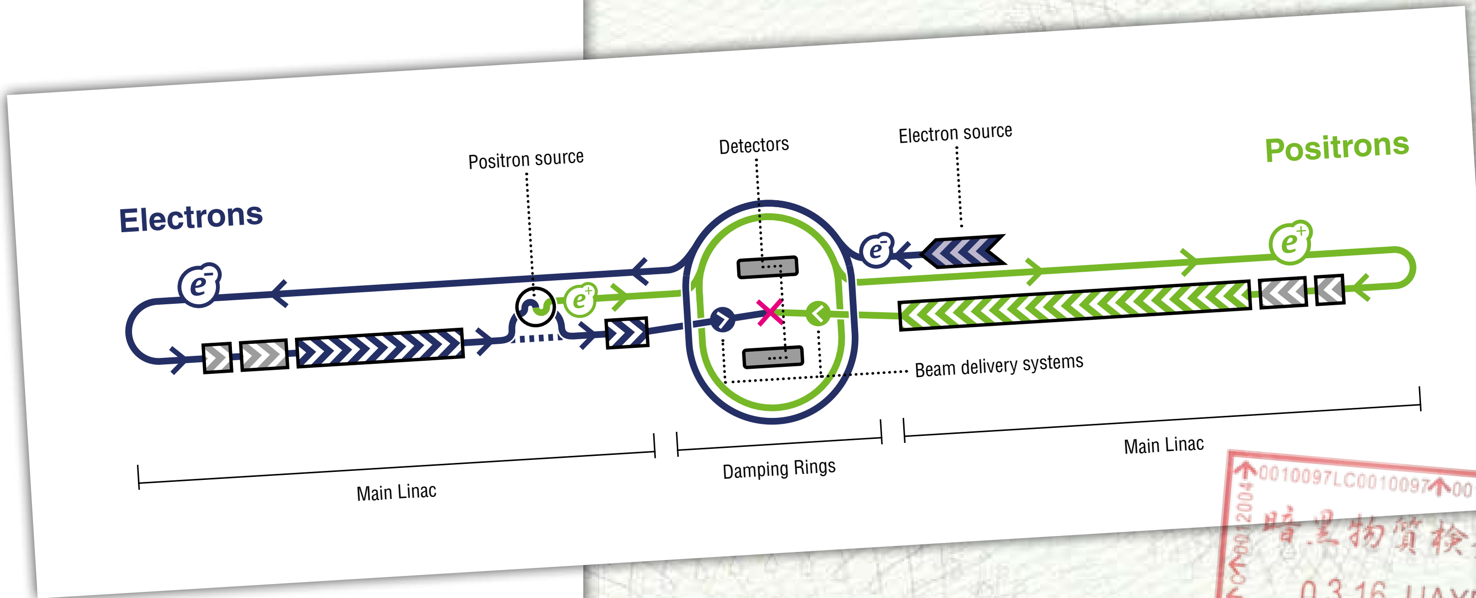
The Quantum Universe is the subatomic realm of the universe, governed by the laws of quantum physics. Particle physics aims to discover what the universe is made of and how it works, questions that must be answered on this sub-atomic quantum scale. The recent revolution in particle physicists' understanding of the universe and the next generation of particle accelerators will bring the Quantum Universe firmly within our grasp.

Terascale and quantum leap: powers of ten

10^{-12}	pico	p	0.000 000 000 001
10^{-9}	nano	n	0.000 000 001
10^{-6}	micro	µ	0.000 001
10^{-3}	milli	m	0.001
10^{-2}	centi	c	0.01
10^{-1}	deci	d	0.1
10^{0}			1
10^{1}	deca	da	10
10^{2}	hecto	h	100
10^{3}	kilo	k	1 000
10^{6}	mega	M	1 000 000
10^{9}	giga	G	1 000 000 000
10^{12}	tera	T	1 000 000 000 000

In the next few years, the *Large Hadron Collider* (LHC) will give us a first broad view of the Terascale. We want to build on LHC discoveries with the *International Linear Collider* (ILC). The ILC will allow us to zoom in on the new landscape with exquisite precision, revealing its richness and new layers of detail. The ILC will give us a view of the universe at energies last seen when it was only a billionth of a billionth of a second old. Together, the ILC and LHC will transport us to places where both anticipated and unanticipated discoveries will abound.

Particle physics inspires. The ILC will attract the best minds to science and technology and allow us to train future generations of scientists and engineers. These great minds will continue to advance technology, yielding many applications in science and industry. The knowledge generated from fundamental research in the past century has transformed the global economy and culture.



We cannot yet predict how extra dimensions or dark matter will further transform society, but the benefits from the tools we are developing are easier to imagine: applications in medicine, transportation, real-time biological imaging, development of new computer tools and new imaging devices for communications and graphics industries, to name but a few.

Above and beyond the direct impact that fundamental research has on our lives, we gain satisfaction from understanding the world we inhabit. Our innate instinct to explore and understand how things work is essential to our core as human beings. It is this curiosity that spurs us on to build the ILC and that will lead ultimately to discoveries that solve the greatest mysteries of the universe.

ILC by the numbers

Collisions:
Between electrons and their antiparticles, positrons, in bunches of 5 nanometres (5 billionths of a metre) in height each containing 20 billion particles and colliding 14,000 times per second

Energy:
Up to 500 billion electronvolts (GeV) with an option to upgrade to 1 trillion electronvolts (TeV)

Acceleration Technology:
16,000 superconducting accelerating cavities made of pure niobium

Length:
Approximately 31 kilometres, plus two damping rings each with a circumference of 6.7 kilometres

Accelerating Gradient:
31.5 megavolts per metre

Cavity temperature:
2 K (–271.2 °C or –456 °F)

Detectors:
2, based on complementary technologies

Site:
To be determined in the next phase of the project

ILC Community:
Nearly 300 laboratories and universities around the world are involved in the ILC: more than 700 people are working on the accelerator design, and another 900 people on detector development. The accelerator design work is coordinated by the *Global Design Effort,* and the physics and detector work by the *World Wide Study.*

On the Web:
http://www.linearcollider.org


EXTRA DIMENSIONS
DARK MATTER
HIGGS
DARK ENERGY
SUPERSYMMETRY
UNIFICATION
UNKNOWN
QUANTUM UNIVERSE
ALL

02 THE QUANTUM UNIVERSE

A revolution has begun in the way we see the universe.

In recent years, experiments and observations have revealed a universe far stranger and more wonderful than we had ever imagined: a universe filled with mysterious substances called dark matter and dark energy, where ordinary matter – everything we are, we see and feel – forms only a tiny fraction.

The next generation of particle accelerators will stretch our imaginations even further and aims to reveal these new forms of matter, new forces of nature, and new dimensions of space and time. These accelerators will survey a new territory, the Terascale, so named after energies approaching Tera-electronvolts (trillions of electronvolts or TeV), that are needed to open it up for scientific discovery.

We know today that something new is out there – many precise experiments from the past decades, performed by international teams, have told us so. We just do not know exactly what we might find. By exploring the Terascale, we expect to discover answers to our questions through a revolutionary new view of the universe and its physical laws – the Quantum Universe.

Universal questions

We are asking fundamental questions about the universe:

1. Are there undiscovered principles of nature?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the lab?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

The next-generation particle accelerators will help us to discover the answers.

The next-generation accelerators

The *Large Hadron Collider* (LHC) at CERN, the *European Organization for Nuclear Research,* Geneva, Switzerland, turns on in 2008. In a circular tunnel 27 kilometres in circumference, the LHC will smash together beams of protons. Flying around the LHC, each proton will have an energy of 7 Tera-electronvolts. But because protons are bags of particles called quarks and gluons, only a fraction of each proton's energy is used when individual quarks and gluons collide. Collisions that can create massive new particles will occur at LHC with total energies up to a few Tera-electronvolts.

The *International Linear Collider* (ILC) will hurl together beams of electrons and positrons, the antimatter partners of electrons. Facing each other, two linear accelerators – one hurling electrons and the other hurling positrons – will stretch a total of approximately 31 kilometres. At the centre, electrons and positrons, each with an energy of 250 billion electronvolts, will travel at nearly the speed of light and smash together. They will create spectacular collisions with a total energy of 500 billion electronvolts, all of which is available for creation of new particles. The ILC's design allows for an upgrade to a machine with energy around 1 Tera-electronvolt.

Why is the ILC linear rather than circular? When an electrically charged particle is forced onto a curved track, it emits X-rays and loses energy. The higher its energy, the more energy is lost. This energy loss is much more severe for electrons and positrons than for protons in the LHC. The solution to reach high energies for electrons and positrons is to eliminate the curves, hence the 'Linear' in ILC.

Gateway to the Quantum Universe

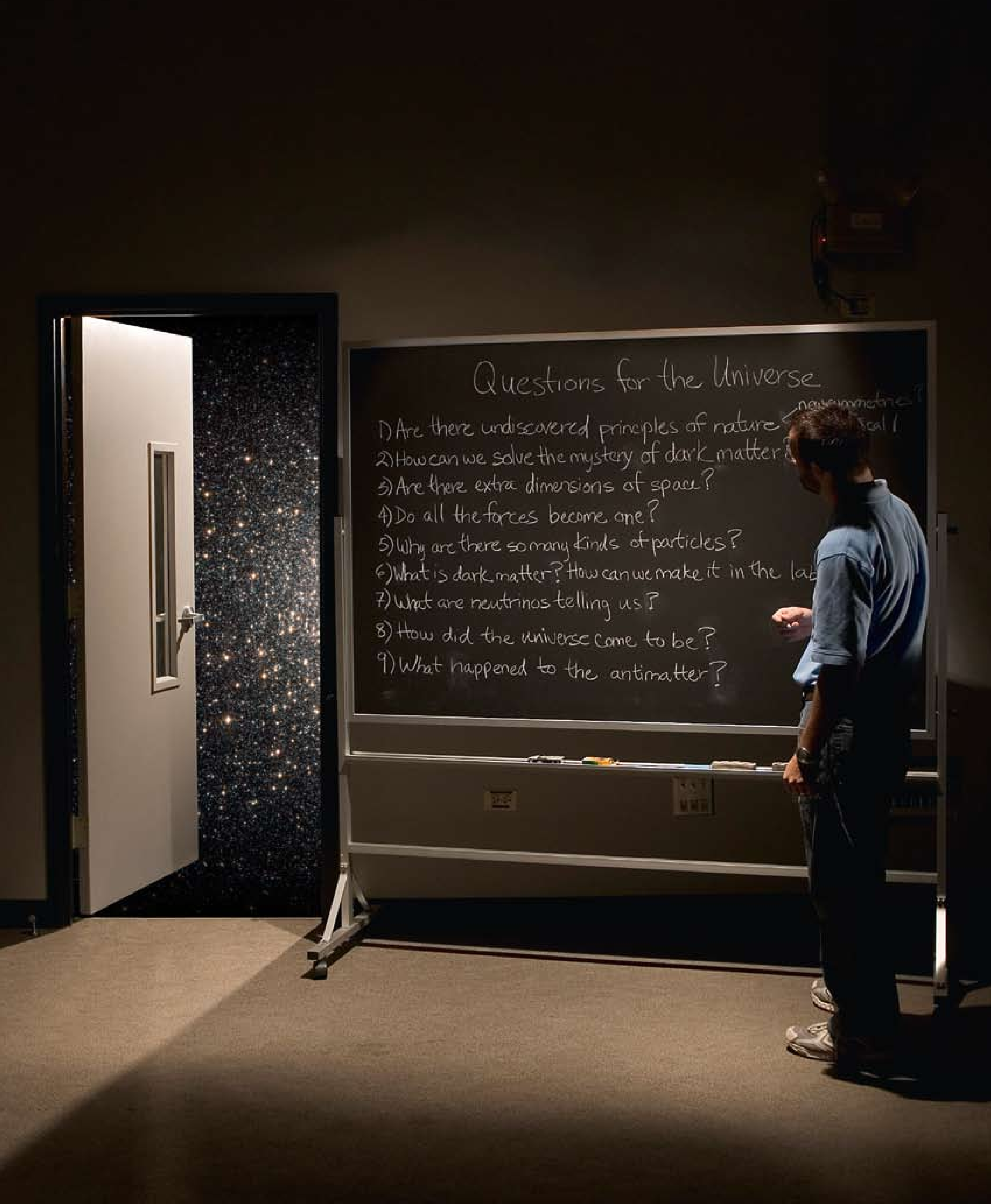
To take this leap into the unknown, physicists around the globe are working together to design and build the most advanced accelerators ever conceived. The ILC will chart this new territory with unprecedented precision. The first map of the Terascale will come from the LHC currently under construction at CERN in Geneva, Switzerland. No one knows exactly what the LHC will find, but the territory is vast and the potential for discovery is enormous.

The ILC will allow us to home in with exquisite precision on the new landscape that the LHC will initially find. It will expand on the discoveries made by the LHC and reveal the new laws of nature at the Terascale.

Together, these unprecedented discovery machines will bring the Quantum Universe into focus.

Secrets of the Terascale

Based on experiments and discoveries over the last decades, physicists believe that the Terascale will yield evidence for entirely new forms of matter, and possibly even extra dimensions of space. The new matter might include the Higgs particle, as well as an extended family of elementary 'superparticles', the heavier cousins of the particles we already know. These discoveries will tell us about the nature of the universe and how the laws of physics came to be.



credit: Fermilab, NASA, ESA, G. Piotto (University of Padua) and A. Sarajedini (University of Florida)

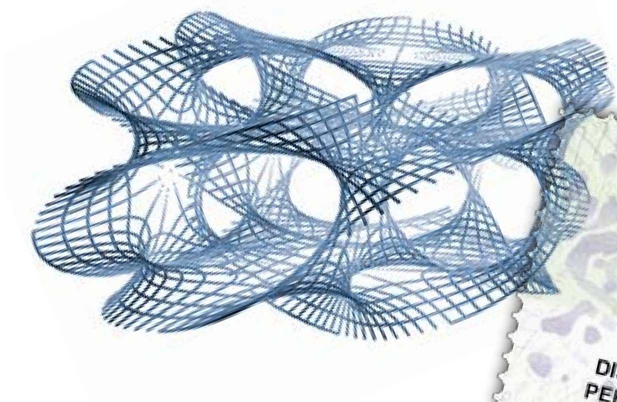
The Higgs particle

Today's Standard Model of particle physics describes nearly all high-energy phenomena observed with existing particle accelerators. Its accuracy is remarkable, but it works only because of an unverified hypothesis: the Higgs mechanism. The Higgs particle is the only Standard Model particle not yet observed. In the Standard Model it plays a key role in explaining the origin of the masses of the elementary particles. Like an invisible quantum fluid, the Higgs field fills the vacuum of space, slowing particle motion and giving mass to matter. When this quantum fluid is disturbed at sufficiently high energies, we expect it to release observable Higgs particles, shaking them off one by one.

Precise measurements of the observed elementary particles allow us to estimate at what energy the Higgs particle will appear. This energy is at the limit of today's particle accelerators, but well within the range of the LHC and the ILC.

At the ILC, we will create Higgs particles in the electron-positron collisions and then measure very accurately their properties: mass, the intrinsic rotational momentum called 'spin', and the strength of their interactions with the other elementary particles. Will the Higgs properties be as predicted by the Standard Model? Or will they indicate a more exotic Higgs superparticle? Will nature be even more complicated than that? The ILC will allow us to find out.

Credit: Jean-Francois Colonna



Revealing the ultimate: extra dimensions?

In our current understanding of the universe, the laws of the very large and the laws of the very small do not mesh. We have already discovered that three of the four known forces share the same mathematical structure described by quantum theory. Is it possible to reconcile gravity (the law of the very large) with quantum theory (the law of the very small)? Could there be a single underlying *theory of everything?* The ILC's unique properties could point the way towards the ultimate theory.

String theory is one promising candidate to unify the laws of the large and small. The theory holds that all particles and forces can be thought of as tiny vibrating strings. One pluck of the string makes it a quark, while another makes it a photon – a particle symphony of sorts. String theory brings with it a number of dramatic concepts including supersymmetry and extra dimensions of space.

These extra dimensions are not visible in our everyday world. They are thought to be curled up so small that they will only become visible if probed with powerful accelerators. If new dimensions exist at the Terascale, the LHC could discover them, and the ILC could determine the number of new dimensions, their size and shape, and which particles live inside them. Together, the LHC and ILC could thus open a window into a new world of quantum gravity.

The Standard Model (and beyond)

The Standard Model of particle physics is a theory that describes the known particles that make up ordinary matter and three of the four known fundamental interactions between them. These interactions, or forces, are the electromagnetic force (which we use and rely on every day), the strong force (which holds quarks together inside the atom's nucleus) and the weak force (which is responsible for many radioactive decays). The scope of the Standard Model does not include the fourth force, gravity.

Antimatter

For every fundamental particle there is a corresponding antimatter partner. The pair is identical in many aspects except, notably, for their opposite charge. For example, an electron and positron are identical except that the electron has a negative charge while a positron has a positive charge. When a particle and its antiparticle meet, they annihilate into a state of pure energy.

Supersymmetry

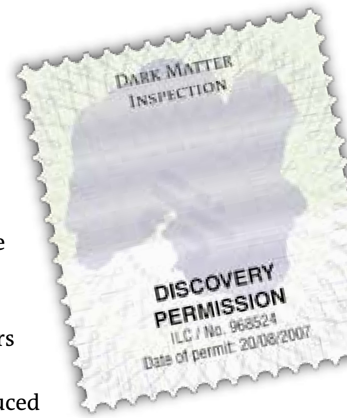
Supersymmetry is hypothesised to be a property of the universe, but it is yet to be experimentally observed. It requires every type of particle to have an associated supersymmetric particle, called its superpartner. The superpartner is a heavy replica of a particle, with one other significant difference. All particles are classed as either fermions or bosons. A particle belonging to one class has a super-partner in the other, thereby 'balancing the books' and making nature more symmetric. For example, the super-partner of an electron (a fermion) is called a selectron (a boson).

Supersymmetry describes a grand dance of particles through the universe, but we can currently see only one partner from each pair. The unseen particles might be the source of the mysterious 'dark matter' in galaxies. Although superpartners have not yet been observed in nature, they might soon be produced at the LHC and ILC.

Like the jelly beans in this jar, the universe is mostly dark: 96 percent consists of dark matter and dark energy. Only about four percent (the same proportion as the coloured jelly beans) of the universe – including the stars, planets, and us – is made of familiar atomic matter.

Shedding light on dark matter

The past decade has brought the startling discovery that 96 percent of the universe is not made of ordinary matter, but instead consists of 'dark energy' (about 74%) – causing the accelerated expansion of the universe – and 'dark matter' (about 22%) – a mysterious form of matter that does not emit light, and which is hence difficult to detect with ordinary observation methods.



Clear evidence, however, for the dark universe comes from many sources, including astrophysical observations of clusters of galaxies that would have flown apart if ordinary matter were the only thing holding them together. Dark matter seems to hold the universe together.

But what is dark matter? Particle physics offers an explanation. Most predictions about the Terascale include dark matter particles. Produced copiously in the fiery cauldron of the big bang, enough particles might have survived until today to be the cosmological dark matter. To know for sure, we need to produce the particles and measure their properties precisely.

Theories of supersymmetry provide a case in point. The LHC and ILC should be able to produce and study supersymmetric particles if they exist in nature. Those supersymmetric particles could make up the dark matter content of the universe. By precisely measuring the masses of these particles at ILC and comparing them with increasingly precise cosmological measurements, we can determine whether supersymmetric particles make up all of the dark matter or whether anything else is missing.

Credit: Fermilab

Two forces become one

For centuries, scientists suspected a connection between electricity and magnetism. For example, when lightning struck a ship on the high seas, sailors noticed it disturbed a compass needle. In the 19th century James Clerk Maxwell successfully unified electricity and magnetism in one theoretical framework. His combined theory, electromagnetism, is the foundation of many familiar technologies in our modern lives, ranging from light bulbs to television to computers.

Today we are on a quest to discover whether the four forces – electromagnetism, gravity, the strong force and the weak force – originate from a single force that manifests itself at high energy scales. We are not yet able to comprehend what the ultimate unified theory will yield, but the possibilities are endless.

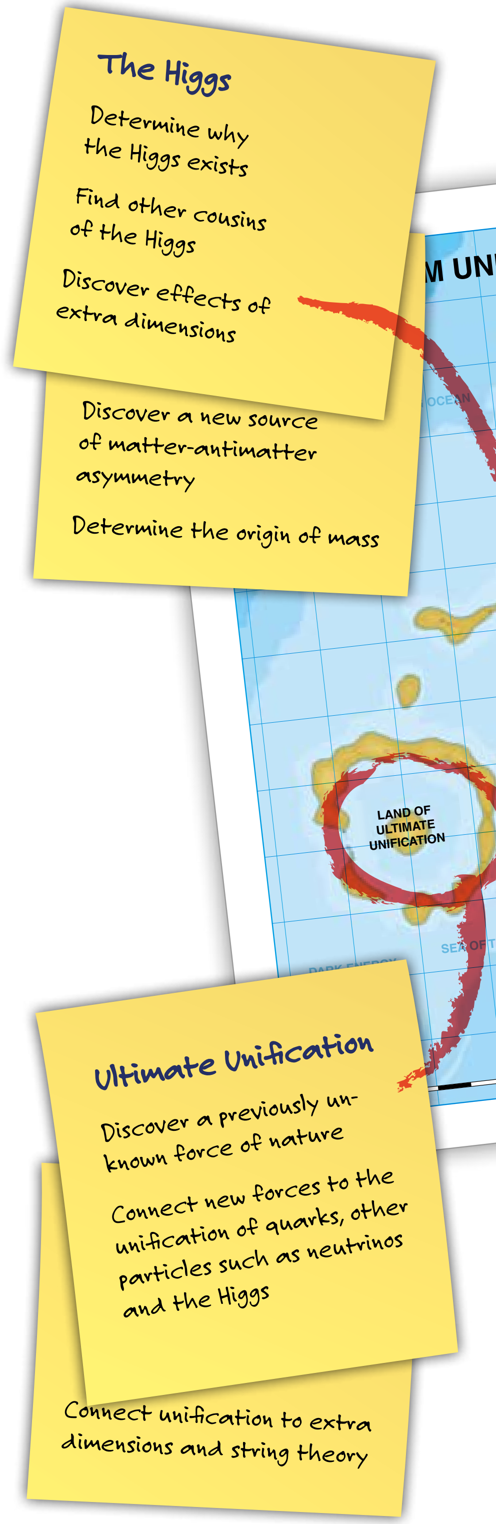
A parallel superworld

In addition to dark matter, supersymmetry predicts a world of superparticles that partner the elementary particles we know today. The ILC will illuminate this parallel superworld, if it exists. The ILC's high-energy electron-positron collisions could produce these superparticles, allowing us to study the different types and measure how they interact with each other. These observations will determine the structure and definition of this superworld.

A telescope to the unknown

The great precision of its electron-positron collisions would allow the ILC to act as a telescope to explore energies far beyond those that any particle accelerator could ever directly achieve.

For now, though, our view is obscured by a lack of knowledge of Terascale physics. Data from the ILC would bring the Terascale into focus and give us a telescope to the beyond. The ILC would provide a view of energies a trillion times beyond its own – into the ultrahigh-energy realm where nature's forces might become unified.

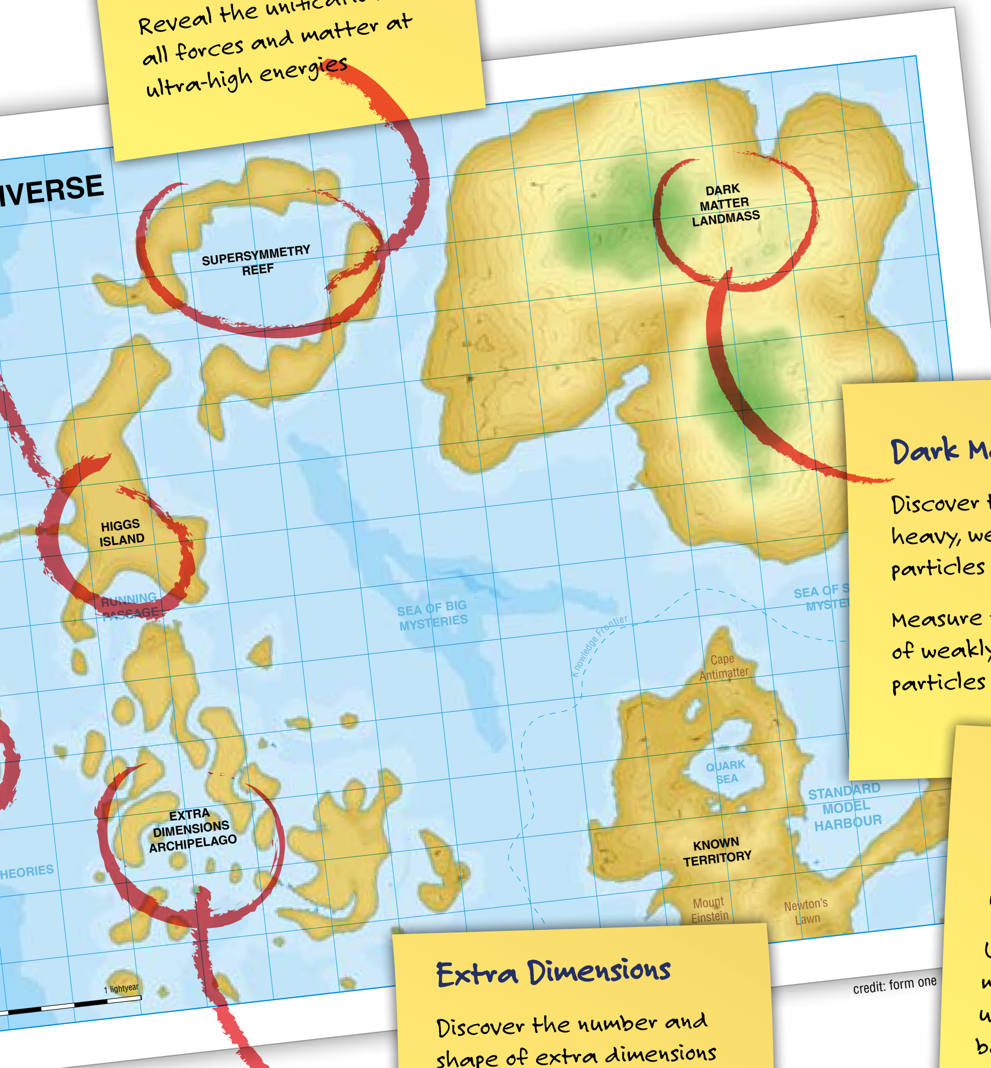


Supersymmetry

Detect the nature of supersymmetry

Discover the supersymmetric nature of dark matter

Reveal the unification of all forces and matter at ultra-high energies



credit: form one

Discovery scenarios

Whatever the LHC discovers, the ILC is the machine needed to bring those discoveries into clear focus and expand upon them. The exact discovery scenario will depend upon what nature has chosen, but there is an abundance of exciting opportunities.

Dark Matter

Discover the identity of heavy, weakly-interacting particles as dark matter

Measure the abundance of weakly-interacting particles

Connect dark matter candidates to deeper theories of extra dimensions, supersymmetry and the ultimate unified theory

Use properties of dark matter to probe the early universe, giving us a window back to the big bang

Extra Dimensions

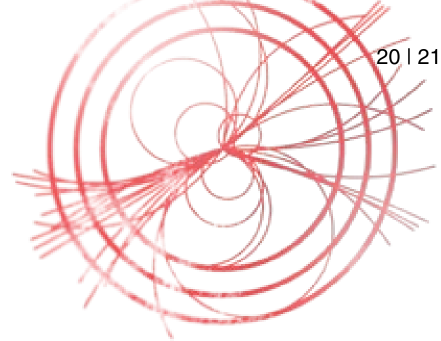
Discover the number and shape of extra dimensions

Determine which particles travel in extra dimensions

Map out the locations of particles within extra dimensions

Scientists and engineers from around the world are collaborating on R&D for the International Linear Collider.

Credit: Fermilab



03 ILC: THE MACHINE FOR THE FUTURE

Reaching our ambitious physics goals will be a major challenge. The International Linear Collider will not only enable us to expand the frontiers of our knowledge of the universe; it is already challenging us to push boundaries in such diverse areas as advanced accelerator technology, materials engineering, and detector development. International teams of scientists and engineers are hard at work developing the design.

Creating the right tool

Exploring the Quantum Universe with accelerators is like sweeping a searchlight methodically to find something small in the dark.

We know that we want to collide electrons and their antiparticles, positrons, at total energies up to 500 billion electronvolts (0.5 Tera-electronvolts), as this is the energy range where we expect to gain access to many of the described mysterious phenomena. When the electrons and positrons smash into each other, they will release their energies and create new particles that we can detect. This provides an environment that will allow us to make precise, incisive measurements. We know that we need a certain rate of electron-positron collisions, or 'luminosity', in order to produce enough interesting interactions to measure and study. These facts allow us to set the parameters for the design of the ILC.

The ILC is our searchlight to illuminate the unknown. We know about some of the things we are looking for: dark matter, the Higgs boson, extra dimensions, and superparticles. And we know where to direct the searchlight to find them – and possibly discover things along the way that we didn't expect. Up until now, our searchlights have not reached far enough. By building the ILC, we will have one that does.

The ILC – a step-by-step guide

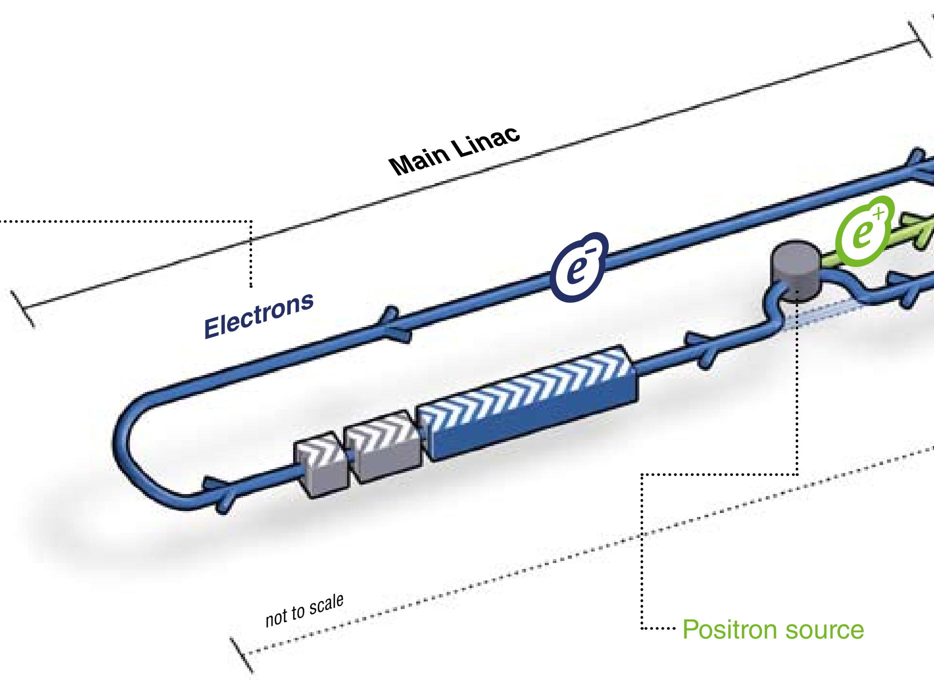
How does the ILC work? Like any complex machine, the 31 kilometre-long accelerator is made up of several systems – each one an essential component for launching particles at close to the speed of light. This step-by-step guide explains how the ILC works.

Electrons

To produce electrons we will direct high-intensity, two-nanosecond light pulses from a laser at a target and knock out billions of electrons per pulse. We will gather the electrons using electric and magnetic fields to create bunches of particles and launch them into a 250-metre linear accelerator that boosts their energy to 5 GeV.

Positrons

Positrons, the antimatter partners of electrons, do not exist naturally on Earth. To produce them, we will send the high-energy electron beam through an undulator, a special arrangement of magnets in which electrons are sent on a 'roller coaster' course. This turbulent motion will cause the electrons to emit a stream of X-ray photons. Just beyond the undulator the electrons will return to the main accelerator, while the photons will hit a titanium-alloy target and produce pairs of electrons and positrons. The positrons will be collected and launched into their own 250-metre 5-GeV accelerator.

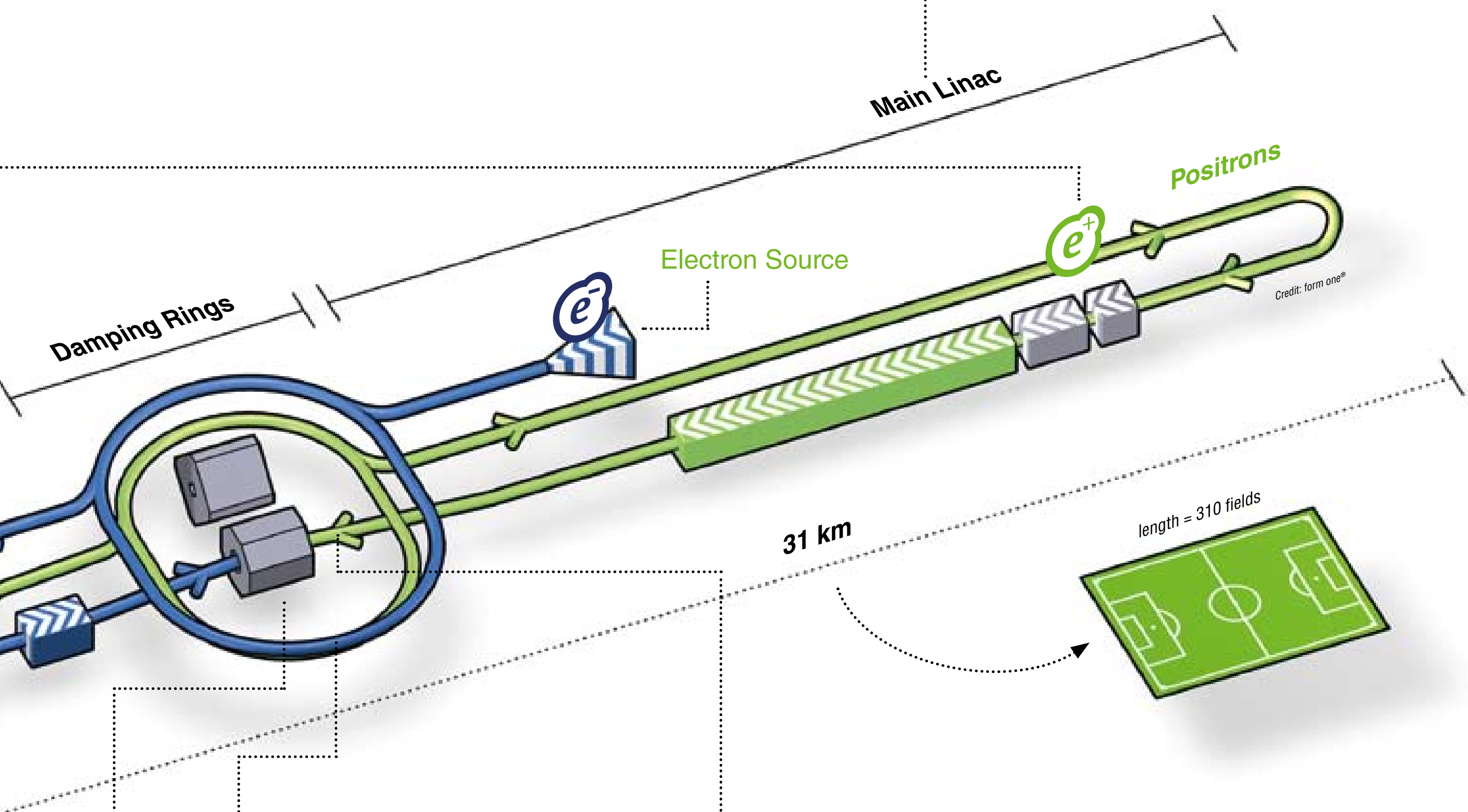


The detectors

Travelling towards each other at nearly the speed of light, the electron and positron bunches will collide with a total energy of up to around 500 GeV. We will record the spectacular collisions in two interchangeable giant particle detectors. These work like gigantic cameras, taking snapshots of the fleeting particles produced by the electron-positron collisions. The two detectors will incorporate different but complementary state-of-the-art technologies to capture this precious information about every particle produced in each interaction. Having these two detectors will allow vital cross-checking of the potentially subtle physics discovery signatures.

The linacs

Two main linear accelerators (called linacs), one for electrons and one for positrons, each 12 kilometres long, will accelerate the bunches of particles toward the collision point. Each accelerator consists of hollow structures called superconducting cavities, nestled within a series of cooled vessels known as cryomodules. The modules use liquid helium to cool the cavities to –271 °C, only slightly above absolute zero, to make them superconducting. Electromagnetic waves fill the cavities to 'push' the particles, accelerating them to energies up to 250 GeV. Each electron and positron bunch will then contain an energy of about a kilojoule, which corresponds to an average beam power of roughly 10 megawatts. The whole process of production of electrons and positrons, damping, and acceleration will repeat five times every second.



The damping rings

When created, neither the electron nor the positron bunches are compact enough to yield the high density needed to produce copious collisions inside the detectors. Two 6.7 kilometre-circumference damping rings, one for electrons and one for positrons, will solve this problem. In each ring, the bunches will repeatedly traverse a series of wigglers, devices that causes the beam trajectories to 'wiggle' in a way that makes the bunches more compact. Each bunch will spend approximately two tenths of a second in its damping ring, circling roughly 10,000 times before being kicked out. Magnets will keep the particles on track and focused in their circular orbits around the ring. Upon exiting the damping rings, the bunches will be a few millimetres long and thinner than a human hair.

The beam delivery systems

In order to maximise the luminosity, the bunches of particles must be extremely small. A series of magnets, arranged along two 2-kilometre beam delivery systems on each side of the collision point, will focus the beams to a few nanometres in height and a few hundred nanometres in width. The beam delivery systems will scrape off stray particles in the beams and protect the sensitive magnets and detectors. Magnets will steer the electrons and positrons into head-on collisions.

Credit: KEK

All cryomodules have to go through series of thorough tests.

Credit: DESY

The major challenges

Energy

The energy scales we will probe with the ILC are far beyond anything electron-positron colliders have ever achieved. To attain the beam energy of up to 250 GeV per particle, adding up to 500 GeV per collision, would require 167 billion standard AA batteries placed end to end.

Superconducting technology

A charged particle can be accelerated only by an electric field. To provide the necessary acceleration, we will use superconducting niobium cavities. The accelerating electric field is established by supplying energy pulses to the cavities, which are immersed in liquid helium at a temperature of –271 °C. The cavities sit inside vessels surrounded by thermal shields and an outer tank – a cryostat – to insulate them from the exterior, which will be 300 °C hotter. As many as 8,000 cavities per linac, each roughly a metre long, and placed end-to-end in cryomodules, will drive the electrons and positrons forward.

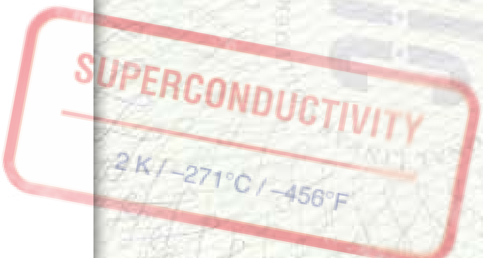
The accelerating gradient

For particles, acceleration means both an increase in speed and an increase in energy. The challenge lies in giving them the highest possible energy over the shortest possible distance. The accelerating gradient is a measure of how much an accelerator can increase the energy of a particle over a certain stretch, typically given in volts per metre. The higher this gradient, the shorter, and hence cheaper, the ILC can be made. For a given length of the machine, the gradient determines the final energy of electrons and positrons before they collide. Basic physics defines an upper limit for superconducting cavities. We are trying to push our cavities as close to this limit as we can. Fifteen years ago the highest gradient achieved was about five million volts per metre. With intense R&D this has increased dramatically, and our target gradient for the ILC is now 31.5 million volts per metre.

Superconducting niobium cavities

How do superconducting cavities work? A voltage generator fills each hollow structure with an electric field. The voltage of the field changes with a certain frequency: a radio-frequency, or rf. Charged particles feel the force of the electric field and accelerate. Build the cavity out of a superconductor, such as niobium, and chill it to near absolute zero and you have a 'superconducting rf cavity.' They conduct electric current with almost no loss of energy, which means that nearly all the electrical energy goes into accelerating the beam, rather than into heating up the accelerating structures themselves.

Designing and building the optimal cavity is not simple. The 1 metre-long cavities are made from nine cells, polished to provide micrometre-level surface smoothness, and free of impurities. Significant surface blemishes or dust could cause them to lose their superconductivity without sustaining the electric field needed to accelerate particles. A series of detailed chemical treatments and processes make the cavities literally sparkle.

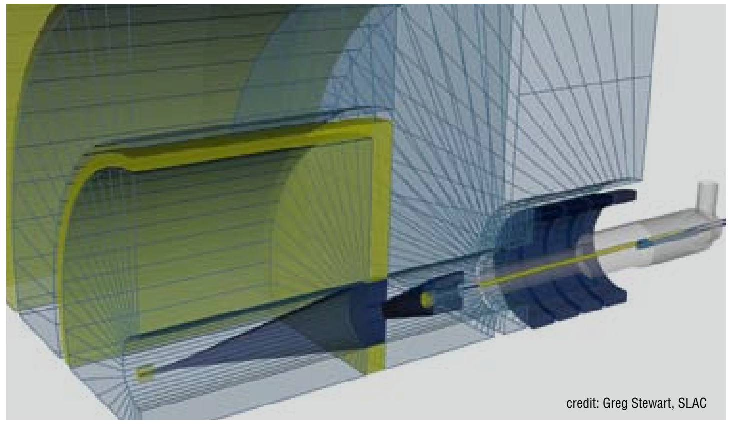


Global collaboration on detectors

For over a decade the exploration of the physics menu, as well as work on the detector designs, their technologies, and related R&D, have been coordinated through a global effort called the *World Wide Study.* The WWS holds annual international workshops, attended by hundreds of physicists. At these meetings, participants present and debate new physics scenarios, and develop and optimise techniques for discovering and measuring the new phenomena.

The vertex detector

At the heart of the massive ILC detector system, the vertex detector, a compact tracking device about the size of a wine bottle, surrounds the interaction region. Consisting of cylinders of silicon detectors, this high-tech device will contain about a billion pixels in total – equivalent to hundreds of the finest digital cameras. It works just like a 3D camera or microscope because it measures the tracks of outgoing particles with micron precision. A few of the colliding particles might contain exotic heavy quarks, which live for a trillionth of a second before they decay to familiar forms of matter. These quarks reveal themselves by decaying at 'vertices' very near the collision point. The exotic quarks, made visible by the vertex detector, are pointers to new physics.



credit: Greg Stewart, SLAC

Luminosity

In order to make discoveries, we require large amounts of high-quality data. The more often electrons and positrons collide, the larger the amount of interesting data that will be produced. This requires a high luminosity, or rate of collisions per cross-sectional area. The ILC requirement of luminosity in excess of 10^{34} electron-positron collisions per square centimetre per second represents a major design challenge. We can achieve this high luminosity by cramming as many electrons and positrons as possible into the smallest beams we can make, and ensuring that the beams collide head-on. In practice this means squeezing more than 10 billion electrons and positrons into beams roughly 5 nanometres tall by 500 nanometres wide, and then steering the bunches into collision using advanced feedback systems.

The particle detectors

The particle detectors will literally provide the centrepiece of the ILC. The detectors will enclose the point where electrons and positrons collide, and they will yield the information needed to unravel the Quantum Universe. Twelve metres long, high and wide to contain all the components, cables and a powerful magnet, they will be as big as a three-storey building and weigh several thousand tonnes.

Employing state-of-the-art technologies, many of which were inconceivable 10 years ago, the detectors will record every collision that takes place and each particle produced. Millions of electronics channels will record the precious information and ensure that nothing is missed.

Armed with this information, we will be able to reconstruct every collision and examine each such 'event' with sufficient precision to understand what happened. This analysis will allow us to find those events that contain dark matter particles, the Higgs particle, superparticles – or completely unanticipated things – and study them in great detail. We intend to use the ILC detectors to measure collisions more precisely than ever before.

The 1 metre-long superconducting cavities are made from pure niobium, treated and tested by scientists to ensure high-performance capabilities for accelerating particles.

Credit: KEK

Credit: Fermilab

04 A GLOBAL PROJECT

The International Linear Collider will be one of the world's largest and most sophisticated scientific endeavours. Planning, designing, funding, and building the ILC will require global participation and global organisation. The particle physics community is used to collaborating globally, but the ILC requires this on a scale larger than ever before.

The Global Design Effort

The *International Committee on Future Accelerators* (ICFA) charged a subgroup, the *International Linear Collider Steering Committee* (ILCSC), with planning a global strategy for the ILC. To carry this strategy forward, the ILCSC established in early 2005 the *Global Design Effort,* an international team of more than 60 scientists and engineers. The GDE team, led by Barry Barish, sets the strategy and priorities for the more than one thousand scientists and engineers at universities and laboratories around the world who are now collaborating on the project.

The GDE team supervised the production of a baseline design for the ILC, which was completed in late 2005. This baseline design has been used as the foundation for the more detailed *Reference Design Report,* which provides a technical description of the project and includes an initial value estimate. The RDR represents a major milestone on the path to reaching a final engineering design and a more detailed cost estimate.

The RDR is a basis for identifying priorities for the next engineering phase of the ILC project, as well as for developing the worldwide R&D programme that will lead to further cost reduction and improved performance.

In parallel, the World Wide Study has produced a *Detector Concept Report.* This document gives the latest snapshot on the conceptual designs, layouts and technologies for the particle detectors.

The GDE process has been monitored by a high-level international group comprised of representatives of funding agencies from around the world: *Funding Agencies for Large Colliders* (FALC). Further international planning, including preparations for construction, will continue in a similar globally collaborative fashion.

Site considerations

The design and R&D effort of the accelerator and detectors for the ILC is distributed among laboratories and universities around the world. Within the next few years we hope to progress to a project with an internationally agreed site. This immense step will depend on input from technical studies as well as considerations by the governments of the nations who might express interest in hosting the ILC.

In producing the RDR, the GDE evaluated sample sites in the Americas, Asia, and Europe. The site must accommodate the 72 kilometres of tunnel complex needed to build the 31 kilometre-long machine, with some sections as much as several hundred metres below ground. There will be 13 major access points with shafts and tunnels up to nine metres in diameter. In total, more than 450,000 cubic metres of underground construction will be required, consisting of the long main tunnels, alcoves, and halls for the detectors and service equipment.

The primary concerns for any site include geological stability, the quality of the rock in which the tunnels would be bored, the mechanical vibrations in the floor of such tunnels due to seismic activity, industrial 'noise' resulting from construction work and traffic, and issues of sealing the tunnels from ground water. Cost estimates were made for the civil engineering at each of the sample sites, involving local construction experts. While there are regional cost variations for particular services, the site-specific cost turned out to be approximately the same for each sample site considered.

The final site selection will involve consideration by many nations of a proposal to host the facility. The procedures will need to be agreed on by the international funding partners.

Credit: DESY


Credit: KEK


Credit: DESY

Cost estimate for the ILC machine

The *Reference Design Report* provides the first detailed technical snapshot of the ILC. One of the most important components in developing this reference design is to understand enough about the costs to provide a reliable indication of the project's scale. Equally important, this preliminary estimate will help guide the final engineering phase of the project. The estimate will be used to study options for further reducing costs, improving performance, and developing a prioritised global R&D programme. The estimate will also provide important information on the relative value of the different components and thereby enable partners to assess their contributions.

This estimate gives a first evaluation of the ILC cost. It serves as a preliminary basis for continuing ILC engineering, and these estimates will continue to evolve. It should not be interpreted as the final or full cost of the project.

What did we estimate?

We estimated two quantities: the VALUE for items provided, and the LABOUR (in person-years). These quantities are independent of individual national costing methods but can be translated into any local currency or costing system. The total VALUE has two components: the value of shared components and the site-dependent value for hosting the machine.

What are shared components?

These are the high-technology components and other technical parts where there is global capability, and we can make a single world estimate. For example, all regions can supply many industrially-made products for accelerators, such as magnets, vacuum pipes, cables, control electronics and power supplies.

What does 'site-dependent' mean?

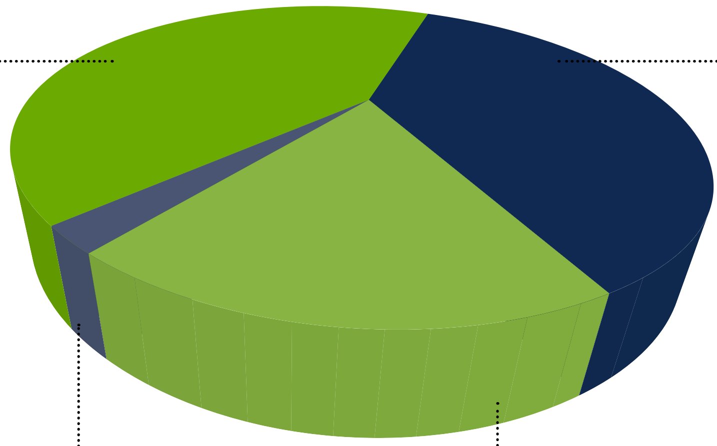
These are such things as tunnelling, where we make separate estimates for each region. The site-dependent elements include all the civil engineering and utilities such as electrical power distribution, water and air cooling, and safety systems. These are generally expected to be the items whose costs will be borne by the host country.

How did we arrive at the estimate?

We obtained our cost estimate by involving technical and costing experts in Europe, Asia, and the Americas. We used a value accounting process that is becoming standard for international scientific projects such as the *International Thermonuclear Experimental Reactor* (ITER). Based on the detailed technical requirements of the ILC, we determined the values of components based on a worldwide call for tender to obtain the required quality at the lowest reasonable cost.

Both LABOUR and VALUE are universally-accepted estimates for each technical component. These figures will be used by partner nations to apportion their contributions fairly. The VALUE and LABOUR estimates can be converted by individual funding agencies to determine costs in their own costing systems and in local currency units.

An approximate breakdown of the ILC estimate by main categories.



What is the estimate?

The estimated value for the shared ILC components or work packages is 4.79 billion ILC Value Units. An important outcome of the shared value costing has been to provide a sound basis for determining the relative value of the various components or work packages. This will enable us to equitably divide the commitments of the world-wide collaboration. The site-specific components and civil construction, which are related to the direct costs to provide the infrastructure required to build the machine, are estimated to be 1.83 billion ILC Value Units. The site-specific values were determined to be almost identical for the American, Asian and European sample sites. The actual site-specific costs will depend on where the machine is constructed and the facilities that already exist at that location. The total shared and site-dependent value excluding labour is therefore estimated to be 6.62 billion ILC Value Units. For this estimate, one ILC Value Unit corresponds to 1 US Dollar (2007), 0.83 Euros or 117 Yen.

The explicit labour required to support the construction project is estimated at 14,000 person-years or 24 million person-hours; this includes administration and project management, installation and testing and assumes 1,700 person-hours per person-year. This labour may be provided in different ways, with some being contracted and some coming from existing labour in collaborating institutions.

What does the estimate include and exclude?

The VALUE and LABOUR amounts include:

- construction of a 500 GeV machine and the essential elements to enable an optional future upgrade to 1 TeV;
- tooling-up industry, final engineering designs, and construction management;
- construction of all conventional facilities including tunnels, surface buildings, detector assembly buildings, underground experimental halls, and access shafts; and
- explicit labour including that for management and administrative personnel.

The VALUE and LABOUR amounts exclude:

- engineering, design or preparation activities that must be accomplished before project funding, such as R&D, proof-of-principle studies, and prototype tests;
- surface land acquisition or underground easement costs;
- detectors, which are assumed to be funded by a separate agreement;
- contingencies for risks; and
- escalation (inflation).

Credit: KEK

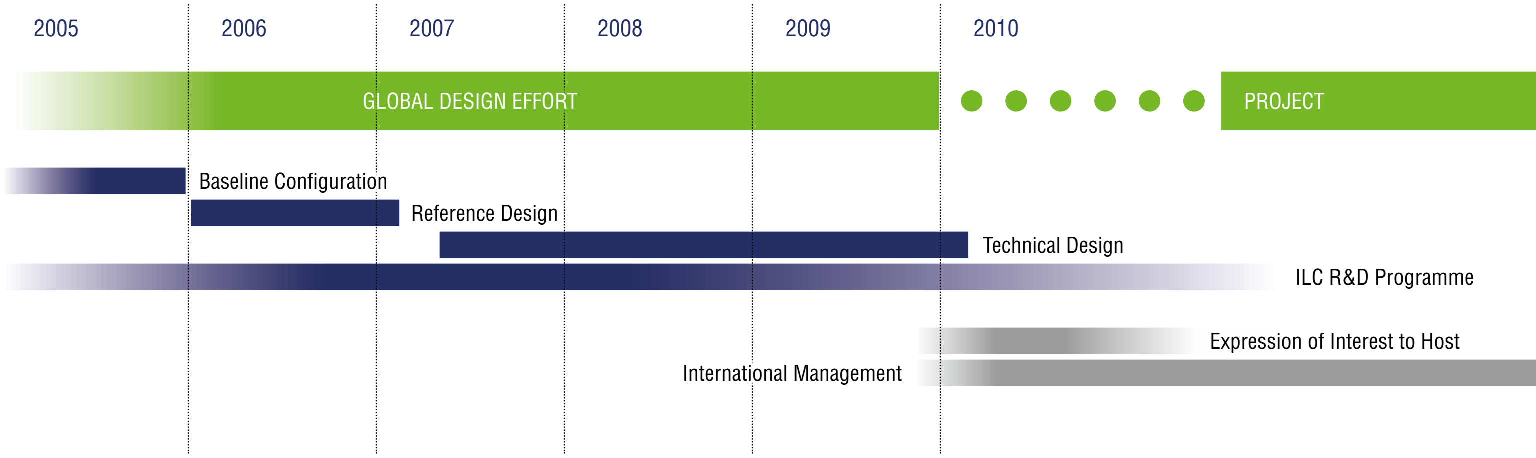
ILC scientists from America,
Asia and Europe meet regularly via
videoconference.

To arrive at an estimate, the GDE used a value accounting process that is becoming standard for international scientific projects.

The next steps

Since the decision to use superconducting technology in mid-2004 and the subsequent foundation of the GDE in early 2005, the ILC has made remarkable progress. The publication of the RDR completes this initial phase and marks the beginning of a new era.

In the next steps we will evolve and improve the design through continuing R&D and value engineering. We aim to make engineering choices for further optimising the performance relative to cost. This process will take several years using the solid basis provided by the RDR, and will lead to a detailed technical design. This design will form a 'blueprint', with a refined cost estimate, so that ILC construction could start at the selected site early in the next decade. In parallel, the World Wide Study teams will continue to perfect the designs of the particle detectors. Starting from the formal project approval, we estimate the time for construction of the accelerator complex and detectors to be approximately seven years.



A possible technical timeline for the ILC

Credit: KEK

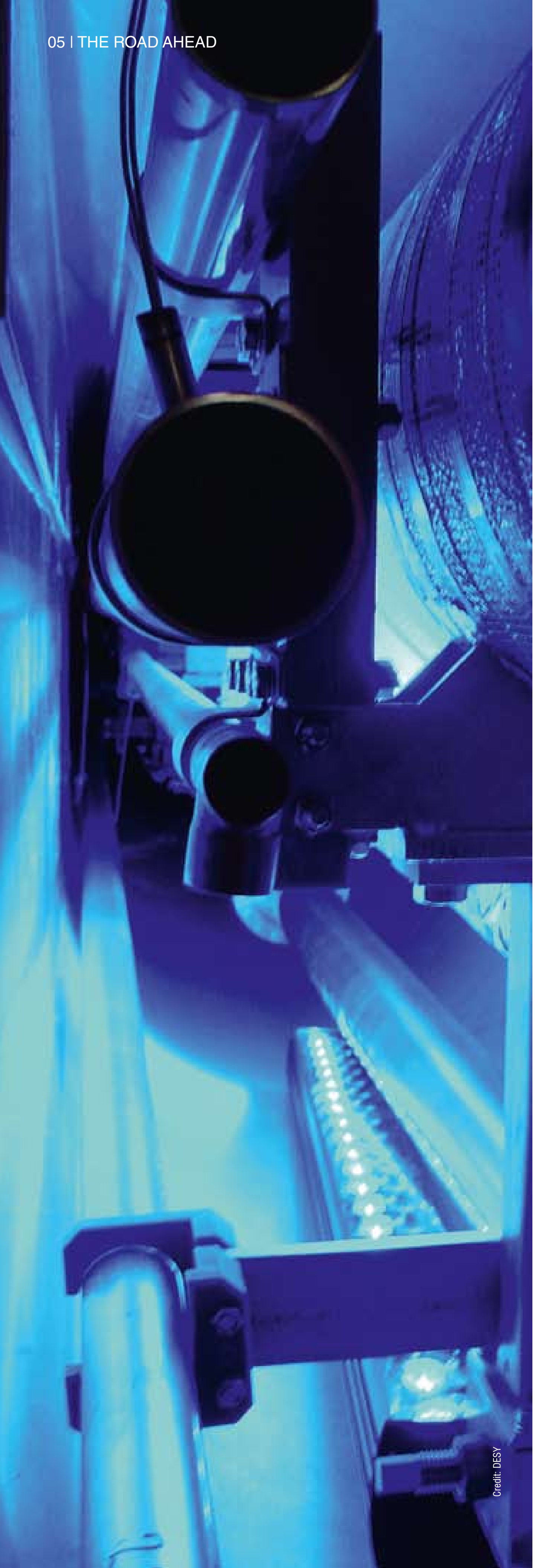
05 THE ROAD AHEAD

Every day, hundreds of thousands of people board aeroplanes to places they want to explore. They return with stories, impressions and new perspectives on everyday things. Every day, hundreds of thousands of babies are born. As they grow, they learn to ask questions about the world and their place within it. Curiosity, exploration and discovery drive our lives, and it is up to us to set the boundaries of the things we wish to know.

The next generation

In order to explore the subatomic world, high-energy physicists need to navigate the everyday world. A typical physicist might have studied at university with Americans, Germans or Indians, shared an office with Korean or Japanese graduate students, solved problems at a summer school with Russians and French, shared friendships with Britons and Italians, worked on data with Canadians and Japanese, and attended meetings in Finland and China. These experiences and the knowledge of different cultures become second nature. Physics graduates take their open-mindedness with them to jobs beyond universities and laboratories. More than half of the students who gain their PhDs in particle physics go on to work for high-tech industry, financial institutions, and information technology businesses. Demand for their talents arises because of their broad skills, as well as their physics knowledge. This benefits all of us.

Today at laboratories and universities around the world, several hundred students, under the guidance of senior scientists and engineers, are already contributing to the ILC. They are working together across time zones, borders, and languages. The ILC provides a beacon for future worldwide collaborations in science, technology, and beyond. It will take international collaboration in science and technology to new levels and can be a model for the emerging science projects of our new century.



Credit: DESY

Industries around the world will play a major role in building the ILC, including these cryomodules.

Fast track for industry

We need strong partners in industry and technology to help us realise the ILC. Companies across the globe will be part of the adventure. They will produce the millions of components, from the tiny to the huge, from the delicate to the robust. Many will push the state-of-the-art in terms of precision, reliability, and volume of production. We need, for example:

- 16,000 superconducting cavities made from pure niobium;
- 2,000 cryomodules to enclose the cavities, at temperatures as low as deep outer space;
- 700 klystrons, pacemaker-like devices that power the machine, firing in synchronisation with precision timing;
- Over 70 kilometres of tunnel complex.

These, and many more, are truly staggering requirements. We are confident that industry will take up the challenge; it will put companies on a fast track towards new products and life-changing technologies. Scientists, engineers, and industry representatives are already talking to each other to understand how to achieve these goals. In ILC industrial forums around the world, experts from the scientific and industrial partners are cooperating to develop prototypes, optimise designs for large-volume production of high-quality technical components, and figure out how to meet the tolerances and specifications. All of this must be done at an affordable cost.


Credit: DESY

The ILC will need 16,000 of these superconducting cavities, produced by the project's industrial partners.


Credit: Fermilab


Credit: KEK


Credit: Fermilab

Technical components from all corners of the world will have to fit together seamlessly. For example, the beams should never know or care where a niobium cavity was made. Voids, impurities or imperfections in a cavity could spoil its superconductivity; at best this would compromise performance, and at worst affect our science achievements. We need to understand the risks, minimise them, and take account of them in the industrial design so as to maximise overall performance.

The particle physics community is used to developing special tools, and we already know that many of our technologies have significant applications in other fields closer to everyday life. The World Wide Web is an example known to everyone that has transformed society. Perhaps less widely known, but of profound importance, are the roughly 20,000 accelerators in applied use around the world today. Roughly half are used for medical diagnosis and treatment, including cancer therapy. Medical advances based on these technologies will continue to make a huge impact on our lives.

The same will be true of the technologies that we are working on for the ILC. Today, accelerators based on superconducting technology are being planned and built for use in many areas of science and medicine, such as next-generation X-ray imaging facilities. Our development of advanced diagnostic tools and techniques, control systems, and methods for handling vibration isolation, for example, are all key technologies for these new facilities.

Beyond the horizon

We know our destination: the answers to the big science questions. We know our means of transport: the International Linear Collider. Our next milestone on the journey is the *Technical Design Report,* which will form the basis for proposals to governments for siting and building the ILC. Even in the years that lie between here and this milestone there will be great advances: we will improve our technologies; the LHC will deliver its first glimpse of the Terascale. The results will capture all our imaginations. New questions will emerge, and the ILC will be our vehicle for understanding what we find with the LHC.

When we launch the ILC, huge tunnel boring machines will eat their way through more than 70 kilometres of tunnels and shafts. The milestones will come thick and fast: tunnels completed, manufacturing processes perfected, first cryomodule delivered, last magnet installed, detectors lowered into their cavern, first beams in the accelerator, first collisions, first science. We are eager to get there.

What are the building blocks of matter, and how do they fit together to shape the world? Are there more dimensions than the three known to our everyday senses? Are all the forces of nature aspects of a single unified whole? Where does matter come from? What is the nature of the dark matter that binds galaxies together?

We want to solve these mysteries.

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