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NEW PHYSICS WITH THE COMPACT LINEAR COLLIDER

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Abstract

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Introduction

Over the past decades, physicists' understanding of elementary particles and the forces that bind them has become enshrined in the picture known as the Standard Model. According to this model, the constituents of matter are particles of two basic varieties — quarks (which come in six varieties and, combined in threesomes, form protons and neutrons) and leptons (again, in six types, including the familiar electron, the muon, the tau and three types of neutrinos) (see Box 1). The forces between these particles are mediated by the exchanges of further particles, the 'messenger' bosons, the most familiar example of which is the photon, mediator of the electromagnetic force. The Standard Model is a highly successful theory, agreeing perfectly with all confirmed data from particle accelerator experiments, and describing accurately the characteristics of three of the four fundamental forces, the electromagnetic force and the strong and weak nuclear forces.

But the Standard Model has its limitations. As a theory, it is not entirely satisfactory, incorporating many arbitrary parameters. Moreover, it tells us nothing about gravity, the fourth and weakest of the fundamental forces; and there are hints from non-accelerator experiments observing neutrinos — ghostly particles that barely interact with other matter — that their behaviour cannot be fully accounted for in the Standard Model.

Therefore, in the twenty-first century the top priorities at particle accelerator laboratories around the world will be experiments probing beyond the Standard Model[1]. Indeed, this is surely the only motivation for major new particle accelerators that is easy to explain to funding agencies, other scientists and the general public.

Problems beyond the Standard Model may conveniently be gathered into three main classes: those of mass, unification and flavour. Let us take these one at a time. What is the origin of the particle masses? One possibility is that they arise through interaction with an all-pervading 'Higgs' field, which makes the vacuum behave like a superconductor. The question then is whether this field is composite, like the Cooper pairs of conventional superconductivity, or whether there is an elementary Higgs boson particle. If so, two related questions that arise are why the particle masses are so different (the mass of the top quark, for instance, is around 180 times that of a proton), and why they are so small. (One might well ask, 'Small relative to what?' The answer is that there is a natural scale of mass known as the Planck mass, obtained by combining the three universal constants — the speed of light *c*, Planck's constant, and *G*, the gravitational constant — and this mass is more than a billion billion times that of the proton.) Keeping the known particle masses small seems more natural mathematically if the Higgs boson is accompanied by a whole spectrum of new particles related to the known ones by supersymmetry: they would have the same interactions as the known matter particles, but be bosons rather than fermions.

Next is the problem of unification. The electromagnetic and weak nuclear forces can be regarded as different manifestations of the same underlying phenomenon; their theories have been successfully combined into one 'electroweak' theory. Is there likewise a simple framework containing the strong, weak and electromagnetic interactions, and does it predict new observable phenomena such as proton decay and neutrino masses?

Finally, flavour. Why are there so many types of quarks and leptons? Looking at Box 1, we can see that there are six of each variety, not counting their antiparticles. How can one understand their weak mixing and the small, observed difference between matter and antimatter? Perhaps because the quarks are composite?

To probe ever deeper into the structure of matter, one needs to go to higher energy experiments. Accelerator experiments essentially do two things: by smashing vastly accelerated particles into each other, they can either probe the particles' internal structure or create new particles. If one is looking at structure, higher energies provide improved resolution; if one wishes to create new particles, higher energies can create heavier species (remember Einstein's famous equation $E = mc^2$). There are good reasons to expect a wealth of new physics in the teraelectronvolt range (1 TeV is 10^{12} eV, about 1,000 times the energy required to make a proton), in particular that connected with the origin of particle masses. This new physics might include a Higgs boson, but most physicists would expect the new physics to be more complex, perhaps including the new spectroscopy of supersymmetric particles mentioned above, or perhaps something even more exotic. (At the time of writing, there is speculation whether a Higgs boson may have been produced already at the Large Electron–Positron Collider (LEP) at the European Organization for Nuclear Research (CERN); if true, it suggests that supersymmetric particles might be 'just around the corner'[2].) Another possibility is that there might be extra dimensions of space-time that might show up in particles' internal structures, or be associated with new particles produced in the TeV energy range.

CERN is fortunate to have the Large Hadron Collider (LHC), a proton–proton collider with a centre-of-mass energy of 14 TeV, as an approved project. The LHC is currently under construction and scheduled for completion in 2006, which will provide a first glimpse of any new physics at energies up to about 1 TeV (in collisions between complex, multi-quark particles, not all of the energy is available for creating new particles). What it will find cannot be foreseen, but it is impossible to expect that experiments at the LHC will answer all the questions concerning this new physics. For example, particle physicists are likely to want more information about any kind of Higgs boson than the LHC can give us. Moreover, if nature has chosen supersymmetry, it can be expected that the LHC will reveal a number of supersymmetric particles but not all of them. And if the mechanism for generating particle masses turns out not to be an elementary Higgs boson but some new strong interaction, the hints that the LHC would provide should be followed up by other experiments.

Many of the open questions may be addressed best by a lepton–antilepton collider — one in which, for instance, electrons collide with their antiparticles the positrons, annihilating each other in a burst of pure energy, which in turn can create new particle–antiparticle pairs. In such a machine, all the centre-of-mass energy may be made available for the collisions between elementary particles, the experimental environment is relatively simple and clean, and all charged particles are produced democratically with similar cross-sections. Proton colliders and lepton colliders are complementary: the $W^{\pm}$ and Z^0 bosons were discovered in the Super Proton Synchrotron (SPS) proton–antiproton collider, but it was LEP which made possible precision measurements of their properties and detailed tests of the standard electroweak theory.

Various laboratories are proposing electron–positron colliders with maximum centre-of-mass energies around 1 TeV, including SLAC (Stanford Linear Accelerator Center) and Fermilab (Fermi National Accelerator Laboratory) in the United States (1 TeV)[3], DESY (Deutsches Elektronen-Synchrotron) in Germany (0.8 TeV)[4] and KEK (High Energy Accelerator Research Organization) in Japan (1 TeV)[5]. Such machines would be able to explore in detail the properties of any relatively light Higgs boson and have a chance of producing lighter supersymmetric particles, but would probably not be able to explore all the supersymmetric spectrum, or study in detail any new strong interactions. Complete coverage of these issues, and hence full complementarity with the LHC, probably requires a lepton–antilepton collider with a centre-of-mass energy of 2 TeV or more.

This is the objective of the Compact Linear Collider, or CLIC as it is known. Plans for CLIC have been under way for several years at CERN, in collaboration with other accelerator laboratories[6].

As we will describe later, the CLIC study team is proposing a new scheme of beam acceleration to enable electrons and positrons to be collided at energies ranging possibly from 0.2 TeV (for some overlap with LEP) up to a maximum of about 5 TeV (in stages). A road map has been drawn up to complete the research and development (R&D) necessary over the next several years to demonstrate the technical feasibility of a 3-TeV centre-of-mass collider. The alternative of colliding muons and antimuons at comparable energies is also being explored at CERN and elsewhere[7]. In particular, CERN is conducting studies of the intense proton source that would be needed for such a muon collider. Bringing muons into collision at high energies would, however, require considerable R&D on cooling and other issues, so construction of any such high-energy muon collider is almost certainly on a longer timescale than CLIC.

The conceptual design of CLIC

One of the bugbears of high-energy electron–positron machines is synchrotron radiation: that is, the radiation emitted whenever beams of charged particles change direction. To combat the resulting energy loss, the circumferences of circular machines must increase rapidly with the energy. Scaling up CERN's present LEP accelerator, which is 27 km in circumference, one sees that a circumference of thousands of kilometres would be required to reach a centre-of-mass energy of 3 TeV. For this reason, future electron–positron colliders will be designed as linear machines.

CLIC's proposed overall layout is sketched in Fig. 1. The particles are accelerated to high energies by very high on-axis electric fields produced by the radio-frequency (r.f.) accelerating structures. Although the parameters correspond in terms of energy and luminosity to the desires of the physics community, there is a price to bear: to achieve the required luminosity requires the beam sizes at the interaction point to be very small (in the nanometre range), and the resulting very intense beam–beam interaction creates a spread in beam energy owing to photon radiation.

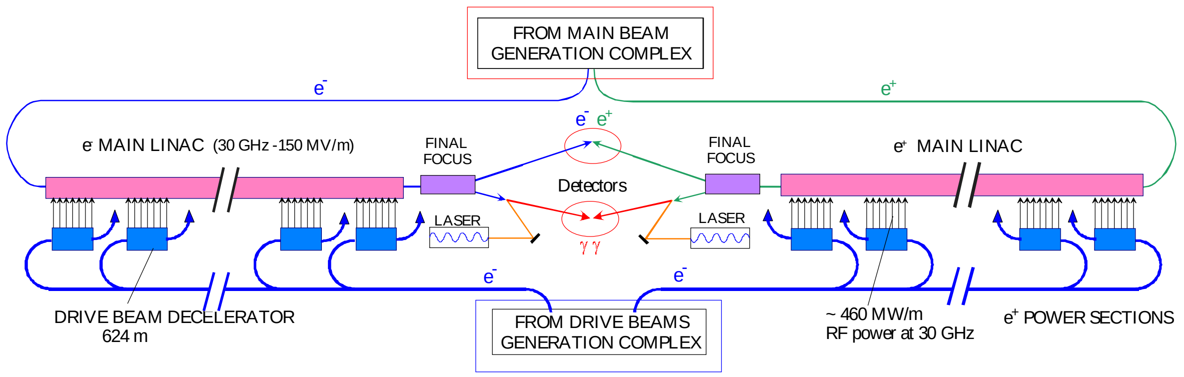

Figure 1: Overall layout of the CLIC complex.

The CLIC scheme[6] has two key features that distinguish it from other, lower-energy linear collider studies[8]. The first is the operating frequency of the accelerating structures in the main linacs. To limit the length and cost of these linacs, high accelerating fields are mandatory, and experience has shown that these can be obtained (with conventional acceleration mechanisms) only by operating at a high frequency. CLIC has therefore chosen to operate with a radio frequency of 30 GHz, in the hope that it can achieve accelerating gradients as high as 150 MV m^{-1}. The resulting total length of 37.5 km for a 3-TeV collider is comparable to the circumference of CERN's present LEP accelerator.

The second distinctive feature of the CLIC scheme is the way in which it generates the r.f. power that produces the accelerating field. High-intensity but low-energy ‘drive beams’ of electrons run parallel to the main beam, and the power is extracted from these by specially designed decelerating structures. This is a particularly attractive feature, because the energy for r.f. power production is in the electron beam, which can be transported over long distances with very small losses, and the r.f. power is generated locally only where it is required. In fact, the transport distance from the drive linac to the main linac is then only about 60 cm. It should be noted that to generate an accelerating gradient of 150 MV m^{-1} requires the production of peak pulsed powers of 460 MW per metre length of the linacs but only for a very short time of 120 ns.

Generating the intense CLIC electron drive beams is far from straightforward. Years of study at CERN have resulted in a scheme involving the manipulation of intense electron beams to achieve both r.f. multiplication and power compression[8]. The scheme involves the following steps. First, generate the electron beam, using either a thermionic gun or a laser-illuminated photocathode. The second option is particularly demanding because it requires the generation of a huge charge from the photocathode (750 μC during 92 μs), and an average laser power of 860 W in the infrared to give 23 W in the ultraviolet. This is well beyond what can be achieved at present. Next, accelerate this beam to 1.2 GeV using a fully loaded linac operating at a relatively low frequency (937 MHz). The description ‘fully-loaded’ means that the beam takes almost all the energy (96%) from the structure, which is good for efficiency but makes the linac more difficult to operate. The r.f. power for the low-frequency linac is provided by about 200 50-MW klystrons. These klystrons would normally be very classical, were it not for the fact that the pulse length required is about 100 μs. The development of such long-pulse klystrons is one of the many challenges of the CLIC scheme, and is being studied by European industry.

The electrons in the beam at this stage are in bunches spaced 64 cm apart, which is a requirement to be able to accelerate the beam with the available low-frequency technology. The beam has all the required bunches for the 22 drive beams needed for one linac of a 3-TeV collider. But the spacing has to be reduced to 2 cm, to be able to generate the 30 GHz power, and this is done by funnelling the beam in compressor/combiner rings. The trick is to take successive parts of the beam and interleave them to reduce the bunch spacing (this is called frequency multiplication), and it also results in an increased line density of the charge, which is effectively pulse compression. There are three stages of frequency multiplication in the CLIC scheme (the delay line and two combiner rings) giving a total compression factor of 32.

The layout of the r.f. power source is shown in Fig. 2. The resulting long train of separated drive beams is then sent into the main tunnel. Each drive beam is used to provide r.f. power for a 625-m section of the main linac, after which the beam is sent to a dump and the following drive beam takes over, as in a relay race.

If this scheme is considered as a black box, 1 GHz r.f. power is put into one side, and pulse-compressed 30 GHz r.f. power comes out from the other side. An attractive feature of this scheme is that generating more or fewer drive beams to power a higher or lower energy collider requires only a longer or shorter modulator pulse, but the number of klystrons does not change. This so-called ‘two-beam’ acceleration scheme is generally acknowledged to be the only cost-effective way of building multi-TeV electron–positron colliders. A virtue of this scheme is that it leads to a simple tunnel layout. The tunnel has only to house the two linacs, supported on a solid concrete base the width of a table-top (albeit a long one), and the various beam transfer lines together with their beam-focusing quadrupole magnets. A tunnel diameter of 3.8 m, the same as LEP, would be adequate.

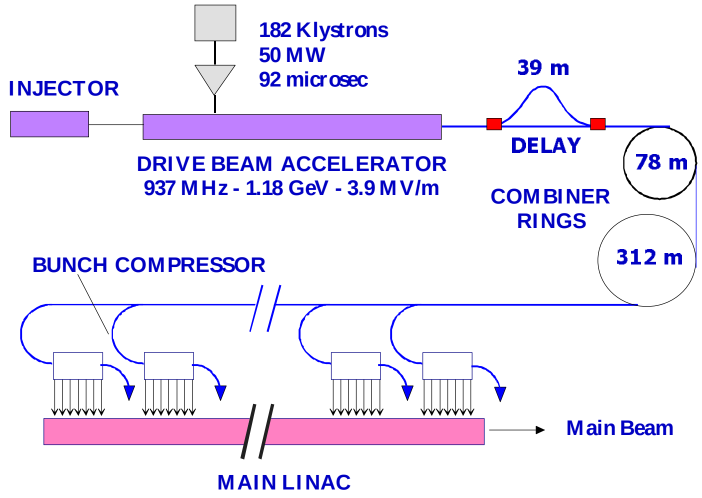

Figure 2: Layout of the r.f. power source.

Turning our attention now to the interaction point, we see that a steep technical challenge is imposed. The interaction rates for the processes of interest generally decrease as the square of the centre-of-mass energy. So the collision rate (luminosity) of a high-energy collider should be much greater than that of LEP, which reached around 10^{32} collisions cm^{-2} s^{-1} at a centre-of-mass energy near 200 GeV. Hence the request to the accelerator designers is for a machine capable of around 10^{34} collisions cm^{-2} s^{-1} at a centre-of-mass energy of 1 TeV (or 10^{35} collisions cm^{-2} s^{-1} at 3 TeV). Therefore, the CLIC study team has been forced to select beam parameters that are at the edge of what is considered to be technically feasible. The vertical beam size, for example, has to be focused down to 1 nm at the interaction point. This implies the generation of very small emittance beams using damping rings with a performance more than five times better than has been achieved in the present state-of-the-art damping ring at KEK in Japan[9]. (Emittance is a measure of the density of the particles in the transverse plane of the beam.) This emittance has then to be preserved during the acceleration process, in spite of perturbing transverse deflecting fields, which increase as the cube of the frequency. Potentially this is a large disadvantage of using 30 GHz, but it can be surmounted if other parameters are chosen carefully. Indeed, it has been shown that the same beam stability can be achieved in a high-frequency linac as in a low-frequency linac, by making a judicious choice of parameters according to general scaling laws[10].

This analysis of beam stability assumes that the accelerating structures can be designed to suppress any generated perturbing fields by a factor of 100 in a time of 0.7 ns. Such a structure has been developed at CERN[11], and tested with an electron beam at SLAC[12]. It consists of a regular copper travelling-wave accelerating structure with each of its 150 cells damped by its own set of four radial waveguides.

Working at 30 GHz provides huge technological challenges. The fabrication of the 30-GHz accelerating structure, for example, requires the machining of copper component parts to a precision of 1 µm, using state-of-the-art lathes developed initially for the mass-production of contact lenses. Another consequence of choosing 30 GHz is that the beam aperture, which is inversely proportional to frequency, is only about 3.5 mm in diameter along the 13.75 km length of the linac. Seen from the outside this is stunningly small, but should provide adequate space when viewed by the electron beam.

To keep the perturbing fields within acceptable limits imposes another stringent condition. The components in the linacs have to be aligned transversely and maintained in position to within 5–10 µm along typical lengths of about 200 m. This requirement means that a static one-time alignment of the linacs is insufficient, and imposes an active-alignment system that automatically reacts to the continuous drifts of the components. Such a system has been developed at CERN using state-of-the-art technology including 0.1-µm resolution stepping motor drives, capacitive position monitors (in which the position of a conducting wire between two capacitive plates changes) and hydrostatic levelling systems, and has been used in a real accelerator environment to maintain components in position to within 1–2 μm.

Colliding and maintaining 1-nm beams in position is clearly far from easy. It imposes a jitter tolerance of 0.2 nm on the final focusing elements of the beam delivery system. Stabilization of magnetic quadrupoles to this level is a huge challenge and demonstrating its technical feasibility is a priority. Two stabilization schemes are being considered: the first is an optical anchor to the nearby bedrock using laser interferometers, the second is based on inertial sensing and compensation using piezo-movers.

Tests and prospects

Preparing such a novel accelerator concept requires years of R&D before a concrete project can be proposed. The ideas proposed by the CLIC study team are currently being probed in a series of test facilities, and outlines prepared for future studies.

The first test facility, operating from 1990 to 1995, demonstrated the feasibility of two-beam power generation, albeit at lower field gradients than will ultimately be required. A second test facility is now being operated[13]. It consists essentially of a 6-m long, two-beam test accelerator driven by an intense 40-MeV and 3-GHz bunched beam. The 30-GHz part of this facility is equipped with an active-alignment system capable of alignment to a precision of a few micrometres. This facility is being used as a test bed to study the generation of short intense electron bunches, to develop diagnostic equipment, and to generate high-power 30-GHz r.f. pulses for high gradient testing of accelerator components.

A new facility (CTF3) is to be constructed in collaboration with LAL (Laboratoire de l'Accélérateur Linéaire, France), LNF (Laboratori Nazionali di Frascati, Italy) and SLAC, which would test all major parts of the CLIC r.f. power scheme[14]. To reduce cost, it is based on the use of 3-GHz klystrons and modulators recuperated from the LEP Injector Linac (LIL). Construction will start after the closing of LEP, and its study programme should continue until about 2005. At that time, a conceptual design report could be made for CLIC1, a prototype CLIC test accelerator consisting of one complete drive-beam and acceleration unit. This test accelerator would be capable of accelerating a beam to 75 GeV and would, if successful, provide a convincing demonstration of the technical feasibility of the CLIC two-beam scheme.

What might CLIC see?

For lower-energy electron–positron colliders, detailed studies of the physics abound. These give us clues to the physics that CLIC might have to offer. A more comprehensive study of CLIC's specific possibilities has recently been initiated at CERN.

The preliminary studies indicate clear complementarity between the physics prospects for the LHC and CLIC. In particular, CLIC has unique prospects for finding any new particles that do not have strong interactions. One issue is that, although CLIC is much less wasteful than proton–proton colliders, compared with lower-energy electron–positron colliders it loses a relatively large fraction of the beam energy in the form of radiation from the initial-state particles. It is important to be satisfied that the resulting beam-energy spread permits experimental investigation of the full richness of the available physics[15].

One of the first examples of new physics to be considered is a new Z′ particle akin to the Z boson, the known carrier of the weak interaction, which arises generically in models with new strong interactions or large extra dimensions. It might show up as a 'resonance' — that is, a bump in the plot of the interaction rate against beam energy when the latter is tuned to the Z′ mass. Fig. 3 shows a simulation of what such a Z′ particle might look like at CLIC. Photon radiation reduces the total cross-section by a larger factor than for the Z at LEP, but the resonance is clearly visible. CLIC could easily be a Z′ factory, just as LEP was a Z factory in its initial stages.

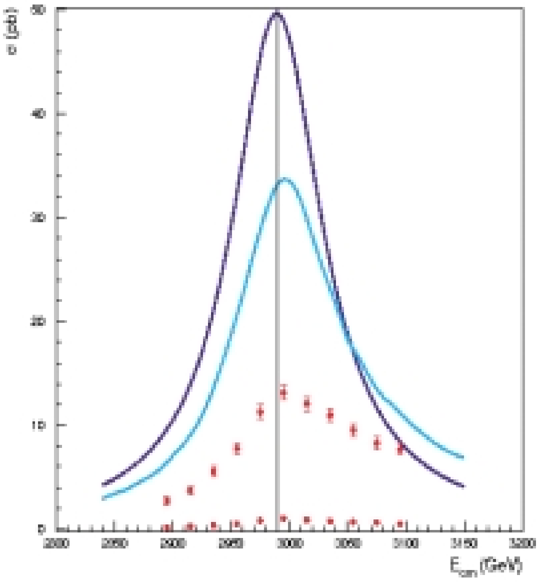

Figure 3: *Simulation — preliminary as yet — of Z′ production at CLIC. The vertical axis measures the event rate (in picobarns), and energy is plotted on the horizontal axis. Solid lines indicate the rates expected without photon radiation (green) and with the minimum amount of radiation possible (purple) in an idealized collider. The simulated data points are for quark–antiquark production (upper blue trace) and lepton–antilepton production (lower red trace), including the photon radiation expected at CLIC. Both processes are clearly visible.*

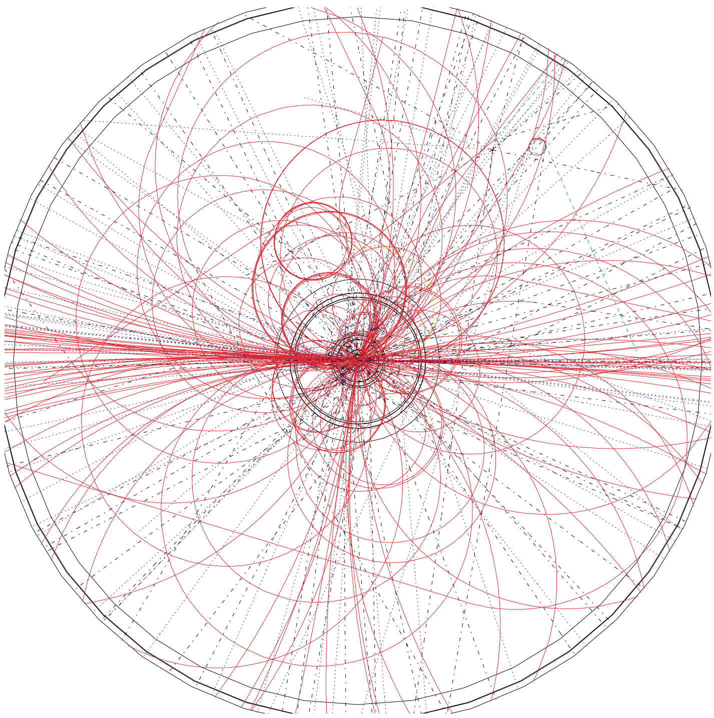

Figure 4 (a): *New physics that CLIC might explore. Simulations of charged-Higgs-boson pair production and decay. Charged Higgs particles are unstable and decay into jets of other charged particles that leave tracks in an experimental detector. The jets need to be combined to identify the charged Higgs bosons.*

In more recent years, LEP has studied the production of pairs of W particles, and has also been looking for a neutral Higgs boson, produced in association with the Z boson. We do not yet know what new particle thresholds CLIC might be called upon to explore, but two examples are shown in Fig. 4. Figure 4a shows a simulation of an event in which a pair of heavy charged Higgs bosons, predicted in supersymmetric models, have been produced, and Fig. 4b shows a simulation of an event in which a pair of selectrons have been produced (these are the proposed supersymmetric counterparts to electrons), one of which decays into a lighter neutral Higgs boson. These events give some flavour of the richness of the new physics that would be accessible to CLIC, including many topics that extend beyond the reach of the LHC.

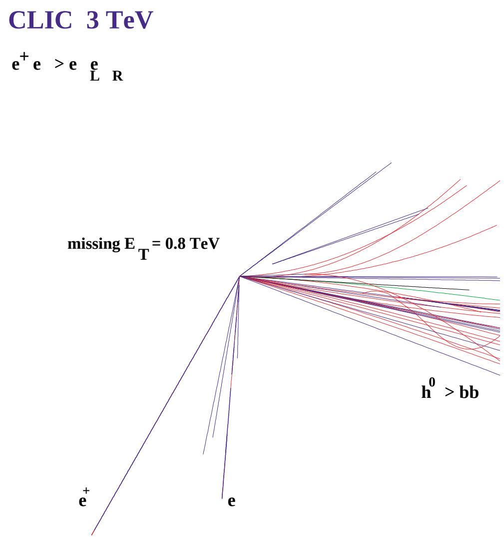

Figure 4(b): *New physics that CLIC might explore. Simulations of selectron pair production and decay. One of the produced selectrons decays directly into an electron and an unseen neutral supersymmetric particle, whereas the other decays via a cascade including a neutral Higgs boson.*

As already mentioned, the interaction rates for many interesting processes such as these decrease as the square of the centre-of-mass energy — hence the request to the designers for a machine capable of 10^{34} collisions cm^{-2} s^{-1} at 1 TeV, and higher still at 3 TeV.

New technologies

What about the technological spin-offs from CLIC? We touched earlier on several of the leading-edge technologies required. Many need considerable R&D, in collaboration with other accelerator laboratories and European industry.

Although the CLIC design has been optimized for a centre-of-mass energy of 3 TeV, the collider could start operation at a lower energy and then be upgraded in stages. These upgrades could be made without major modifications. The basic CLIC scheme could of course be adapted to generate r.f. power at lower frequencies and indeed SLAC is studying a two-beam scheme at 11.4 GHz. The cost advantage of using the two-beam scheme becomes more pronounced as the energy increases and there is a consensus within the community that future multi-TeV colliders will probably be based on the two-beam scheme. In the range 0.5–1 TeV, it is difficult to say how the cost would compare with the lower-frequency classical acceleration schemes currently being proposed in the United States[3], Germany[4] and Japan[5].

More generally, one may wonder whether the principle of a high-gradient (long) table-top electron linac might be of interest in other applications. But we should not forget that there is a price penalty to be paid compared with conventional systems at very low energies, because to produce beams of only a few GeVs requires the building of the entire drive-beam generation complex. Existing electron accelerator technologies are already used extensively for synchrotron radiation sources, and some of the linac designs now being proposed offer exciting prospects for free-electron lasers and X-ray sources. This is an obvious use of the beam generated by the CLIC1 facility, and studies in this direction are starting.

As mentioned above, for CLIC to be successful, its subsystems require technological developments that may find applications elsewhere. Examples include the work going into high-power diode-pumped lasers for CLIC, which could benefit the development of laser-produced plasma sources of extreme ultraviolet light that are used in industry for photolithography. The development of the klystrons for the drive beam is based on multi-beam technology that is relatively new for European industry, and will bring benefits of improved efficiency and lower voltage which will almost certainly find other applications. Furthermore, if the technological challenges of high-precision fabrication, alignment and stabilization can be met, all of these could lead to significant technological spin-off.

Other possible applications of the CLIC technology are under study, and may be found in the least obvious places. When particle accelerators were first developed in the 1940s, nobody foresaw their medical applications (for example, positron emission tomography scanning or hadrotherapy), or their applications to other areas of science (synchrotron radiation was initially regarded as an annoyance). Still less did anybody foresee that accelerator experiments would drive the development at CERN of the World-Wide Web. A recent unexpected application of accelerator technology concerns the flat ribbon-like non-evaporable getter pumps developed for the LEP vacuum system, which will almost certainly be used for flat-panel displays, electron tubes and vacuum-insulated devices. Because past breakthroughs in accelerator technology have found unforeseen uses in other fields besides particle physics, we expect that CLIC will surely do the same.

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Glossary of terms: particles, forces and accelerators

Bosons: Particles of integer spin that carry forces.
CLIC decelerating structure: Device that generates microwave power when driven by an intense bunched electron beam.
Electromagnetic force: Holds atoms together by acting between charged particles, mediated by massless photons.
Fermions: Particles of half-integer spin that compose matter, comprising quarks and leptons.
Flavours: Different types of matter particles.
Gravitational force: Long-range, believed to be mediated by the massless graviton, whose existence has not yet been confirmed by experiment.
Hadrons: 'Heavy' particles that interact via the strong nuclear force, such as the proton and neutron, formed from combinations of quarks.
Higgs: A hypothetical field, believed to permeate the universe, providing masses for all the fundamental particles. Carried by the Higgs boson, whose existence has not yet been confirmed by experiment, although hints have recently been observed at LEP.
Klystron: High-power source of radio-frequency energy.
LEP (Large Electron–Positron Collider): Accelerator colliding electrons and positrons at energies up to 105 GeV each. Housed at CERN in a tunnel with a circumference of about 27 km.
Leptons: 'Light' particles that do not interact via the strong nuclear force. They come in six types (flavours): the electron and its heavier charged cousins, the muon and tau, together with their three neutrinos.
LHC (Large Hadron Collider): Accelerator colliding protons at energies of 7 TeV each, to be installed in the tunnel previously holding LEP.
Linac: Linear accelerator in which large alternating voltages are used to accelerate charged particles in a straight line; the concept dates back to the 1920s.
Quarks: The basic constituent particles of the proton, neutron, pion and stranger relatives. Interact via the strong nuclear force. They also come in six types (flavours): up and down, strange and charm, bottom and top, with increasing masses.
Radio-frequency accelerating structure: Device that produces strong on-axis electric fields when powered by a high-power source of microwaves.
SPS (Super Proton Synchrotron): Accelerator used to collide protons and anti-protons at energies up to 540 GeV.
Standard Model: The theoretical description of the forces of nature and elementary particles. It describes the fundamental forces between matter particles via the exchanges of bosons. Tested to high accuracy by experiments at the LEP accelerator at CERN, and elsewhere.
Strong nuclear force: Holds protons and neutrons in the atomic nucleus, and quarks inside protons and neutrons, mediated by massless gluons.
Supersymmetry: A mathematical theory which suggests that, for every known type of particle, there should be a heavier 'supersymmetric partner', with identical internal properties, but different spin. Hypothetical as yet, the counterparts to the bosons are fermions with names ending in 'ino' (for example, chargino, photino, gluino) and those of the leptons and quarks are bosons whose names have an initial 's' (selectrons, squarks).
Weak nuclear force: Short-range, responsible for beta decay of radioactive nuclei, mediated by heavy W and Z bosons. Their existence was confirmed experimentally in 1983, and they have been studied in detail at LEP during the 1990s.