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Particle accelerators at CERN: From the early days to the LHC and beyond

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ABSTRACT

The Standard Model of particle physics is a theory, developed in the 1970s, which aims to explain how fundamental particles, governed by four fundamental forces interact. The discovery of the Higgs boson has opened up a lively debate as to what is the best way forward to try to crack the Standard Model and to reveal the more fundamental nature of the physical phenomena. This article examines the contribution of particle accelerators to our understanding of this model, by both taking stock of past achievements and future challenges, with a specific focus on the Large Hadron Collider (LHC).

1. Introduction

Over the last 70 years, a remarkably simple model of our universe has evolved in which everything in it is made up from a handful of fundamental particles governed by four fundamental forces. Our best understanding of how these particles and forces interact is encapsulated in a theory now called the Standard Model of particle physics. Developed in the 1970s it successfully explains a wide variety of phenomena.

We now know that all matter consists of building blocks of two basic types called quarks and leptons. There are three "generations" each containing 2 quarks and 2 leptons. The lightest and most stable particles form the first generation and make up the matter in our universe today. The other two generations are heavier and less stable. They can be made in our particle accelerators but do not occur naturally.

There are four fundamental forces through which matter interacts, the strong, weak, electromagnetic and gravitational force. The Standard Model tells us that the weak and electromagnetic forces are two manifestations of the same thing, but there is no place for the oldest known force, gravity. Three of the forces result from the exchange of force-carrying particles called bosons, the strong force is carried by the gluon, the electromagnetic force by the photon and the weak force by the W and Z bosons discovered at CERN in 1984. The Standard Model has recently been completed by the highly acclaimed discovery of the Higgs boson at CERN in 2012 for which the surviving two theoretical physicists of the three who predicted its existence in the 1960s received the Nobel Prize in 2013.

The discovery of most of these elementary particles has only been made possible by building more and more powerful particle accelerators. They work by colliding particles (usually protons or electrons) at very high energy. Since Einstein told us that mass and energy are equivalent, this energy can be converted into mass, giving a fleeting glimpse of the unstable particles of the Standard Model. The heavier the particle, the higher the energy required to produce it. It was only possible to produce the Higgs boson with the world's most powerful machine, the Large Hadron Collider.

Although the Standard Model has been extremely successful in explaining many phenomena, we know that it is not a complete theory. As already mentioned, it cannot incorporate gravity and it cannot explain the dark matter and dark energy that we know exist in our universe. It can also not predict the phenomenon of "neutrino oscillation" recently observed.

The discovery of the Higgs boson at relatively low mass has opened up a lively debate as to what is the best way forward to try to crack the Standard Model and to reveal the more fundamental nature of the physical phenomena. The Large Hadron Collider will be the prime instrument over the next 20 years to tackle this problem but it is not too early to consider what will come after the LHC. However, before looking into the future it may be useful to take stock of how we have arrived at this point.

2. A short history of CERN colliders

Until the late 1960s, the high-energy frontier of nuclear and particle physics was dominated by the great proton accelerators. The Cosmotron at the Brookhaven National Laboratory and the Bevatron at Lawrence Berkeley Laboratory, both in the USA were soon followed by the Proton Synchrotron (PS) in the fledgling CERN laboratory. These machines accelerated protons up to their maximum energy (26 GeV for the CERN PS) after which they were extracted from the machine and brought into collision with the nuclei of particles in a "fixed target". The kinematic inefficiency of these machines was recognized very early. Most of the

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beam energy is used in moving the target nucleon forward, only a fraction is available for making new particles. In the 1950s the idea emerged of colliding two beams travelling in opposite directions, dramatically increasing the energy available, but in those days the technology needed to do so was far from ripe.

In the early 1960s discussion raged at CERN of what would be the best next step for particle physics. Opinion was divided between two camps, one pushing for a very high energy version of the PS, doing "fixed target" physics and the other on an innovative and more risky colliding beam "storage rings" capable of exploring much higher energy. In the end, the storage rings gained the most support although a high energy proton machine, the Super Proton Synchrotron (SPS) was also built later. Although it was not known at the time, this bold decision to build a colliding beam device started CERN on the long road to the Large Hadron Collider (LHC) and to the discoveries that confirmed the Standard Model.

Construction of the Intersecting Storage Rings (ISR) started in 1966 and operation started in 1970. The ISR worked beautifully, exceeding its design performance by an order of magnitude and pushing technology on all fronts. Since the beams needed to be stored for many hours a key element was the performance of its ultra-high vacuum system which pushed the frontier of vacuum science and technology throughout the operation of the ISR.

It was on the ISR that the phenomenon of Schottky noise on a particle beam was first observed. It is caused by small fluctuations of the distribution of particles in the beam and it was this very noise that Simon van der Meer speculated in a paper a few years earlier which could be used for what he called "stochastic cooling", increasing the density of the beam by using a sophisticated feedback system based on the noise signal. Stochastic cooling was tested on the ISR and was shown to work albeit with a very slow cooling rate. At the time it was considered to be of academic interest, of little practical value. How wrong would that be!

Although the ISR was the machine on the energy frontier, its scientific output was far less than it could have been. This was due to the fact that the particle detectors built in those days were not suited for the unexpected conditions at the ISR. It was a learning process for the experimentalist, many of whom would go on to design and build the much more successful detectors for the two next generations of hadron colliders. In fact, in 1973 a very important discovery was made, not at the ISR but on CERN's workhorse Proton Synchrotron operating in "fixed target" mode. This was the discovery of "weak neutral currents", a phenomenon predicted by the nascent Standard Model theory, which put the theory on a much stronger footing. The importance of this was that the Standard Model also predicted the existence of two new force-carrying particles, the W and Z bosons and their approximate masses. The discovery of neutral currents fully justified a Nobel Prize but unfortunately the leader of the collaboration died before it was confirmed (Fig. 1).

During the early 1970s the next great machine of CERN was under construction. This was the long awaited large PS, the Super Proton Synchrotron (SPS), original intended to operate as a "fixed target" machine since it only had a single ring. In 1976, Carlo Rubbia and collaborators made the bold proposal that if the SPS could be converted into a colliding beam storage ring, enough energy would be available to produce the W and Z bosons, whose approximate masses had been predicted by the Standard Model theory, directly. The only way to turn a single ring device into a storage ring would be to collide protons with

Fig. 1. The first hadron collider, the intersecting storage rings.
(Courtesy of CERN).

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their anti-particles (antiprotons) which have the same mass but opposite charge, allowing them to circulate in the opposite direction in the same beam pipe. Protons and antiprotons are collectively known as hadrons.

The big problem was to be able to produce sufficient amounts of antiprotons, which can be made in small quantities by bombarding a target with protons from the PS. The solution was to accumulate antiprotons over days in a purpose-built accumulator ring, applying the new technique of stochastic cooling to slowly increase the density of the beam. When sufficient antiprotons were available, they would be transported to the SPS where they would be accelerated together with a beam of protons. This required considerable technological innovation including the development of fast stochastic cooling. In spite of the enormous technical challenge, it worked beautifully, the W and Z bosons were discovered in 1983 and Rubbia and van der Meer received the Nobel Prize in 1984.

2.1. Protons versus electrons

Until the late 1980s all the machines at CERN were used to accelerate proton beams. However, doing physics with proton beams has advantages and inconveniences. The proton is a composite object containing 3 quarks and the gluons transmitting the force that holds them together. When two protons collide there are occasional hard collisions between quarks or gluons but there are many more “soft” collisions which are of limited scientific interest. Imagine colliding oranges. There will be occasional hard collisions between pips but there will always be the pulp. A proton collider therefore has to operate in a very noisy environment where interesting events have to be identified in the presence of a huge background of totally uninteresting events. In addition, the energy carried by the quarks and gluons inside the proton has a wide distribution. This means that each collision between quarks or gluons will be at a different energy and no information as to the energy of the initial state can be obtained from the beam. This makes the challenge of making precision measurements a hard one but there is one big advantage when one is searching for a particle like the Higgs boson where the mass is not known a priori. The fact that each collision is at a different energy means that the machine is sampling the full energy range at the same time. Take enough data and the mass peak will pop up above the noise (Fig. 2).

Electrons, on the other hand, are truly point-like particles. Collisions between electrons and their antiparticles (positrons) have a perfectly defined energy (twice the beam energy) and they are free from the enormous background of proton machines. Lepton (the generic name for electrons and positrons) colliders allow very precise measurements but there are two disadvantages.

Firstly, the very fact that the beam energy is precisely defined means that one must know precisely at what energy to tune the machine to produce, say the W or Z boson (or be lucky!). The second disadvantage in a circular lepton collider is synchrotron radiation. Charged particles bent on a curved trajectory emit radiation. The power radiated is proportional to the fourth power of the beam energy and the inverse fourth power of the mass. Since protons are 1800 times heavier than electrons this inverse fourth power law means that synchrotron radiation is negligible for protons but very strong for electrons. In addition as the machine goes up in energy the power radiated increases enormously, a factor of 16 for only a factor of 2 in energy, an untenable scaling law if very high energy is required.

In the 1990s a lepton collider (LEP) did operate at CERN (Fig. 3). It made very precise measurements of the W and Z boson previously discovered on the SPS collider. It reached a maximum energy of 105 GeV (too low to make the Higgs boson) by which time it was radiating 23 mW of synchrotron radiation. LEP was shut down in November 2000 against considerable opposition from physicists who erroneously thought that they had glimpsed the Higgs boson, in order to make way for a new machine with much higher energy, the Large Hadron Collider (LHC).

In conclusion, hadron (proton) machines are ideal for probing the energy frontier when the masses of new particles are not known, in spite of the experimental difficulties and limited precision. Lepton machines are excellent for precision measurements as long as one knows where to go in energy. In addition, circular lepton machines are limited in energy by synchrotron radiation. If very high energy is needed then one must develop new technologies (linear colliders) where one avoids bending the beams.

Fig. 2. The antiproton accumulator.

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Fig. 3. The outline of the 27 km circumference Large Hadron Collider with Geneva airport in the foreground and the Swiss-French border dotted.

2.2. The Large Hadron Collider

It is generally agreed that the birth of the LHC was at a Workshop held in Lausanne in 1984, where experimentalists, theorists and machine builders got together for the first time to reach a consensus on where to go after LEP. The great success of the SPS proton-antiproton collider gave confidence that detectors could be built to exploit the harsh environment of a high-energy hadron collider although the trick of using a single ring with protons and antiprotons could not be played again. There would be no way of making enough antiprotons to satisfy the required event rate of such a machine so that it would have to be, like the ISR, a two-ring collider.

The LHC had a difficult birth (Fig. 4). The approval of another proton-proton collider, the Superconducting Super Collider (SSC) in the United States in 1987 put the whole project into doubt. The SSC, with a centre-of-mass energy of 40 TeV would have been almost 3 times more powerful than anything that could be built at CERN. However the SSC soon ran into financial difficulties with a projected cost far in excess of that originally approved. It was eventually cancelled in 1993, making the case for building the much cheaper LHC even stronger, but the financial climate in Europe at the time was not conducive for the approval of a new large project. CERN's largest contributor, Germany was struggling with the cost of reunification and many other countries were trying to get to grips with the problem of meeting the Maastricht criteria for the introduction of the single European currency.

During the course of 1993, an extensive review was made in order to reduce the cost of the LHC as much as possible, although a detailed cost estimate was particularly difficult to make since much of the research

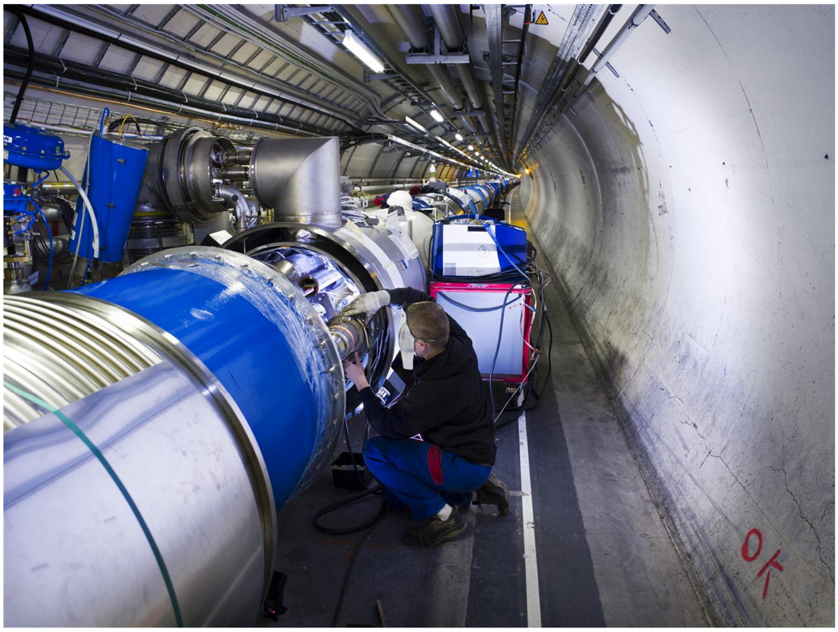

Fig. 4. The Large Hadron Collider.

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and development on the most critical components was still to be done. In December 1993, a plan was presented to the CERN Council to build the machine over a ten-year period by reducing the other experimental program of CERN to the absolute minimum, with the exception of the full exploitation of the Large Electron Positron (LEP) collider, which was the flagship machine of the decade.

Although the plan was generally well received, it became clear that two of the largest contributors, Germany and the United Kingdom, were very unlikely to agree to the budget increase required. They also managed to get Council voting procedures changed from a simple majority to a double majority, where much more weight was given to the large contributors so that they could keep control.

On the positive side, after the demise of the SSC, a US panel on the future of particle physics recommended that "the government should declare its intentions to join other nations in constructing the LHC". Positive signals were also being received from India, Japan and Russia.

In June 1994, the proposal to build the LHC was made once more. Council adopted a very unusual procedure in which the vote on the Resolution was opened so that countries in a position to vote could do so, but neither the vote nor the Council Session was closed. Seventeen member states voted to approve the project. However, because of the newly adopted double voting procedure, approval was blocked by Germany and the UK, who demanded substantial additional contributions from the two host states, France and Switzerland, claiming that they obtained disproportionate returns from the CERN budget. They also requested that financial planning should proceed under the assumption of 2% annual inflation, with a budget compensation of 1%, essentially resulting in a 1% annual reduction in real terms.

In order to deal with this new constraint, CERN was forced to propose a "missing magnet" machine where only two thirds of the dipole magnets needed to guide the beams on their quasi-circular orbits would be installed in a first stage, allowing the machine to run with reduced energy for a number of years, eventually upgrading to full energy. This would have been a very inefficient way of building the machine, costing more in the long run but saving some 300 million Swiss francs in the first phase. This proposal was put to Council in December 1994. After a round of intense discussions between France, Switzerland, Germany and the UK, the deadlock concerning extra host-state contributions was broken when France and Switzerland agreed to make extra voluntary contributions in the form of a 2% annual inflation adjustment, compared with the 1% adjustment from the other member states. In the continuation of the 100th Session of Council, still open from the June meeting, the project was finally approved for two-stage construction, to be reviewed in 1997 after the size of the contribution offered by non-member states interested in joining the LHC program would be known. The tough negotiations with France and Switzerland were couched in diplomatic language in the *Considerata* of the Council Resolution "(The CERN Council) notes with gratitude the commitments of France and Switzerland to make voluntary contributions to help and accelerate the LHC Project".

There followed an intense round of negotiations with potential contributors. The first country to declare a financial contribution was Japan, which became an observer to the CERN Council in June 1995.

The declaration from Japan was quickly followed by India and Russia in March 1996 and by Canada in December.

A final sting in the tail came in June 1996 from Germany who unilaterally announced that, in order to ease the burden of reunification, it intended to reduce its CERN subscription by between 8% and 9%. Confining the cut to Germany proved impossible. The UK was the first to demand a similar reduction in its contribution in spite of a letter from the UK Minister of Science during the previous round of negotiations stating that the conditions are "reasonable, fair and sustainable". The only way out was to allow CERN to take out loans, with repayment to continue after the completion of LHC construction.

In December 1996 Council, Germany declared that "a greater degree of risk would inevitably have to accompany the LHC". The project was approved for single-stage construction with the deficit financed by loans. It was also agreed that the final cost of the project was to be reviewed at the half-way stage with a view to adjusting the completion date. With all contingencies removed, it was inevitable that a financial crisis would occur at some time, and this was indeed the case when the cost estimate was revised upwards by 18% in 2001. Although this was an enviable achievement for a project of such technological complexity and with a cost estimate from 1993 before a single prototype had been made, it certainly created big waves in Council. CERN was obliged to increase the level of borrowing and extend the construction period (which was anyway necessary on technical grounds for both the machine and detectors).

In the meantime, following the recommendation of the US panel, and in preparation for a substantial contribution, the US Department of Energy, responsible for particle physics research, carried out an independent review of the project. They found that "the accelerator-project cost estimate of 2.3 billion in 1995 Swiss francs, or about $2 billion U.S., to be adequate and reasonable". Moreover, they found that "Most important of all, the committee found that the project has experienced and technically knowledgeable management in place and is functioning well. The strong management team, together with the CERN history of successful projects, gives the committee confidence in the successful completion of the LHC project."

The LHC finally started physics operation in March 2010, more than 25 years after the Lausanne Workshop and sixteen years after it was approved by the CERN Council, such is the timescale from conception to construction of such a mega-project. It has needed more resources to build than are available in the CERN Member States, with contributions from Canada, India, Japan, Russia and the United States to the construction of the machine and many more countries contributing to the four huge Detectors. It has been a very successful example of international collaboration on a massive scale.

Technically, the LHC has pushed the limits of technology, both in the design of the machine and the Detectors. In order to achieve the maximum possible energy in the already existing tunnel it was necessary to increase the magnetic field in the superconducting magnets that guide and focus the particle by more than 60% compared to what has been achieved in the past. In order to do this, a bold decision was taken to use superfluid helium to cool the magnet coils down to 1.9 K (around −271 °C).

Helium can be liquefied under normal circumstances at 4.2 K. If its temperature is reduced further, it undergoes a spectacular phase transition at exactly 2.17 K where its properties change dramatically. Its thermal conductivity and specific heat increase enormously and its viscosity disappears, allowing it to permeate the finest capillaries. Its behavior can only be explained by the laws of quantum mechanics, normally reserved for phenomena at the atomic scale. Harnessing these unique properties allows the performance of superconducting magnets to be improved to the level required. The production of these high performance magnets and the superconducting cable required to wind the coils pushed European industry to the limit of what could then be achieved. The cable is made from 36, one millimeter thick strands, each strand containing more than 9000 six micron diameter filaments of Niobium-Titanium alloy (Fig. 5).

Another constraint was the small (3.8 m) tunnel diameter. It must not be forgotten that the LHC is (just like the ISR) not one but two machines. A superconducting magnet occupies a considerable amount of space. To keep it cold, it must be inserted into an evacuated vacuum vessel and well insulated from external sources of heat. Due to the small transverse size of the tunnel, it would have been impossible to fit two independent rings, like in the ISR, into the space. Instead, a novel and elegant design with the two rings separated by only 19 cm inside a common yoke and cryostat was developed. This was not only necessary on technical grounds but also saved a considerable amount of money, some 20% of the total project cost.

Locating the LHC on the CERN site also allows a huge amount of existing infrastructure to be used. In addition to the tunnel, the whole

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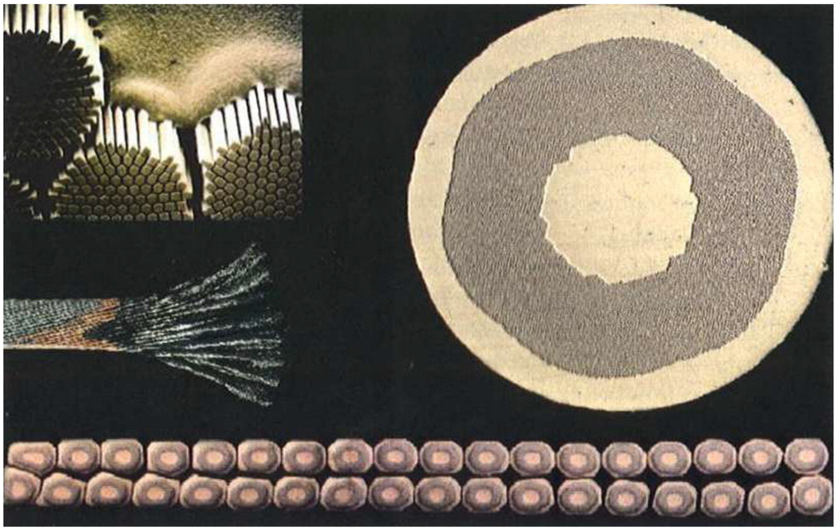

Fig. 5. The superconducting cable of the LHC. It consists of 36 strands of superconducting wire (bottom). Each strand contains more than 9000 filaments of Nb/Ti alloy (top left).

injector chain including the workhorse Proton Synchrotron from the late 1950s and the Super Proton Synchrotron from the 1970s is used to accelerate protons to a high enough energy (450 Giga electron Volts (GeV)) to fill the two rings of the LHC. Once the two rings are filled, the LHC itself accelerates the beams up to a maximum energy of 7000 GeV. This infrastructure alone is worth at least as much as the LHC (Fig. 6).

3. The future

Although the LHC will be the machine on the energy frontier for many years to come, the time scale for bringing these large projects to maturity is so long that studies of future options must already begin today. A lively debate is under way as to what should be the future direction to take. It is generally agreed that a high energy hadron machine

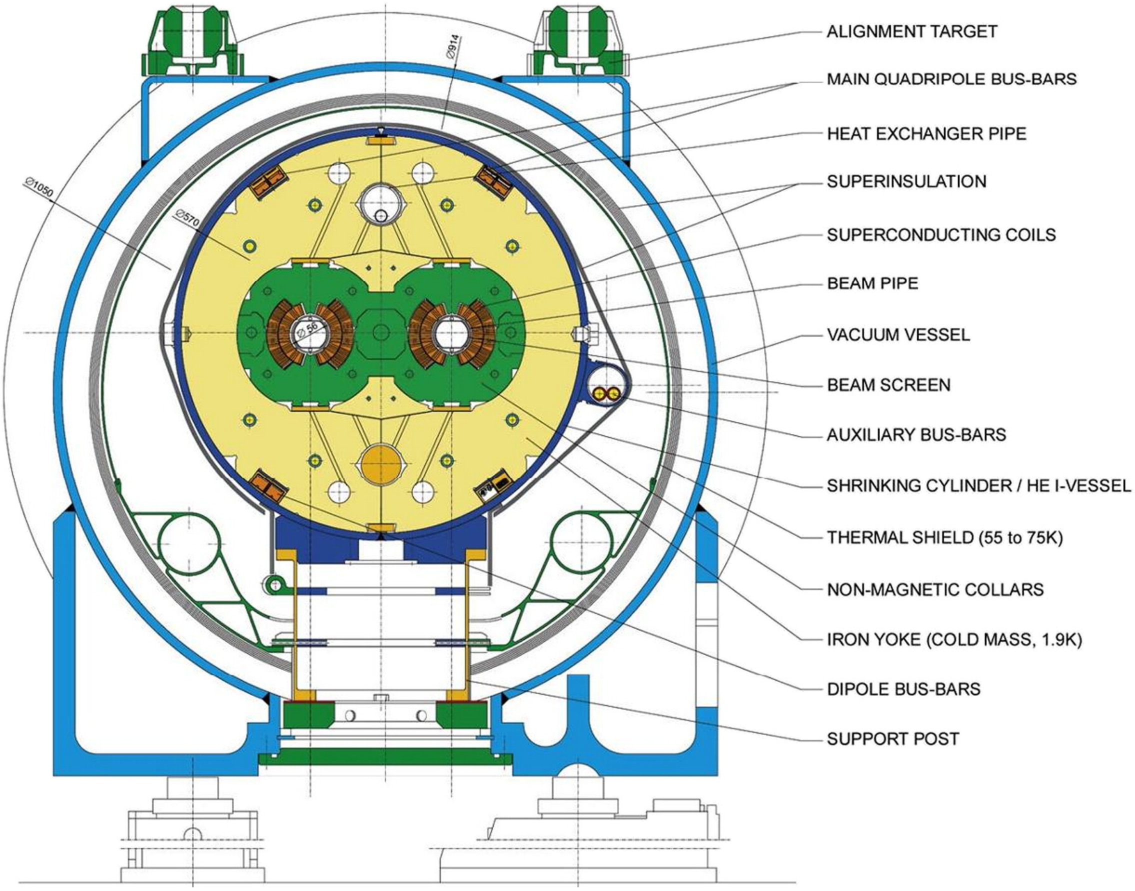

Fig. 6. A cross-section of the two-in-one LHC bending magnet. The two rings are concentrated inside a single vacuum vessel to save space (and money).

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should be the "pathfinder", pointing the direction of new physics. The LHC will play this role for the foreseeable future. It is also generally agreed that a lepton (electron-positron) machine should complement it, allowing precision measurements of new particles, the first being the Higgs boson. Until the Higgs discovery, it was accepted that the lepton machine must be a linear collider, the Compact Linear Collider or the International Linear Collider (see below) to overcome the problem of synchrotron radiation in a circular machine. However, the relatively low mass of the Higgs (125 GeV) has reopened the debate about a big circular machine that could reach the threshold for Higgs production and even go slightly higher in energy to allow the study of top quarks. Proponents of this proposal argue that this could, like LEP before the LHC, finally allow a very high energy proton collider to be installed in the same tunnel once the precision physics has been finished.

In the following chapters proposals from the different regions are discussed.

3.1. Europe

Every five years, the CERN Council sets up a scientific advisory group, the so-called Strategy Group to define the strategy in particle physics in Europe over the next five year period. The process involves consultation of the whole European particle physics community. The latest upgrade of the strategy was initiated by CERN Council in 2011. The Strategy Group was composed of representatives from each CERN member state and of the directors of the major European laboratories. In September 2012 an open symposium was held in Krakow with close to 500 participants. Following this meeting, the Strategy Group drafted a text for the approval of the CERN Council, which was unanimously adopted at a special session of Council in Brussels on 30th May 2013.

The Strategy update identified four activities with the highest priority.

1. The upgrade of the LHC towards high luminosity (the rate of collision) with the aim to collect ten times the integrated luminosity of the initial design. This is a large new project for both the LHC and the experiments requiring world-wide collaboration.
2. Design studies and R&D for an ambitious post-LHC accelerator project at CERN. The decision for a future machine at CERN can only be taken once the physics results from the LHC running at 14 TeV are available. In time for the next strategy update in 2018 details of the physics, technologies and cost of future projects should be made available. The Strategy Update sees CERN as the place for the energy frontier facilities and suggests vigorous R&D programs specifically on high-field magnets and high-gradient accelerating structures.
3. European support for an International Linear Collider. There is a strong initiative from Japan to host the ILC with an initial centre-of-mass energy operating as a Higgs factory and later to be upgraded to 350 and 500 GeV. The Strategy Group acknowledges the physics case for such a machine and suggests exploring European participation.
4. Participation in a long-baseline neutrino experiment. The recent developments in neutrino physics define a clear case for a long baseline neutrino experiment. The Strategy Group proposed to explore a European participation in such experiments in the US and Japan.

In order to address the first two points and prepare for the next Strategy update, a number of studies have been launched.

3.1.1. High luminosity LHC

This is a natural extension of the LHC program. It is proposed to operate in the period 2023–2030 at 14 TeV with a luminosity of $5 * 10^{34}\,\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, a factor of 5 above the design luminosity. In principle it should be possible to go about a factor of 2 higher than this but one of the problems already mentioned in a hadron collider is the very large background from "soft" collisions. These events lose particles from the beam, resulting in a very bad beam lifetime and inefficient data-taking if the luminosity is too high. The solution is to run with "luminosity levelling", operating lower than the peak to get a better lifetime but keeping the luminosity constant in time by dynamically changing machine parameters.

In order to achieve this luminosity upgrade, many improvements in the injector chain need to be made to improve the quality of the beams. One of the most important changes in the LHC itself will be to replace the magnets that focus the beams into the detectors with more powerful ones. This again will push the boundaries of superconducting magnet technology further. These magnets would anyway need to be replaced on this time-scale due to accumulated radiation damage from the collisions streaming from the interaction points.

The luminosity upgrade has already been approved by CERN Council so it will not figure in the 2018 Strategy review.

3.1.2. High energy LHC

The maximum energy of the LHC is limited by the strength of the superconducting magnets that guide the beams on a circular orbit. As already explained, they already push the boundaries, using superfluid helium as a coolant. Increasing the field by another factor of two should be possible by using a new superconducting material Nb_3Sn. This is a difficult material to work with and still requires a lot of R&D if magnets of 16 T can be built, almost doubling the collision energy from 14 TeV to 26 TeV. A possible design of a magnet using new high-temperature superconductor in the inner part of the coil is also under study, giving the potential of 20 T field and collision energy of 33 TeV. Work is underway to bring these technologies to a sufficient level of maturity so that they can give guidance to the 2018 Strategy Review.

3.1.3. Future Circular Collider (FCC)

In order to respond to the second recommendation of the Strategy Group, a study of a very large ring in the Geneva area has been started. It seems that it may be geologically feasible to fit in a ring with a circumference of 80–100 km, which would, in conjunction with the high-field magnets already mentioned, allow collision energy of 80 to 100 TeV. Conforming to present trend in particle physics, this study is, from the outset an international collaboration with several countries from outside the CERN member states involved from the beginning.

This conceptual design study should be ready for the 2018 review. A key issue here, of course will be the cost of such a huge facility.

3.1.4. The Compact Linear Collider

For a number of years, CE5RN, together with a large number of Institutes in Europe and elsewhere has been studying a very high-energy (3 TeV) electron-positron collider as a successor to the International Linear Collider. At such a high energy it is inconceivable that a circular machine could be built because of synchrotron radiation losses. The Compact Linear Collider (CLIC) concept is based on two linear accelerators accelerating electrons and positrons colliding in a central region. In order for it to have an acceptable size the accelerating structures must have a very high gradient (100 MV/m). Conventional power sources cannot be used to energize the structures because of their number and cost. To overcome this, the concept is based on a two-beam acceleration technique where short high-power Radio Frequency (12 GHz) pulses are extracted from a drive beam running parallel to the main accelerating structures. The accelerating structures with the very high gradient of 100 MV/m, would limit the length of the machine to about 48 km.

The key technologies of this concept have been tested at CERN, at KEK in Japan and in Stanford. A Conceptual Design Report for the machine and detectors has been produced together with a preliminary cost estimate.

In view of its very high gradient and compact structure, the CLIC technology is receiving widespread interest in other fields. Small machines powered by conventional sources are being studied for uses from medical applications to free electron lasers.

The CLIC study will be presented to the 2018 strategy review as one of the future options.

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3.1.5. FCC-ee

The discovery of the Higgs boson at relatively low mass has revived the idea of a possible circular collider in the 80–100 km tunnel as a first stage towards the high energy hadron collider FCC. The luminosity of a circular machine, unlike a linear collider decreases with increasing energy so it would be a prolific source of Z particles at around 45 GeV beam energy and would produce a large number of Higgs bosons produced in association with a Z. It could conceivably reach the threshold for the production of top quarks at around 350 GeV although the beam lifetime at this energy would only be a few minutes. It would need an additional “top-up” ring ramping from injection to collision energy every few minutes, topping up the beams in the collider.

Although the FCC-ee was not one of the options supported by the 2013 Strategy Group, a conceptual design will be made available as a further option in the 2018 review.

3.2. USA

A recent study in the USA, similar to the CERN Strategy Group study has come up with a set of recommendations for the future direction of US particle physics.

After the demise of the SSC, there are no plans for a future collider in the US at the moment. Instead, US scientists will collaborate with CERN on the LHC and its upgrades and will participate in the design study of the FCC. The main thrust of the national program will be long baseline neutrino physics. The hope is that this will evolve into an international collaboration.

The US roadmap also identifies the ILC as an important priority for particle physics and recommends a strong US involvement in the design and construction of the machine and its detectors if it is hosted in another region.

3.3. China

Quite recently, a proposal has come from the high-energy physics community in China for a facility similar to FCC at CERN. In a first stage it would consist of a circular electron-positron collider in a ring of 50–70 km circumference which could reach the threshold for Higgs production at about 120 GeV per beam. In a second stage the lepton machine could be replaced by a high-energy hadron collider using high-field superconducting magnets. This project is in an early phase of study. The technical Design Report is expected to be finished by 2020.

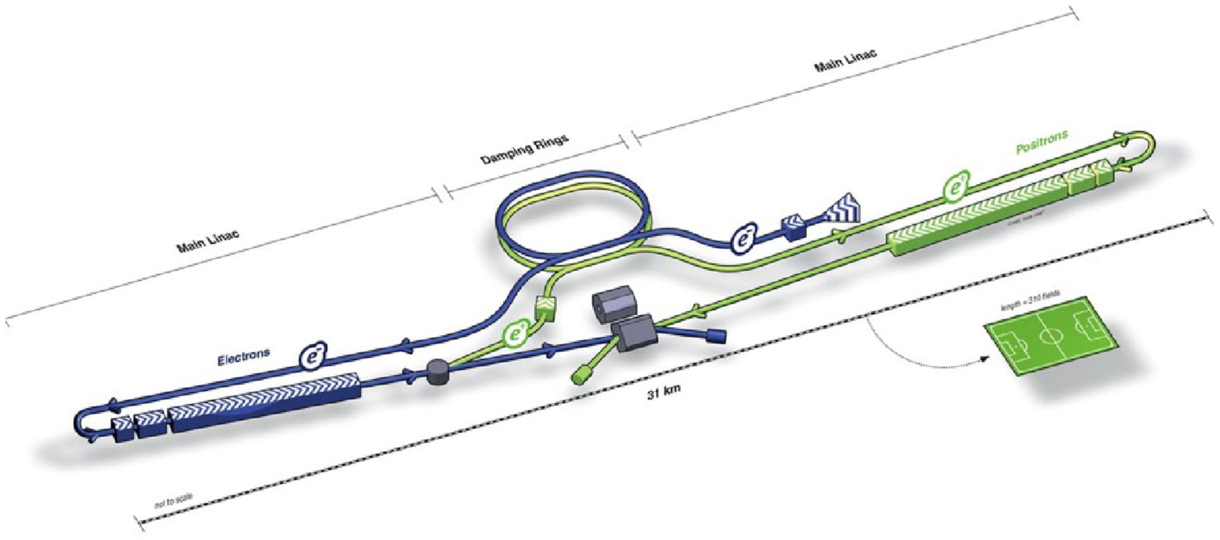
3.4. Japan

The most mature proposal for a future high-energy linear collider is the International Linear Collider (ILC). There are currently intensive discussions about citing it in Japan (Fig. 7).

The International Linear Collider has been under study for more than 20 years. A detailed Technical Design Report (TDR), which describes the facility in great detail, exists and a conceptual design of the two ILC detectors, signed by scientists from over 40 countries, has been completed. The ILC is based on mature technology which is already being used at the European X-ray Free Electron Laser in Hamburg, Germany and will also be used for the recently approved Linear Coherent Light Source-II at Stanford Linear Accelerator Center in the USA. The design reflects significant worldwide developments in the technology with the establishment of R&D infrastructure as well as a significant industrial base in the Americas, Asia and Europe.

The heart of the machine consists of two 11 km-long linear accelerators built from superconducting cavities at a frequency of 1.3 GHz and an operating gradient of 31.5 MV/m. This machine would have a design energy of 500 GeV and could eventually be upgraded to 1 TeV by extending its length and the cavity gradients. One unique feature would be its ability to accelerate polarized beams. This machine would have a much larger scientific potential than the two proposed circular lepton colliders.

As a consequence of the discovery of the Higgs boson, the Japanese physics community has proposed to build it as an international collaboration in Japan. One unique advantage of a linear collider over circular machines is that it could be built in stages, starting at the Higgs threshold at 250 GeV allowing very precise measurements of the properties of the Higgs particle, looking for small deviations from the predictions of the Standard Model which could indicate new physics, eventually extending the machine to 500–1000 GeV over time.



ILC Scheme | © www.form-one.de

Fig. 7. Conceptual layout of the International Linear Collider.

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An internal Japanese study has identified a potential site which has been examined by the international scientific community. It is located in the Kitakami Mountains in the north-east of the main Japanese island of Honshu. In spite of possible seismic activity the chosen location is in a contiguous block of granite more than 30 km long that will insure great stability.

The Project is presently being examined by the Japanese government in order to decide whether they wish to host this machine. If it is built, the ILC will require substantial contributions from the rest of the world. It will be the first truly international laboratory hosted by Japan.

4. Social and economic benefits of collaborative research in Particle Physics

All of the world's great particle physics laboratories work on a model of international collaboration at some level, a prime example is CERN.

CERN was established in 1954 by twelve European nations. Its purpose was to pool resources to provide facilities that no single country could afford, but also to rekindle collaboration between scientists throughout war-torn Europe. The spirit of CERN was well expressed by the first President of Council Sir Ben Lockspeiser.

> *Scientific research lives and flourishes in an atmosphere of freedom, freedom to doubt, freedom to enquire and freedom to discover. These are the conditions under which this new laboratory has been established.*

CERN now has 21 Member States with more than 11,000 users coming from almost 100 countries from all over the world. It is much more than a physics laboratory where the cutting edge technologies needed in the accelerators and particle detectors stimulate innovation in other fields including cancer therapy and medical imaging.

CERN was the place where the World Wide Web was invented. It was born because of two complementary conditions. Firstly, collaborating institutes around the globe needed to exchange much more sophisticated information than just email. Secondly the particle physics community is very computer-literate; computing plays a very central role in particle physics research, so the knowledge needed to build it was widely dispersed. Few dispute the fact that the Web has profoundly changed society. In accordance with the CERN Convention it was given freely to the world, which was certainly an important factor in explaining its rapid success.

CERN plays an important role in education and training. Many hundreds of PhDs are awarded each year to graduate students involved in CERN experiments. Each summer, teachers from all over Europe spend 3 weeks at CERN, working with researchers and learning about the latest scientific developments. The Summer Student program welcomes more than 100 undergraduates to CERN for 2 months every year. As well as receiving cutting-edge lectures, the students are integrated into research groups and play an active part in the laboratory.

There have been a number of studies of the social and economic benefits of CERN, the most recent commissioned by the OECD Committee for Scientific and Technological Policy (OCED, 2014). A particularly interesting study (Florio et al., 2015), applies the formal process of Cost-Benefit Analysis (CBA) to put the evaluation of the benefits of CERN, and in particular the Large Hadron Collider, on a more scientific basis. The general conclusion is that the LHC passes the CBA test. However, this may not necessarily be the case for future large projects at CERN.

Throughout the history of CERN, scientific progress has been made through continuous innovation. The construction of the first storage ring, the ISR in the late 1960s provided the first order-of-magnitude boost in energy. The discovery of stochastic cooling at the ISR opened the door to converting the SPS into a proton-antiproton collider of even higher energy and fixed the parameter space for the design of the LHC. The LHC itself uses quantum mechanics (superconductivity and super-fluidity) on a grand scale to allow a further boost in energy and its first great discovery, the Higgs boson. All of this has been achieved on a more-or-less constant inflation adjusted budget.

5. Conclusions

The success of CERN as a European centre of scientific excellence and as a model for international collaboration is now widely recognized, with new applications for Membership every year.

To continue this role on a budget that Society can accept will require continuous innovation in the future as was the case in the past.

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Lyn Evans, born in 1945, has spent his whole career in the field of high energy physics and particle accelerators, participating in all the great projects of CERN. Since 1993 he led the team that designed, built and commissioned the LHC. He is presently a visiting professor at Imperial College London and Director of the Linear Collider Collaboration. Among his many honours he is a Fellow of the American Physical Society and a Fellow of the Royal Society. He was awarded a Special Fundamental Physics Prize in 2013 for his contribution to the discovery of the Higgs boson. In 2014 he received the inaugural Saint David Award from the Welsh Assembly Government.

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