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Particle accelerators: machines for discovery

Lucio Rossi

European Organization for Nuclear Research (CERN) CH-1211 Geneva 23 Switzerland
Lucio.Rossi@cern.ch

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Abstract

Particle Accelerators have accompanied the adventure toward the infinitely small, the realm of quantum mechanics, for more than eighty years. The growth of accelerators from the hand-size Lawrence cyclotron to the giant size LHC has been marked by a mixture of continuous development and of technological breakthroughs: synchronisation of RF field and steering magnetic field, strong focusing, phase stability, collision mode and finally superconductivity: each step in technology has allowed a jump into a new land of discovery, from the initial few MeV proton energy to the tera–scale energy region, where a spatial resolution as small as 10^{-20} *m is attained. Accelerators are one the biggest endeavors of the scientific community, requiring careful planning, a long term effort and sharing of a common infrastructure. Given the necessary allocation of time and resources, their construction is usually based on a positive hypothesis (such as the Higgs boson in the case of the LHC), which requires experimental verification. In this sense, their history shows well to which extent positive hypothesis plays a fundamental role in science, rather than systematic doubt, as frequently claimed. After a historical review and a description of the LHC as a case study of modern accelerators, the possible evolution of accelerators over the next decades will be discussed, including the new large lepton colliders and the enormous machine for the post-LHC era. Through this work, we emphasize the role of quantum Mechanics, which is at the root of both the feasibility of particle accelerators (allowing for example superconducting magnets) and of the new hypothesis about Nature that we aim to explore (such as the fluctuations of the quantum Higgs field, aka the Higgs boson).*

1. Introduction

Particle Accelerators are a domain where Physics and Engineering work closely together with a cross-fertilization that can rarely be matched in other fields. Particle accelerators were invented because of the urgency generated by the emergent quantum-mechanics for breaking open the atomic nucleus.

The principle of accelerating particle was set in motion when Thomson and Rutherford started to use vacuum tubes to accelerate electrons. In particular since the famous Rutherford experiment, carried out with Geiger and Mansfield and whose results were published in 1911, the experimental program of nuclear physics was laid down: to use nuclear particles to bombard nuclei in a fixed target. To this day many accelerators are used in exactly this way. However it took still a few years before the route to follow was clear enough.

Curiously, until the end of the '30s nuclear physics was the realm of experimental physics while theoretical physics was concentrated more on issues related to the atom. Rutherford himself in his 1927 opening talk as President of the Royal Society set the scene:

> *The advance of science depends to a large extent on the development of new technical methods and their application [...] From the purely scientific point of view interest is mainly centered on the application of these high potentials to vacuum tubes in order to obtain a copious supply of high-speed electrons and high-speed atoms [...] This would open up an extraordinarily interesting field of investigation which could not fail to give us information of great value, not only in the constitution of atomic nuclei but in many other directions.*

Such a talk from the "godfather" of modern physics of the time was not without consequence: one of his students, John Cockroft, in 1928, applied for a research to produce high speed particles. Cockroft and his colleague Walton designed and built in three years a small accelerator capable to accelerate hydrogen nuclei to 200,000 eV of kinetic energy. The most interesting thing is that Cockcroft and all scientist of Rutherford's group knew that this kinetic energy was much lower than the higher–than–million eV energy necessary to penetrate in the nucleus. The value of the electric repulsion between positive proton and positive nucleus was easy to determine: for this reason they bombarded a very light lithium target, to reduce the potential barrier as much as possible. However, the barrier remained much higher than the energy of the accelerated proton.

In contrast with their American colleagues —driven mainly by technology—, the cultural environment of the Rutherford laboratory was impregnated with young quantum mechanics that was offering a chance of success to their experiment: a barrier can be passed, though with low probability, thanks to tunneling effect as they realized inspired by discussion with George Gamow in 1928 (Gamow was among the first and most brilliant scientists who realized the far-reaching consequences of the Uncertainty Principle of Heisenberg of 1927). When in 1932 Cockroft and Walton observed the first nuclear reaction induced by using 200 keV artificially accelerated particle beams, it was really a giant leap for physics. Not only a new domain of exploration (nuclear and then particle physics) was born; not only a new powerful instrument (accelerator) to extend our knowledge was demonstrated: a direct proof of the tunnelling effect and of the underlying Uncertainty Principle was brought about, marking the close ties between accelerators, that were to become the main tool for experimental physics, and quantum mechanics, the framework for our understanding of the subatomic world.

2. A brief history of accelerators

2.1 Cockroft-Walton and electrostatic accelerators

Cockroft and Walton should be credited with having first produced a nuclear reaction in 1932: for this achievement they were awarded the Nobel Prize in 1951. However their accelerator was not the first in absolute terms: as we shall see other teams were working on the subject with more promising ideas, but they missed the idea to use tunnelling to defeat the potential barrier of a nucleus. The Cockroft-Walton (CW) accelerator is a series of capacitors and diodes that act as voltage multiplier (whose principle was discovered much earlier, in 1919, by the Swiss physicist Heinrich Greinacher), transforming a low AC voltage into a high DC voltage (see Figure 1). It is limited to voltages of about a MV at relatively low current, and currently used as the first stage in a number of applications including power source, power electronics, X-ray devices, etc.

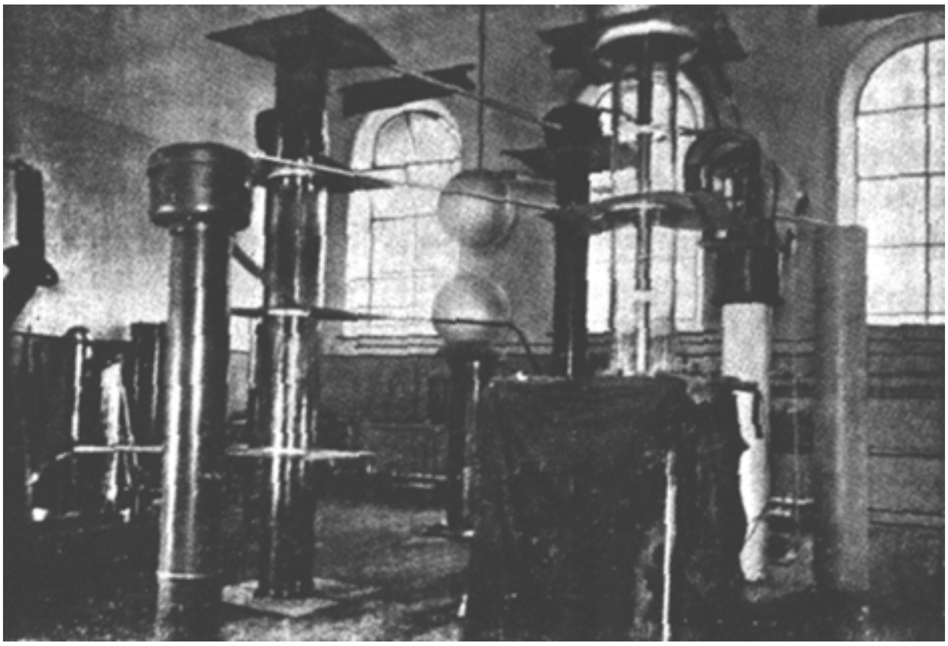

Figure 1: *Cockroft-Walton machine for 400 kV in Manchester.*

An evolution of the CW multipliers is the Van der Graaff machine. Robert van der Graaff was an American student in Oxford in 1928 who, becoming aware of the need of high voltage to accelerate charged particles, invented a purely electrostatic machine (see Figure 2) that became widely used for nuclear physics till the 1970s. These so-called Van der Graaf generators were able to deliver quickly a few MV, and in its most modern version was capable of reaching 15-20 MV. It has been (and still is) used for heavy ion nuclear physics in its "Tandem" version that allows using twice the voltage: a negative ion beam is accelerated from ground to the positive HV terminal. There ions become positive by stripping through a foil of suitable thickness; then the positive ions can be accelerated again by the same voltage in the opposite way. However even with this trick the limitation is given by the 2×15 MV static accelerating potential, enabling to reach a few tens of MeV per nucleon. To go beyond these limits of static field a completely different concept had to be employed.

Figure 2: *The Tandem in the INFN National Laboratory of Legnaro (LNL), Italy, rated for more than 15 MV.*

2.2 Cyclotrons and Synchrotrons: Lawrence and the invention of the Cyclotron

Ernest Orlando Lawrence in 1929, three years before the Cockroft-Walton experiment, had the idea of a new type of machine. Lawrence was a practical young associate professor at the University of Berkeley, and had the inspiration of his device by looking at the drawings of an article published in German by the Norwegian physicist Rolf Wideröe which was the first to publish a system for cyclic acceleration, that we will discuss later. From the drawings of the Wideröe publication, Lawrence picked-up the idea that one needs a radiofrequency system, since an alternating field is not conservative and its voltage can be used to accelerate particles as many time as needed. Lawrence had the idea to use two electrodes connected at an AC voltage source. The electrodes are then put in a magnetic field which is perpendicular to the plane in which the particles travel, thus bending their trajectories in a circular orbit.

By looking at Figure 3, one can see that once the positive particle crosses between the two electrodes when the voltage is such to accelerate them, gaining kinetic energy. Then the particle trajectory is bent on a circular orbit by the uniform magnetic field, within the equipotential region of one electrode. Meanwhile the electrode itself is changing polarity with respect to the second electrode due to the AC powering. The AC frequency is such that when the particle has accomplished half circumference, i.e., when it reappears at the gap between the electrodes the voltage polarity has reversed; therefore the particle is accelerated again through the accelerating gap before entering in the chamber inside the second electrode, where it moves again in an equipotential space, meanwhile the electrode potential changes, and so forth. The revolution frequency is independent on the kinetic energy:

$$\omega_c = (q/m)B\,, \tag{5.1}$$

where ω_c is called *cyclotron frequency*. Therefore if the frequency of the AC voltage driving the electrodes is made equal to the frequency of revolution, $\omega_{rf} = \omega_c$ (the resonant condition), the particles always crosses the gap when the potential produces acceleration. At each crossing of the gap the particle gains energy, makes a larger circle of radius

$$\rho = mv/B\,, \tag{5.2}$$

so the trajectory is a spiral, which gets larger until the particle are extracted with a suitable system (usually an electrostatic plate). In this way a relatively low voltage, 1-10 kV could be summed up hundreds of times to reach energy well beyond the MeV. The accelerated particles are grouped in bunches, since only the ones that are in the right phase with the AC voltage can survive the process. Of course the electrodes must be placed in a vacuum chamber to reduce the energy loss by scattering of the residual atmosphere. Thanks to the perfect synchronization between the particle revolution and the change of the voltage many particles can be accelerated at the same time: on each orbit can be a group of particle under acceleration (see Fig. 3). Because the RF voltage must be accelerating only a fraction of the spiral can be filled, i.e. the particle are grouped or "bunched": typically each bunch last for a $\sim$ 10 degree of the AC phase, when the electric field is at its peak. Lawrence built his first cyclotron, rated at 80 KeV with a 4" (10 cm) pole diameter magnet (an equivalent CW accelerator would have been about 1 m long), using a voltage source of less than 2 kV.

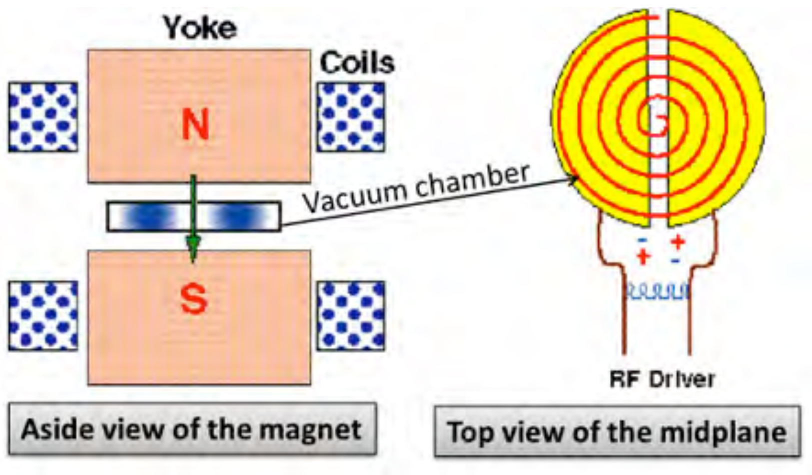

Figure 3: *Scheme of a cyclotron.*

The success of the first machine was such that he planned and built a series of cyclotrons, larger and larger in size and energy. In 1932 he built, together with Stan Livingston, a cyclotron based on an 80 ton, 11" (28 cm) pole diameter magnets, reaching 1.2 MeV, i.e. six times the energy of the larger size Cockcroft-Walton machine (however missing the first artificial nuclear disintegration because of the lack of knowledge of quantum mechanics that the people in the Rutherford laboratory had!). Significantly the publication was entitled "The Production of High Speed Light Ions Without the Use of High Voltage": thanks to the magnetic fields the particles recirculated 150 times to reach the 1.2 MeV energy using only a 4 kV voltage source (see Figure 4). Beside building larger and larger machines, and founding a worldwide approach to this science, Lawrence was a tireless promoter of physics and its application, a successful fundraiser and the first to propose and to use accelerator for medicine: in collaboration with his brother, a medical doctor, he treated his mother in the attempt to cure a cancer. He was awarded the Nobel Prize for Physics in 1939.

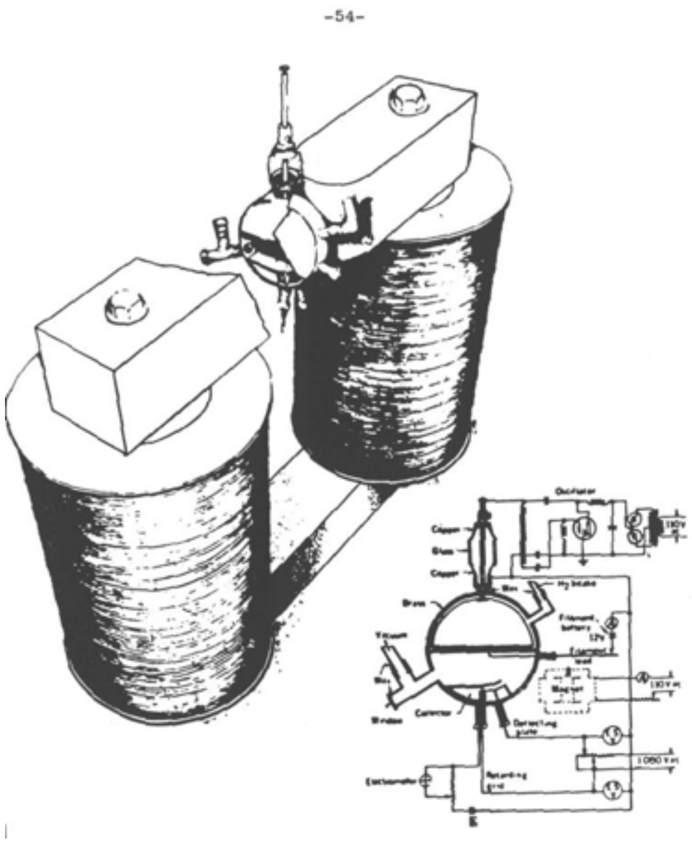

Figure 4: *One of the first cyclotrons built by Lawrence and Livingstone. The vacuum chamber was ∼15 cm diameter.*

2.3 Synchrocyclotrons and Synchrotrons

Lawrence was pushing his machine to larger and larger, since nominally the energy depend only on the nature of the particle and on the field and size (R=radius) of the magnet:

$$E = \frac{1}{2}\frac{q}{m}(BR)^2 \,, \tag{5.3}$$

valid for the non-relativistic case and where E is in eV, all other quantities in SI units (International System). However two important problems had to be overcome. The first was the stability of the particle. An orbit is never precise, the particle having always the position or the direction of speed not perfect. In one word one need to stabilize the trajectory against the inevitable perturbations and deviations from the ideal orbit. This issue was solved by the discovering that if the magnet was made with the vertical field to slightly decreasing with the radius, which is something that occurs almost naturally, the particle motion was stabilized around the stable orbit (weak focusing).

The second is more serious and has to do with relativity. As soon as the proton kinetic energy is beyond a few tens of MeV the mass increase due to relativity is not anymore negligible. The higher energy protons take more time to accomplish the revolution and they accumulate a delay, to the point that they arrive at the accelerating gap when the voltage is already reversed. Lawrence started building before the war a giant cyclotron of 187” (4.7 meter diameter) and 4500 tons to reach 100 MeV without paying much attention to this problem (and to his collaborators who were worried about the effect!). The construction of the cyclotron was then delayed because in 1942 all resources and attention of Lawrence were diverted to use all magnets as mass spectrometers for uranium separation in the framework of the Manhattan project. Once the war was over, Lawrence got back to his project and had the pleasant surprise that the problem of the mass increase was solved: Vladimir Veksler in the Soviet Union and Edwin McMillan in the USA independently discovered in 1943 the phase stability principle. We will not discuss this principle which is one of the bases of modern accelerator theory. However this made possible a “simple trick”: the frequency of the AC voltage source may be slowly decreased in synchronism with the revolution frequency decrease. In this way only one bunch of proton could be accelerated at a time, but the relativistic mass limitation was over. This type of machine is called synchrocyclotron.

The first one, having a 184” magnet pole diameter, built by Lawrence reached 200 MeV proton kinetic energy. The speed of the proton is 55% that of light and the mass increase is 20%. One of the largest synchrocyclotrons was the one built as the first machine at CERN, rated at 600 MeV. In the same years just after the war cosmic rays physicists discovered new particles, among them the charged pions, having the mass within the range of the new machine. When in 1948 a photographic emulsion was used as a target in the 184” cyclotron beam, hundreds of traces were clearly visible, some of them revealing the presence of the new particles. It was the beginning of a new race for discovery, and correctly that moment is reckoned as being the beginning of High Energy Physics (HEP) as we know it, and from then on most of its discoveries were made through experiments at accelerator laboratories. In Figure 5 is reported a famous picture of the 188” cyclotron at the Lawrence Berkeley lab.

The drawback is that to go beyond 1 GeV the magnet become enormous since it has to accommodate orbits from small radius for injection to large for extraction. For example the magnet for a synchrocyclotron producing 1 GeV protons would require approximately 25,000 tons of iron, about 2/3 of total weight of the LHC magnets! The difficulty was overcome thanks to a further evolution of the cyclotron principle. The particles are kept on a constant orbit by increasing the field in a suitable way to follow the increase of the

Figure 5: *Picture of the 188" cyclotron with E.O. Lawrence, and all staff. The picture renders the giant size of the magnet.*

revolution frequency ω_c. Since the RF must be synchronized with the magnetic field, this machine is called synchrotron. In this way a slim tube is sufficient to contain the particle motion and only a channel of field needs to be generated, so the magnet can be much smaller in cross section. However the magnets, and the whole accelerator, get inevitably longer. At the time the field was determined in practice by the magnetic saturation of the iron in the yoke - about 1.8 T. The orbit for very energetic particles becomes huge. The relation between magnetic field, size of the accelerator and beam particle is particularly simple for fully relativistic particles:

$$E \simeq 0.3BR\,, \tag{5.4}$$

where the beam energy E is in GeV, the magnetic field B is in tesla and the machine radius is in m.

2.4 Linacs

The idea of Wideröe that triggered the invention of the cyclotron by Lawrence, was to use a series of radiofrequency resonators, called RF cavities. The electrodes are connected as shown in Figure 6, with the particles flowing in a straight line. In this way one does not need dipole magnets to bend the beam. Each voltage gap is used only once by each particle. As in the case of a cyclotron only the group of particles that are in phase with the accelerating field can survive the process, so the particle beam is bunched. Like for the cyclotron the "trick" is that when the potential between the electrodes changes sign, say from negative (the polarity that attract protons) to positive, the particles drift peacefully in the equipotential field within the electrode. However, since the speed increases, and because it takes always the same time to make a 180 degree phase change for the electrode, the drift in the equipotential space must increase. So the electrodes must become progressively longer. Of course when a particle is relativistic, in practice the electrodes are of constant length. That is why linacs are very convenient for electrons that are fully relativistic already at a few MeV of kinetic energy. Linacs for accelerating electrons to a few MeV electrons are very compact (less than 10 m long), are cheap and are widely used in hospitals for producing X-rays for radiotherapy.

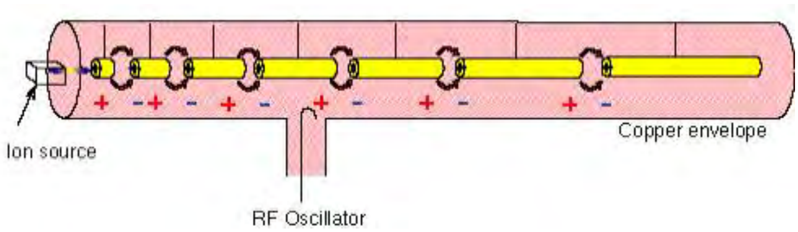

Figure 6: *Scheme of a Linac.*

A laboratory where linacs for electrons have been extensively developed is SLAC, the Stanford Linear Accelerator Center. The famous 2-miles long linac (see Figure 7) with its 30 GeV electron beam allowed to make the precise measurement of the "parton distribution functions" that were of key importance for the understanding of the nucleon structure and to confirm definitively the models based on quarks.

Figure 7: *The 2-miles linear accelerator at the Standford University.*

2.5 Colliders

A further concept that allowed increasing dramatically the "useful energy" of accelerator beams, making a jump in the physics reach of accelerators, is the use of colliding beams. The idea was not new, but it seemed impossible to make useful collision between clouds of particle (the beam bunches) that were essentially empty. The Austrian scientist Bruno Touschek, in Italy at the turn of the sixties, was able to convince the management of the newly founded Frascati Laboratory to build the first electron-positron accumulator and to make the two beams collide. Technically the function of the collider is similar to the one of a normal synchrotron, however two beams circulate in opposite sense in the same vacuum chamber. At the collision particles and antiparticles annihilate and the kinetic and mass energy is transformed in other new particles, whose mass is generated by the energy released in the annihilation process: an exquisite quantum mechanical process! A picture of AdA ("Anelli di Accumulazione"), the first e^+e^- collider, is shown in Figure 8

Figure 8: *The first* e^+e^- *collider: ADA (Anello di Accumulazione) at the Laboratori of Frascati (LNF), Italy.*

Several Nobel Prize discoveries have been made at collider experiments. One of the most important is the discovery of the vector bosons, W^+, W^- and Z^0, for which Carlo Rubbia and Simon van der Meer were awarded the Nobel Prize in 1984. The declared motivation for this award was that they had made a decisive contribution to the large project that led to discovery of the weak force mediators. Both Rubbia and van der Meer had worked previously at the first hadron collider, the CERN Intersecting Storage Rings (ISR), and thanks to technology developed there were able to propose the courageous idea of transforming a fixed target proton synchrotron, the CERN SPS, into a colliding beam accelerator. Here we do not discuss the technical issues but remark the fact that the large enterprise was possible because a positive hypothesis had to be verified. It was an essential "brick" of the unified quantum field theory, now usually called the "Standard Model" (SM). It would have been difficult to persuade the funding agencies to allocate the money and resources necessary for the project if it had only been based on "doubts". It is not systematic doubt that can be the basis of such a large project, rather the reasonable likelihood that something should be in the region to be explored. Somehow the story of the Z and W is very similar to that of the LHC and Higgs boson. The positive hypothesis (the theory) cannot be taken for granted before experimental proof, however it gives an explanation that takes into account all elements of a complex picture, and so it becomes reasonable to start an adventure such as to build a new accelerator with its experiments.

3. Superconductivity and the further energy jump

K. H. Onnes discovered zero resistance in a mercury sample at 4 K on 8 April 1911: however, it was not until November 1911 that he realized it was a new, completely unexpected, phenomenon, later called superconductivity. Already in 1913, the same year he received the Nobel Prize, he was dreaming of the possibility of designing a 10-tesla magnet, opening a new frontier for the exploration of the properties of matter. However very soon he had to record the "annoying" fact that the superconductivity is limited, in addition by a critical temperature, also by a critical field and a critical current. This was the first sign, at that time impossible to decode, of the quantum mechanical character of superconductivity.

After the phenomenological theory based on the two-fluid model of Gorter and Casimir and the phenomenological electromagnetic theory of F. and H. London, the theory of Ginzburg-Landau made use of quantum-mechanical concepts to offer a deeper comprehension of superconductivity. It uses the concept of the complex order parameter field ψ, whose squared modulus is proportional to the fraction of electrons that condense into the superfluid state. This phenomenological quantum theory correctly predicts the coherence length ξ in which the superconducting fluid density can vary and the exponential decay of a magnetic field in a superconductor, dominated by the London penetration depth λ. It has been noted that the exponential decay is equivalent to the Higgs mechanism. Then finally the BCS theory (Bardeen-Cooper-Schrieffer) proposed in 1957 describes superconductivity as a microscopic effect caused by a condensation of Cooper pairs into a boson-like state. The theory is also used in nuclear physics to describe the pairing interaction between nucleons in an atomic nucleus. The binding energy of the Cooper pair is very small: a few meV, so a sample needs to be cooled below that threshold in order to reduce the thermal energy to allow superconductivity to occur. Superconductivity appears at cryogenic temperatures — indeed, in the range 1-20 K for classical superconductors. Only in the oxide superconductors, discovered by Bednorz and Muller in 1986, can the critical temperature T_c be as high as 140 K (curiously the record is held by a mercury composite, so the first superconductor is still the best, in terms of T_c).

It is wondrous to observe that a boson condensation occurring at very low temperature, below 10 K, provides the ground for the main technology that has enabled the construction of the collider leading to the discovery of the Higgs boson condensate, which occurs at a temperature of greater than 10^{15} K!

In the same period when the BCS theory was devised, the first practical alloys capable of achieving significant critical current in a large field were discovered. In the sixties Nb-Ti was discovered, from which superconducting magnets were built and improved over more than thirty years. It is interesting to note that the main improvement has to do with another exquisite quantum-mechanical effect in superconductor. Because of the wave nature of Cooper pairs, the magnetic flux in a superconducting material is quantized, the flux quantum being:

$$\Psi_0 = h/2e \simeq 2\ 10^{-15}\ \mathrm{Wb}\,, \tag{5.5}$$

where the fact that the electric charge is $2e$ is considered one of the most compelling evidence that the current carrier is an electron pair. Incidentally, the measure of magnetic quantum flux in superconductor, though the Josephson effect, provide the most precise measure of the Planck constant, the fundamental constant of quantum mechanics. Coming back to a practical superconductor, because of the quantization, the magnetic field is disposed in an array of flux quanta, called also flux vortices since each flux bundle is surrounded by a vortex of persistent supercurrent (first hypothesized by Abrikosov — see Figure 9). Actually, this penetration of the magnetic flux in quanta is a critical ingredient of the mechanism allowing a type II superconductor to remain superconducting also in presence of fields of 10-20 tesla or more. However this has a drawback: when a transport current is fed into a superconductor, the interaction between flux bundles and the resistance-less current is such that the flux vortices start to move, generating heat and eventually driving the superconductor into the normal state.

A crucial point of superconductor technology is to find ways to “pin”, literally, the flux vortices, in such a way that there is no dissipation, despite the large transport current. Pinning can be obtained by generation of suitable defects: if the core of the vortices is non-superconducting, it has the energetic advantage of containing a zone that is already normal without having to spend the energy to drive it into the normal state. The stronger the pinning mechanism the higher the critical current density J_c that can be transported by a

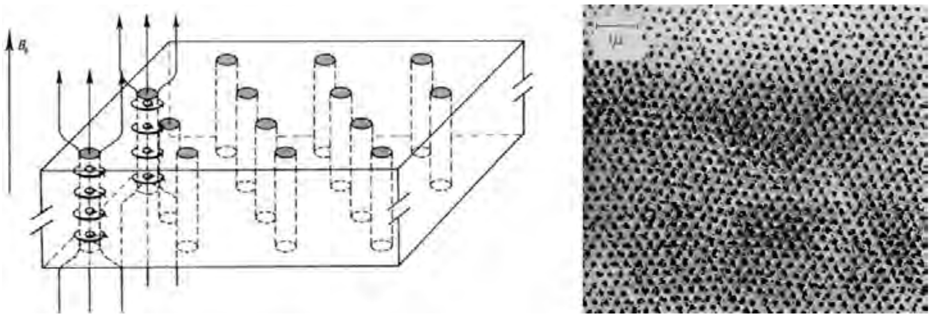

Figure 9: *Scheme of the quantization of the magnetic flux in a superconducting slab (left picture), with shown the superconducting current vortex surrounding the normal zone where field is pinned, see text for details. On the right picture is reported a famous photo that demonstrated the existence of the flux bundles (V. Essman and H. Trable in MPI fur Metallforschung).*

superconductor, according to

$$J_c \times B = f_\rho \,, \tag{5.6}$$

where B is the average field (basically given by the density of flux vortices) and f_ρ being the volume density of the pinning force given by the pinning mechanism and the number of pinning centres. Thanks to continuous improvement in metallurgy and pinning technology, the current density of Nb-Ti continued to improve over the years, according to the graph of Figure 10. Once the current was available magnet designers and engineers were able to take advantage of it by making more and more powerful accelerator magnets, as shown in Figure 11.

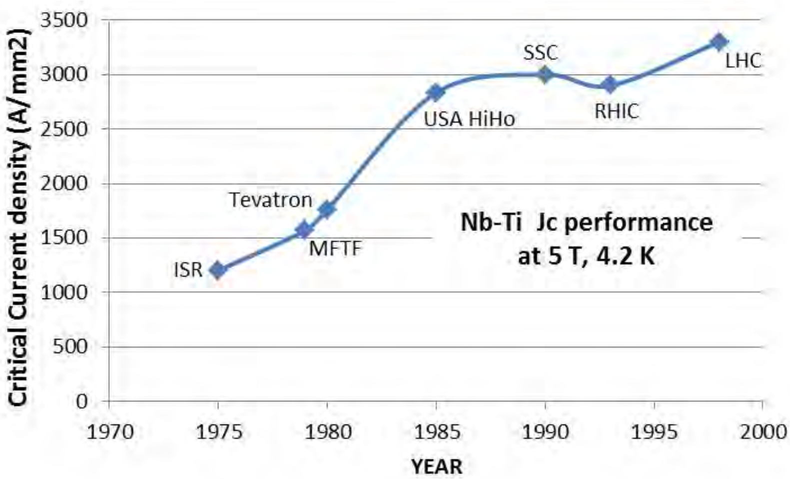

Figure 10: *Evolution of the critical current density for the Nb-Ti alloy during the years.*

Superconductivity has brought a clear advantage in accelerator technology. In case of circular accelerators, whose maximum energy is determined by eq (5.4), the advantage of high magnetic field is evident. LHC is a ring of 27 km in circumference (18 km covered by dipole field) and reaches 7 TeV/beam by using dipole magnets that produce a field of 8.3 T. A sophisticated cryogenic system maintains the Nb-Ti superconducting dipoles at 1.9 K, requiring about 40 MW of wall plug power. This is considerable electric power, but if LHC had been

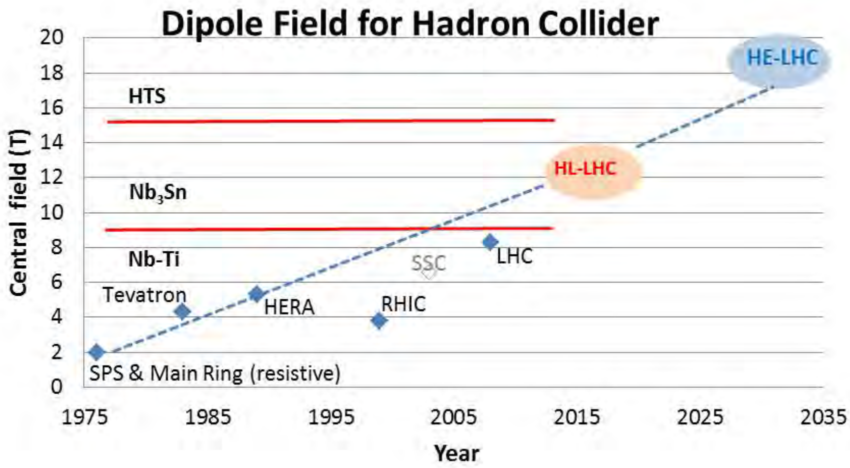

Figure 11: *Evolution of the operating field for past colliders (diamonds) vs. time. All accelerators magnets made use so far of Nb-Ti superconductors. The two future projects, HL-LHC and HE-LHC, will be discussed later in the text.*

built with normal technology employing resistive magnets, limited by iron saturation at 1.8 T, it would have required a ring of 100 km in circumference and 900 MW of electric power (the power delivered by a large nuclear plant) to achieve the same energy. A tunnel of that length and such power consumption would have resulted in a prohibitive cost of investment and an unreasonably high cost of operation. From the pioneering work of Tevatron, the case for superconducting magnets for high energy proton synchrotron and colliders is clear and understood.

Less compelling is the case of SC radiofrequency (SCRF) cavities. In case of a linear accelerator the voltage of a cavity is used only once and the energy is just the sum of the voltage of the series of cavities: $E = GL$, where G is the electric field, or voltage gradient, and L is just the length of the accelerating structures. Actually the highest gradient values are held by normal conducting cavities. For the CLIC project, cavities capable of 100 MV/m are employed, while SCRF is basically limited to 30 MV/m. However the dissipation on the cavity wall in the copper is such that normal conducting linacs all works with a low duty cycle, while the dissipation-free SCRF can work in CW (Continuous Wave, the RF equivalent of D.C.) or with much higher duty cycle and bunch length; duty cycle is required in SCRF not because of dissipation, rather to have time to refill the cavity with power after the beam has taken away the energy from the cavity. A summary of HEP accelerator is reported in Figure 12, showing the importance of projects based on the use of superconductivity. With the notable exception of CLIC, superconductivity dominates the scene over the last 30 years.

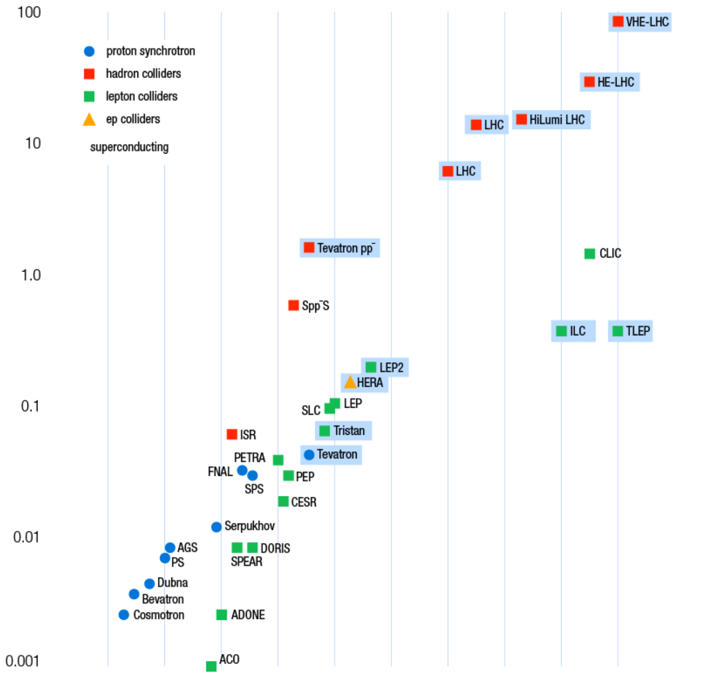

Figure 12: *Collider energy vs. time (non-complete compilation). The energy is reported in terms of center-of-mass of the collision. Evidenced are the accelerators based on superconducting technologies.*

4. LHC: the accelerator and the contribution of superconductivity to the discovery of the Higgs Boson

In terms of technology and know-how the LHC is the culmination of thirty years of development of hadron colliders and superconducting technology. Thanks to ISR p-p and SPS p-pbar colliders, CERN and the community learnt how to deal with hadron colliders. Then thanks to the ISR lowbeta insertion (the first accelerator making use of SC magnets in operation), to the R&D for the ill-fated Isabelle project and especially thanks to the pioneering work on the Tevatron (the first really large enterprise relying on superconductivity), this technology has become an essential ingredient of any new project. The *ep* collider HERA at DESY, and the ions collider RHIC at BNL (installed in the tunnel remaining after the cancellation of Isabelle) marked the era of industrialization of superconducting accelerator magnets. Finally the LHC made the great jump, by pushing the technology of classical Nb-Ti close to its limit (see Fig.10). Also apparent in that plot is the gap left by the SSC, the 86 km long p-p collider in Texas that rivalled the LHC until it was halted by US Congress in 1993.

LHC magnets are based on Nb-Ti/copper composite, arranged in flat cables as shown schematically in Figure 13. For the accelerator magnets about 7000 km of wide, 13 kA superconducting cable was manufactured. All cable units have been tested at 4.2K and a sample (few per cent) at 1.9 K. Indeed to boost the performance of critical current, the magnets are cooled at 1.9 K by mean of superfluid helium.

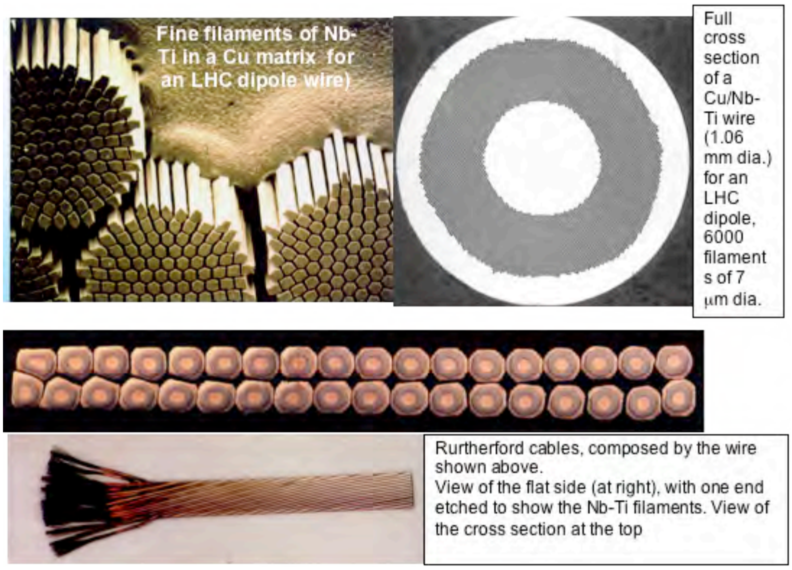

Figure 13: *Schematic view of accelerator magnet superconducting cable, composed of strands (wires) which are a composite of copper and Nb-Ti fine filaments.*

The main LHC dipoles are shown schematically in Figure 14 in an artistic view. The critical points of accelerator magnet design can be summarized as follows:

- Necessity of operating at very high current density, $J_{\text{overall}} \simeq 400\ A/mm^2$. To put this figure into context, the large superconducting magnets for particle detectors and for fusion tokomaks are operated at about 40 A/mm^2.
- The stored energy and the high current density make the protection of the magnets a challenge. The 7 MJ of magnetic energy a dipole unit must be discharged in about 100 ms to avoid excessive heating in the hot spot of the superconducting coils, which would cause thermal stresses, damage to insulation and too high voltages.
- The field quality must be controlled in each magnet to better than 10^{-4}, which implies to control the position of the conductor at the 10-30 μm level over the 15 m length of magnet units; and this in presence of strong forces, since $F \propto JB$, and both J and B are very large.

These challenges are really a step beyond what was done with previous accelerators, as Figure 11 shows. It took more than twenty years to develop the LHC superconducting magnets from the first ideas presented at the Lausanne workshop in 1984. The first model magnet was tested in 1988 and the first full size prototype was tested at CERN in June 1994; the last production dipole was delivered to CERN on 7 November 2006. In Figure 15 the LHC Magnet timeline is reported. Thanks to the 8.3 T dipole magnets covering 18 km or 2/3 of the ring, protons in the LHC can reach a momentum of 7 TeV/c. The associated wavelength is about $\lambda = h/p \simeq 10^{-19}$ m, i.e. 0.1 actometer or 100 zeptometer, inaugurating a new prefix in the space scale - another quantum mechanical effect of our accelerator!

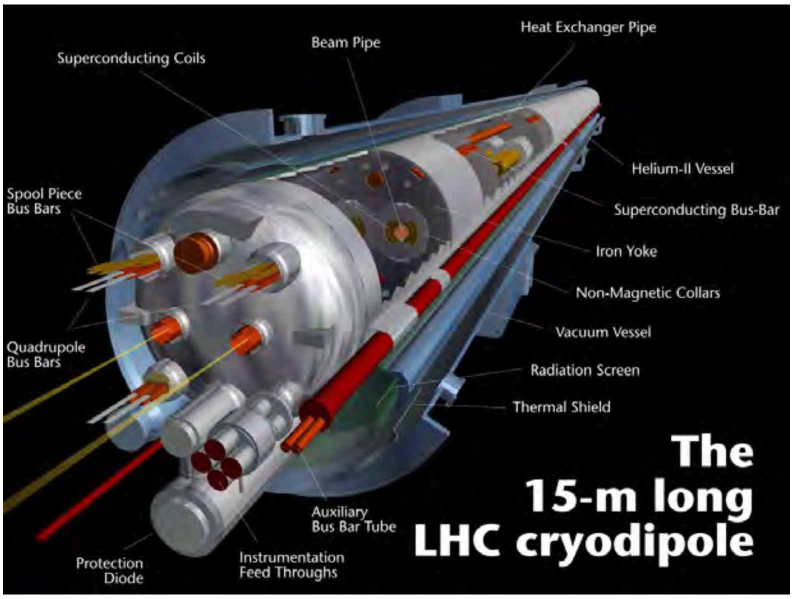

Figure 14: *Artistic view of the LHC dipole in its crypostat.*

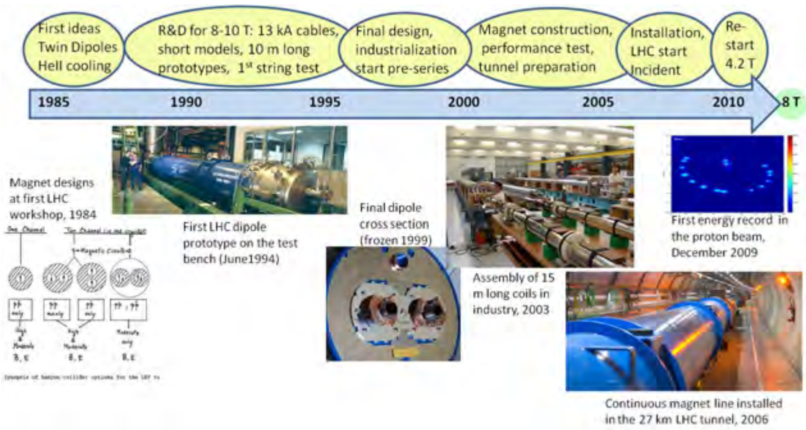

Figure 15: *The LHC construction timeline form conception (Lausanne workshop 1984) to the achievement of the beam energy record in December 2009.*

The particle detectors also employ large and powerful superconducting magnets. Magnetic field in detector magnets is required for charge identification of the particles and for spectrometry. If the detectors are placed outside the magnetic field, the resolution in momentum of various particles is proportional to BL, where L is the path length inside the field B of the particle. This is a dependence on field and length very similar to the one of accelerator. However, if the particle detectors are placed inside the magnetic field, i.e. the resolution is given by accurately reconstructing the particle track in order to allow the measurement of the sagitta, the resolution scales as:

$$\frac{\Delta p}{p} = \frac{1}{BL^2} \tag{5.7}$$

From Eq. (5.7) one can see that large volume pays off much more than higher field. This is one of the reasons why modern detectors are enormous with huge magnets, in most cases superconducting. In Fig. 15 a picture of the main superconducting magnets of the the ATLAS experiment, the Barrel Toroid, is reported. Because of the toroid configuration the average field is relatively low, about 1 T however the volume is enormous, with a diameter of 20 m and a length of more than 25 m.

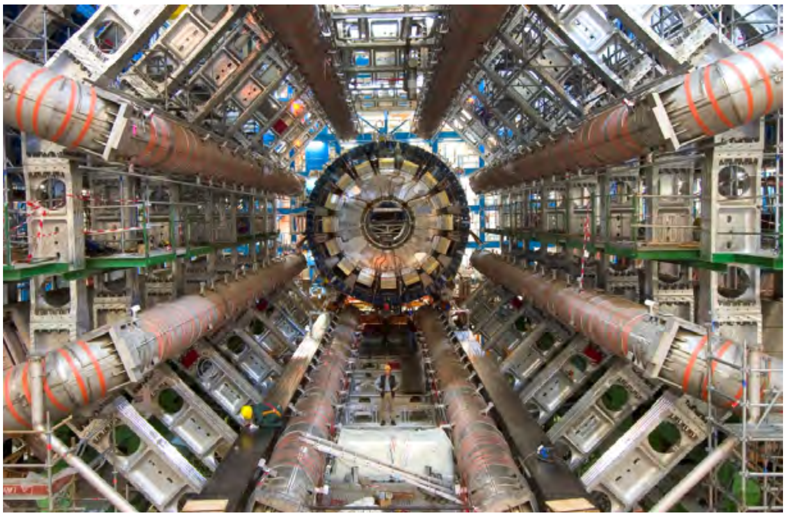

Figure 16: *The ATLAS barrel toroid superconducting magnet is shown right after assembly in the P1 cavern of LHC. This was the status before the assembly of all particle detectors and before the positioning of the End Cap and the Solenoid superconducting magnets.*

A well-known picture from the ATLAS experiment is presented in Figure 16. This picture shows the final decay of a Higgs event into four muons. The precision of the reconstruction of the muon momentum is critically based on a large, air-cored superconducting toroid, which with its 25 m length is one of the largest SC magnets ever built. Although the useful field is fairly modest (about 1 T average, with a peak of 4 T on the coils), the very large size (more than 20 m in transverse dimension) bends the trajectories of energetic muons with a sagitta of more than 0.5 mm. By means of an accurate detector system this can be measured with 10-50 μm accuracy, to provide a precise determination of momentum.

5. Outlook to the future

In the compilation shown in Fig. 11, together with many accelerators from of the past, a number of future projects are envisaged. We do not know today what will be the next step for HEP, and then which accelerator will provide the best instrument for the future of our science. Only after LHC will have given results at maximum energy, 13-14 TeV, after 2015, can we have an idea where to look for finding the trace of physics beyond the standard model. So we review briefly the main accelerator projects for HEP.

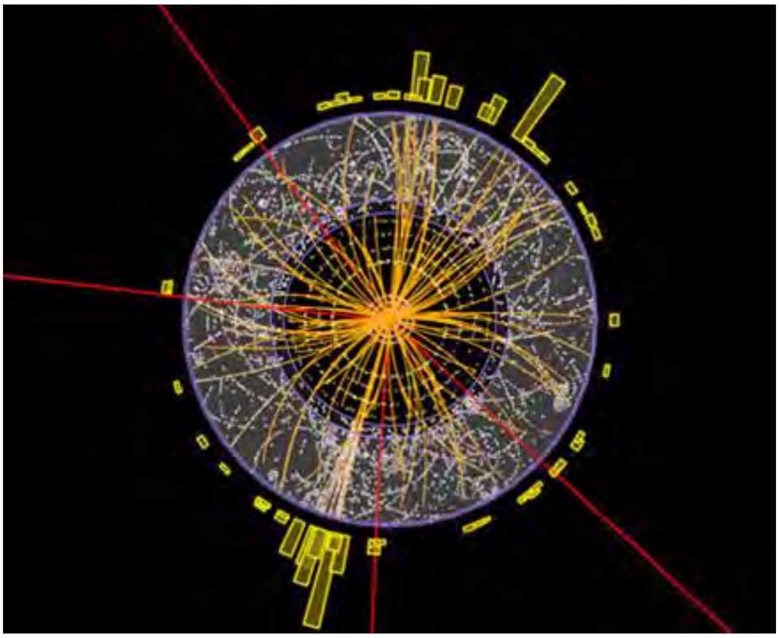

Figure 17: *An event which is compatible with the production of a Higgs particle decaying into* $2Z$ *and then into* 4μ *which are represented by the red traces that on this scales appear as straight lines.*

5.1 High Luminosity LHC

LHC is designed to provide an integrated luminosity of 300 fb^{-1}, a figure that should be reached in about 2020-2022, see Figure 12. Then, limitations of the machine and detectors, including possible radiation damage of some components, call for a program of hardware consolidation. This also provides the opportunity to replace some components with new more advanced devices that should allow reaching, over the following ten years, the extremely high level of 3000 fb^{-1}. To this end we need to replace some magnets with magnets based on a more advanced superconductor, Nb3Sn, which allows going beyond the 10 T wall in Nb-Ti magnet technology. For the High Luminosity LHC (nicknamed as HiLumi) dipoles rated at 11 T and quadrupoles capable of more than 12 T are needed, as shown by the pink region labelled as HL-LHC of the plot in Fig. 10. The number is relatively small, some 10 dipoles and 20 quadrupoles, which make this program affordable in terms of cost, but it will be necessary to prove the new technology by extensive testing of full-size magnets before risking their installation in the accelerator.

We also need to develop a new type of superconducting RF cavity, in order to increase further luminosity by cancelling the geometric reduction factor due to the finite crossing angle. These devices are called Compact Crab Cavities and they are able to kick the beam transversally rather than longitudinally, as a usual cavity does to increase energy. We will require four cryo-modules, each equipped with four cavities.

The project has been recently singled out as first priority in the approved European Strategy for High Energy Physics and is now in an advanced phase of design and prototyping.

5.2 High Energy LHC (HE-LHC)

Once HiLumi LHC has exhausted its physics program, around 2035, the LHC will be available for other use. An obvious possibility is to go beyond the LHC energy, but for this we would need more powerful magnets. Already HiLumi LHC will set the technology standard to 12-13 T, well beyond the 8.3 T of LHC. Recently a program has been launched in Europe to reach the new threshold of 20 T for dipole magnets (see Figure 10). This is a very challenging development which will requires at least ten year for R&D, because it requires use of HTS, the High Temperature Superconductors (the ceramic copper oxides based on Bismuth or Yttrium) in addition to pushing Nb_3Sn technology to the limit; then another ten years would be required for construction followed by five more for installation and commissioning. The program fits well with the life span of HiLumi and would aim at providing p-p collisions at 26-33 TeV c.o.m. by 2035-2040.

5.3 Very High Energy LHC (VHE-LHC)

This project is based on the same technology of High Energy LHC but would be in a new larger tunnel. The goal is to reach 100 TeV c.o.m. for p-p collisions. In Figure 18 the sketch of such tunnel in the CERN region is shown, for both cases: an 80 km and a 100 km tunnel.

In the first case to reach 100 TeV would require the 20 T magnets that are also pursued for High Energy LHC, while in the second case the longer tunnel allow decreasing the magnetic field down to 16 T. This last choice is attractive because it is a level that could in principle be covered by using Nb_3Sn, and should not require HTS.

A design study has just started for this larger machine, under the name of Future Circular Collider (FCC). This study will include the possibility of using the same tunnel to house an e^+e^- collider and eventually ep collisions.

5.4 International Linear Collider (ILC)

This project consists of a 30 km linear accelerator, for e^+e^- collisions, based on SCRF cavities capable of electric field of 30 MV/m with moderate power consumption (thanks to Superconductivity and to an appropriate duty cycle). The project has been pursued in an international collaboration after agreeing in 2003-2004 to select between the normal conducting technology of SLAC (NLC, Next Linear Collider based on 3 GHz copper cavities) and the SCRF 1.3 GHz project called TESLA, pursued by Europe, based in the DESY laboratory in Hamburg. The SCRF project was chosen and since then the community has

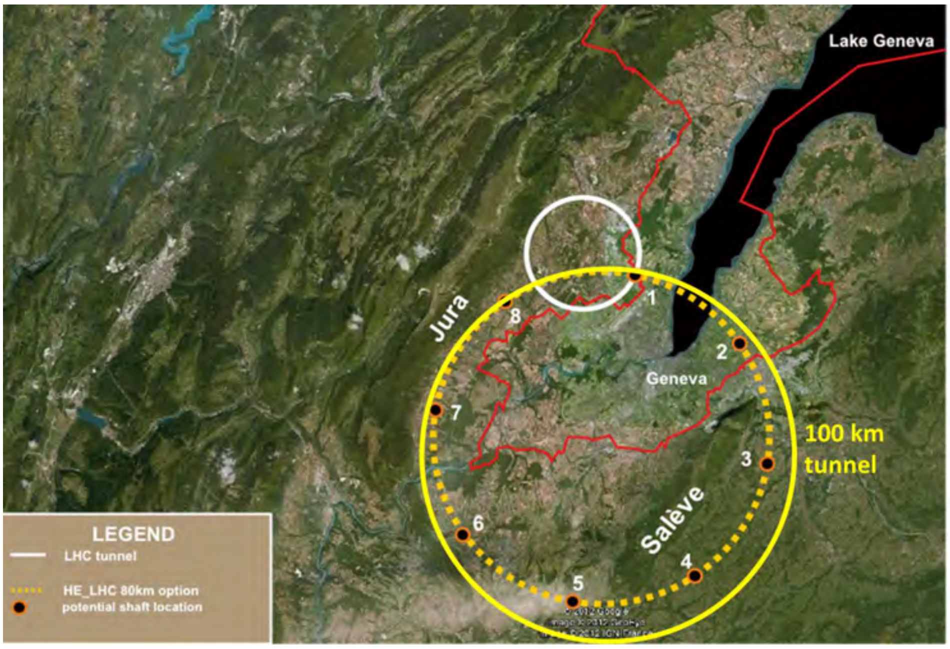

Figure 18: *The Geneva region with the footprint of the LHC tunnel (white circle), of the 80 km tunnel for VHE-LHC (yellow dashed circle) and of the 100 km tunnel (yellow, solid line).*

worked hard to bring the project to a good state of maturity. However, given the high cost, only one Nation is so far considering to host such a project: Japan. Should the plan for construction go ahead, the project would most likely be staged: first it will build the machine for 250 GeV c.o.m, and then it would upgrade it to 500 GeV. The study began some 20 years ago targeting the TeV region, but this now appears to be out of reach for such a machine. The 500 GeV project is budgeted nominally at 7 G$, and the time scale is such that physics data-taking could start around 2030.

5.5 Compact Linear Collider (CLIC)

This machine is an e^+e^- collider powered via a parallel drive beam, and is based on the use of high frequency copper cavities. The frequency is now 12 GHz (after having been 30 GHz for many years). Here superconductivity is only required for the wiggler magnets, at the heart of the damping rings, which are necessary to reduce the transverse size of the beams. The electric field in the cavities is up to 100 MV/m which in principle would allow, with a 50 km long tunnel, to reach 3 TeV c.o.m. In terms of a rough energy scale, CLIC would match the HE-LHC but would stay largely below VHE-LHC, but of course with the much cleaner collisions of leptons. A drawback of this accelerator is the high power consumption, about 600 MW (LHC and its injectors consume less than 150 MW and a HE-LHC would consume about 200 MW, including the injector chain). The CLIC collaboration has produced a Design Study and is now considering a roadmap featuring a staged approach. In principle one could have 500 GeV from CLIC initially and only later implement 1-3 TeV, in a second phase. The project is however less mature than ILC.

6. Conclusion

To satisfy the need for better instruments to investigate the infinitely small, the realm of quantum mechanics has been explored by the use of increasingly sophisticated accelerator and particle detectors. In the last 30 years accelerator technology has been dominated by a technology that can be considered to be a macroscopic effect of quantum mechanics: superconductivity. The similarity between the boson condensation which is at the base of the superconductivity and the one at the base of the Higgs mechanism (proven thanks to the superconductivity-based LHC) is intriguing. Even more fascinating is that the field is not yet at its limit and new exciting projects, capable to explore new lands beyond the realm of the Standard Model, are under construction or in a design phase.

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