Chapter

From the Eloisatron to the Pevatron

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Abstract

In the late 1970s the experimental physics community was active in promoting the Large Electron Positron (LEP) collider and its associated experiments to study the Z- and W-bosons, and with the expectation that the tunnel could subsequently house a hadron collider (LHC), providing a center-of-mass energy for discoveries at the frontier of knowledge. At this time, Antonino Zichichi, who had chaired a Working Group in charge of promoting LEP among the community of experimental and accelerator physicists, realized that one should envisage building as large a ring as possible, for which LEP/LHC would be but a scale model, and it was thus the idea of the Eloisatron, or ELN, in a ring of about 300 km in circumference, was born. CERN and IHEP, China, are now engaged in studies for future colliders of 100 km in circumference, aiming to extend center-of-mass energy in hadron collisions to 100 TeV by using very high field magnets. The ELN idea lives on, but it is time to envision an update. A ring of diameter 300 km would make possible the installation of a sequence of increasingly complex accelerators culminating in one eventually capable of providing a center-of-mass energy of 1000 TeV, i.e. a peta-electron-volt or PeV.

Keywords: particle physics, standard model, CERN, colliders, ISR, LEP, LHC, FCC, Eloisatron, 100 TeV, 1 PeV, Pevatron

1. Introduction

Following the success of the first hadron collider, the Intersecting Storage Rings (ISR) [1] at CERN in the early 1970s, colliders have been the experimentalists' main tool for exploring, in laboratory conditions, particle physics at the frontier of knowledge. Enthusiasm for the large collider that was to become the Large Electron-Positron collider (LEP), was amplified in 1976 by the workings of the so-called LEP Working Group [2], which produced several visionary reports regarding the future possibilities of an accelerator of about 30 km in circumference [3]. Thanks to technological advances at the ISR, the Z- and W-bosons foreseen in the Standard Model were first observed (1984) in the proton-antiproton collider in the SPS tunnel at CERN [4], before LEP was completed. The lepton collider LEP, an accelerator of 27 km in circumference targeted detailed study of the intermediate bosons that had been previously discovered, providing unprecedented precision that helped to entrench the Standard Model of fundamental physics between 1989 and 2000 as being the best, albeit incomplete, description of the physical world of elementary particles at the present time [5]. In parallel, the feasibility of performing comparable experiments with leptons with linear colliders was ably demonstrated at SLAC, and a more powerful proton-antiproton collider was put into service at the Fermilab Tevatron [6]. Experimental particle physics had well and truly embraced the advantage of laboratory-based colliders for probing deeper into the unknown. In the quest for still higher center-of-mass energies, the 80 km Superconducting Super Collider (SSC) [7] in the USA was destined to provide conditions for experiments at center-of-mass energies of 25– 30 TeV, but due to funding problems this was not to be. It was therefore at the Large Hadron Collider [8], installed in the LEP tunnel, that events revealing the elusive Higgs boson were observed in 2012 [9]. Now the community is studying the possibility of providing the discovery potential of still higher center-of-mass energies, as well as precision measurements of the Higgs boson in a lepton collider in much the same way as was done at LEP for the Z- and W-bosons.

The idea of the Eloisatron, or ELN, to be installed in a tunnel of about 300 km of circumference, was born in 1979. Zichichi, an experimental physicist who had played an active role in the first g-2 experiment at CERN, and led experiments at the ISR, clearly understood the value of storage rings and colliders. He had been very active in promoting work on LEP and its associated experiments [2]—fully aware of the fact that the tunnel could be used subsequently to house a hadron collider. He realized the importance of equipping as large a ring as possible to enable to perform experiments at the highest possible center-of-mass energy, and for which LEP/LHC would be but a scale model. It was thus that he came up with the idea of the Eloisatron this being the largest that could be accommodated on the island of Sicily. Zichichi argued that such an instrument could be built for roughly the same cost as a bridge that was envisioned to join the island to the mainland, and this and several other sites in Italy were considered (perhaps the most appropriate being in the geologically stable island of Sardinia) [10]. Kjell Johnsen, who had previously led the highly innovative ISR project, was put in charge of the first studies for such an accelerator. However, this was to be overshadowed by work on the ill-fated 83 km Superconducting Synchrotron Collider (SSC) project in the USA, and on the LHC at CERN, only to be revived later in the ephemeral Very Large Hadron Collider (VLHC) studies for a 233 km long collider at Fermilab [11]—itself largely inspired by the Eloisatron concept. Nevertheless, it should be emphasized that it was due to the recognition of the importance of studies on detectors associated with the potential ELN (and *a fortiori* the LHC) that the LAA project was born. This auxiliary project provided the framework for vital work to be performed on detectors, enabling the adoption of techniques to address problems inherent with equipment required to observe very high energy collisions at the LHC [12].

Today we have the LHC, which will be upgraded to provide increased luminosity from 2026. Studies for a future generation of accelerator/colliders focus on either a linear collider (for leptons) aimed at detailed study of the Higgs (or Higgs-like) events seen at the LHC, or a large (100 km) circular collider. The idea is that this would first provide e^+e^- collisions (as a simpler alternative to the linear collider for a so-called Higgs factory), both in the European Future Circular Collider (FCC) and Chinese Circular Electron-Positron Collider (CEPC) versions, to be followed by installing a hadron collider with discovery potential [13, 14]. To achieve a sought-after 100 TeV center-of-mass energy, the new machine would require a large number of yet-to-be-developed, very high field superconducting magnets (16 T dipoles). The experimental physics community hopes that at least one of the large circular machines will be constructed, even if, as likely, it does not quite reach the presently advertised performance, it will allow groundbreaking studies both in particle and in accelerator physics and technology. However, the philosophy behind the idea of the ELN lives on. Closest to the ELN concept, there is a proposal [15] for a minimum cost route to a 100 TeV center-of-mass hadron collider: the idea being to finish the SCC tunnel in Texas, in which an injector synchrotron would be installed, and to bore a second tunnel, of length 270 km to house the main collider, using affordable 5 T superconducting dipoles. The SCC tunnel could also house an efficient circular e^+e^- collider to be used as a Higgs factory. The terrain in the vicinity of the SCC is propitious for tunneling, the per meter cost being less than that near CERN, at least in the sections of limestone [16] (but for a global costing this would have to be offset by the value of the existing laboratory infrastructure at CERN). However, unlike for LHC, where there was an identified goal (to reveal Higgs), indicating an appropriate energy, it is now desirable to foresee being able to access far higher collision energies, so the goal should perhaps evolve. It is thus proposed that one should consider a ring of about 300 km *in diameter*, enabling the installation of a sequence of accelerators culminating in one capable of achieving a hadronic center-of-mass energy of 1000 TeV, i.e. a PeV, or peta-electron-volt. In this chapter, a vision is presented of what would probably be the world's Ultimate Circular Collider, based on proven and foreseeable accelerator physics and engineering science: i.e. the UCC, or Pevatron.

2. The requirement

It is first assumed that a Higgs Factory, either in the form of a linear collider or phase 1 of an FCC or CEPC (or possibly "LEP3", an ultimate e^+e^- collider in the LEP/LHC tunnel) will have done its work before the first phase of experimentation starts at the UCC. While the tunnel could (and should, initially) undoubtedly be used to house an exciting e^+e^- collider, it is supposed to be principally an instrument for performing frontier physics using hadron collisions. The second assumption is that suitable stable sites can be identified for efficiently boring or excavating an approximately circular tunnel of about 300 km in diameter. For the first phase of operation of the hadron collider, the accelerator should be capable of delivering comfortably a center-of-mass energy of 100 TeV in at least two experiments using the simplest (and cheapest) possible guiding magnet system. This accelerator would serve as the injector for subsequent upgrades of the collision energy, culminating in 1000 TeV and (like the FCC) would depend on the development of affordable high performance superconducting material. The first phase would feature extremely simple magnets based on the use of existing low-cost superconductors. This, together with the fact that synchrotron radiation, and other effects associated with the deflection of stiff beams would not be a problem, could mean that the first phase of the proposed machine may even be cost-competitive with the hadron versions of FCC/CEPC. An added incentive to read on....

3. The site

There are undoubted advantages in using present laboratory infrastructure if at all possible, as has been done to render the sequence of accelerators at CERN both performant and affordable. The longstanding international nature of Geneva also facilitates the hosting of such a center. It is thus evident that one candidate should be CERN. However, the terrain is not ideal, as the tunnel would have to pass through many kilometers of mixed rock including limestone, which would complicate the process and have clear implications on the scale, cost and timescale of civil engineering. Other sites must therefore be considered for a larger circular accelerator than the FCC, and the cost analysis should consider what would be required to develop (or establish) suitable infrastructure for another, possibly entirely new, laboratory. As such an accelerator must be a fully international endeavor, and it will certainly take decades to achieve the ultimate goal, mechanisms will have to be enacted that render it attractive and guarantee its perennity. What springs to mind is a development of the successful CERN model, and CERN should most definitely be central to its establishment. Suitable geologically stable sites with good tunneling attributes certainly exist in China, Europe, Russia and the United States, but socio-political support will be as important as geographical location.

Considering the evident urbanization of the planet, this new collider would provide the incentive for a farseeing nation or region to combine the excitement of creating a laboratory to explore the very forefront of natural science, with that of establishing a cluster of cities, including some that are radically new. These should feature all the latest developments in sustainability and form a living exhibition of what can be done to enhance the quality of life and quest for perfection. Besides accelerator scientists and experimental physicists, architects, engineers, social scientists, artists and philosophers should all share the excitement of working together to create such a holistic ensemble showing the way for a harmonious future of the region of the world that is farsighted enough to seize the opportunity. We consider the establishment of at least four major agglomerations, or sub-cities, each housing at least 5 million inhabitants clustered around a circle defined by the accelerator, inter-linked by rapid train and highway systems. Ideally, to facilitate the setting up of the complex, at least one or two of the cities would be developments of existing conurbations. Each city would feature its own local subway system. The airport should be located approximately at the center of the circle with rapid local trains connecting to each of the mainline stations at the city nodes. Such an arrangement is shown schematically in **Figure 1**, but the actual layout would depend on local geography and a consensus based on overall requirements and planning, and responding to the constraints of sustainability, comfort and efficiency. Some of the glue holding the enterprise together would be the pride of hosting a forefront laboratory probing the mysteries of science using a unique instrument. It is confidently expected that such a complex of cities would be a breeding ground for experimentation in urban living as well as in physics research and associated technological developments and would pioneer advances in social well-being as well

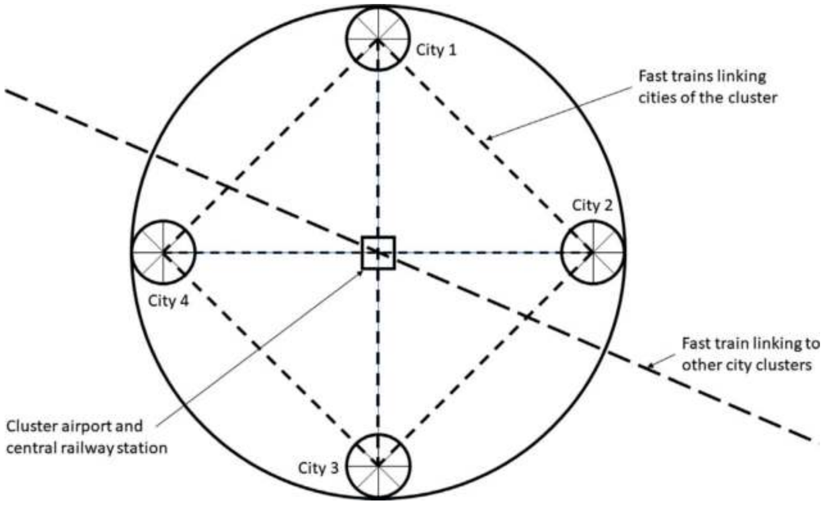

Figure 1.
Schematic layout of a cluster of cities hosting a very large particle accelerator/collider. The large circle represents the main ring. It is supposed that the injector synchrotron would be located at one of the cities, and the two major experiments at two of the other cities.

as science proper. It has been observed that clustering cities can lead to the creation of hotbeds of efficiency, creativity and innovation, and it is on this premise that China, for example, has already identified 19 regions that it intends to endow with the necessary infrastructure [17]. Other large nations are also considering moving in the same direction. It is opined that the fundamental research orientation of the complex suggested here would be more effective in providing the impetus for getting such a city cluster to work, than either bureaucratic edict or simply hoping that lavish infrastructure would somehow engender efficiency.

4. The accelerator/collider complex

It is foreseen that such a collider would be operated in three major phases, each phase taking its performance to new heights.

4.1 Phase 1

A large fraction of the experimental particle physics community is presently of the opinion that to provide worthwhile discovery potential the next hadron collider after the LHC should deliver a center-of-mass energy of about 100 TeV. This is the ultimate goal of the FCC as seen today, and it would be the target for the first phase of the UCC. For the 300 km diameter accelerator considered here, this would imply having a main dipole magnet field of 1.7 T. The transmission line magnet (pipetron), first developed for the VLHC study [11] provides such a field very efficiently. As shown in **Figure 2**, this device consists of field-shaping iron poles and yoke excited by a single superconducting cable carrying up to 100 kA and is extremely cost effective. Since the VLHC study, new cables based on magnesium diboride (MgB_2) material, which work comfortably at 20 K as opposed to 4.2 K for Nb-Ti, have been developed at CERN for interconnecting equipment required for the luminosity upgrade of the LHC [18]. As the specific heat of metals is proportional to the cube of the absolute temperature, such a cable is very stable, and, compared with the previous study for the VLHC, its use would also lead to a simplification of the associated cryogenic envelope and cooling system. To make best use of this technology the main magnet guiding and focusing system could be of the combined function type featured in the ISR. The estimated cost for such a

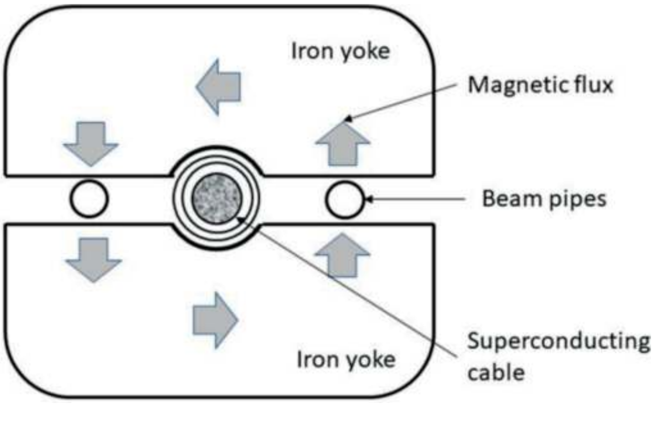

Figure 2.
Schematic cross-section of a transmission line magnet for bending the counter-rotating beams of elementary particles in a collider. The magnet is excited by a large current (about 100 kA) flowing in a superconducting cable. Such a device can deliver a field of up to about 1.7 T—sufficient for delivering a center-of-mass energy of 100 TeV to protons in a collider of 300 km in diameter.

magnet system for the UCC is of the order of twice the cost of the magnet system for the 8.3 T system for the (very much smaller) LHC, and probably more affordable (and certainly less risky) than that of the presently envisaged high field magnet system for the FCC. The accelerator would require an injector system to supply 4 TeV protons, consisting of a linear accelerator and two pulsed synchrotrons.

4.2 Phase 2

By adding a pair of rings, powered by coils wound from classical Nb-Ti conductor cooled to 4.2 T, delivering a dipole field of about 5 T, the second phase of the UCC would provide a center-of-mass energy of up to 330 TeV. By using pre-accelerated beams from the transmission line arrangement, the new magnet system would only be required to increase the momentum of circulating particles by a factor of 3.5 to 4, simplifying the process and enabling the inclusion of beam screen within a relatively small magnet aperture. It is reasonable to assume that, by careful design, the cost per meter of such a magnet system would be less than half that of the LHC system, and as the system is entirely classical, the technological risk would be low. The layout of the transmission line magnet in the tunnel will have to be such that the new magnet system can be installed during shutdowns without disrupting the Phase 1 operation.

4.3 Phase 3

It is confidently expected that during the construction and exploitation of phases 1 and 2 of the UCC, a vigorous R&D program on high field superconducting materials, and on their engineering into reliable, cost-effective cables, will have delivered conductors comparable to Nb-Ti today. That being the case, a third set of rings, with dipoles providing fields of up to 18 T, would allow us to envisage a center-of-mass energy of 1000 TeV, or 1 PeV, the ultimate goal of the complex. It is emphasized that such superconductors do not exist at present and that once they have been identified, it will also be necessary to identify a long-term use for the material that generates the need for its engineering development, just as MRI provided the "killer application" for Nb-Ti, and which led to it becoming an affordable commodity. The sole application to particle accelerators, being "one-off" in nature, is not sufficient. The push for increasingly high field magnets for NMR is an immediate application, but essentially small-scale; as seen today, the most likely long-term large-scale application would be for fusion containment—should that develop into a viable energy source. The technological development of such material, identification of applications, and the industrialization of the manufacture are examples of the high-tech activity that one could expect to flourish in the collider city complex.

5. The host laboratory

It is generally recognized that CERN provides a good example of how to organize a large international laboratory [19]. This is not an accident. The success of the laboratory is based on a combination of several important principles:

- A simple, well drawn-up convention
- Consistent rules-based funding and purchasing

- Accumulation of skills of the workforce
- Tight technical control of projects
- Skill in the use of infrastructure to build increasingly sophisticated accelerators
- Location in an internationally-oriented city

A new aspiring global laboratory should consider carefully the implication of each of these when planning how to undertake the work.

5.1 The convention

The CERN convention is a visionary 32-page document that spells out clearly the purpose of the Organization and the rules for its governance. The governing body is the CERN Council, made up of two delegates from each member state. The Council is assisted by the Finance Committee—which deals with material and personnel budgets, and the Scientific Policy Committee—which advises on the research agenda. The convention is drawn up in such a way as to vest the Council with significant autonomy and authority to negotiate and take decisions in the interest of the Organization, to empower its scientists, and to reduce to a strict minimum the bureaucracy.

5.2 Funding

Council allocates the annual budget, with funds provided by the member states in proportion to Net Nation Income. Any activity—in particular research and development—suffers from erratic funding. In the case of CERN this is avoided by a procedure of rolling forecasts: each year the budget for the following year is established, together with firm estimates for the next 2 years and provisional estimates for the following 2 years. This has provided the laboratory with a stable funding profile and enabled planning of both the day-to-day running and that of the medium and long-term scientific program. Purchasing of equipment is subject to strict rules that favor the lowest bid for a supply satisfying carefully drawn-up specifications. While there is not a policy of fair return ("juste retour"), some effort is put into distributing contracts fairly among member states.

5.3 Skills

Scientists, engineers and technicians are encouraged to hone their skills through their work on projects. This enables them to write comprehensive specifications for equipment that is available industrially, to follow up constructively the contracts, and to design and prototype special equipment that is not available on the market. The laboratory maintains well-equipped workshops for this purpose and for that of resolving technical problems which may occur due to accidents or malfunction of equipment.

5.4 Control

CERN maintains control of projects. The normal way of acquiring equipment is through buying from industry to a tight specification, written by staff competent in the field, and close technical follow-up. Cost is minimized by in-house design and prototyping, and by limiting the risk to manufacturers by confining the requirement to that of satisfying engineering standards: CERN specifically bears the technical risk for the correct functioning of complex equipment. While the LHC collider was mainly funded via CERN, that of the experiments was mainly financed via the participating institutes and universities, which led to frequent use of “in-kind” supplies. It was found to be necessary to ensure compliance of such equipment by tight control from the host laboratory. For this to work it is essential to have dedicated, competent, experienced and respected staff which is empowered with appropriate authority.

5.5 Infrastructure

The maintenance and development of infrastructure is of vital importance for a laboratory. As CERN has evolved, it capitalized on existing accelerators and associated equipment to build successive increasing complex and energetic accelerators and colliders at minimum cost. In parallel, there has been a continuing development in the technology of particle detectors required for the evolving experiments, and of course in that of the supporting informatics hardware and software. The maintenance of efficient and well-equipped workshops has also been of vital importance for the Laboratory. It is an understatement to say that the experience of laboratories established harboring the specific intention of excluding integrated workshops (i.e. relying exclusively on purchasing) has not been good.

5.6 Location

Geneva is a city with a long tradition of hosting international organizations. This activity is an important source of income for the city, and it makes a corresponding effort to simplify the bureaucratic problems that can occur with international staffing. Permanent staff is not subject to local income tax, and goods are not subject to value-added tax, which helps to keeps costs under control. The city also has a conveniently located international airport and an efficient public transport system that provides excellent access to the laboratory. The laboratory itself lies astride the frontier between Switzerland and France, so that both countries are in fact host states and provide facilities over and above their reglementary contributions to compensate for the advantages incurred. The country or region wishing to host a laboratory providing facilities for international big science projects is strongly advised to set up a framework of a similar nature.

6. City clusters and project funding

One of the reasons for proposing to associate the new collider with a cluster of cities is that it could facilitate the funding. If it is recognized that to host the collider has some value—be it for education, innovation, regional pride or some other factor—then investing in the success of the project could be rendered acceptable, compared with less well-focused requests to central government. Viewed alone, the cost of a very large particle accelerator/collider, just as an array of telescopes for astronomy, or a nuclear fusion device, is perceived to loom large in a national budget, even though much of the cost is simply pumping money around the economy. And to put the figures into perspective, the cost of running CERN, presently the largest collider facility in the world, is equivalent to that of a proverbial annual cup of coffee of the population of the member states—a small price to pay for motivational news generated directly by the laboratory, without considering the economic fall-out, and innovation derived from the activity [20, 21]. The complexity inherent in the forming of city clusters calls for the injection of capital investment on a huge scale, and the additional percentage cost of hosting a large research facility of the type discussed here would be small, whereas the publicity and enhancement of the attractiveness of the cluster would be considerable. It is anticipated that in the medium term, competition between the clusters will grow, and this will in turn accelerate the performance—and stimulate the desire to host big science projects.

7. Conclusion

While the FCC and the CEPC are thought of as being the next, and possibly final step in colliders, these do not reach the size dreamt of already 40 years ago—the Eloisatron, or ELN. The proposal for an accelerator in the USA, using the defunct SSC tunnel to house the injector gets close [15], but in the study presented here the possibility of going still further is addressed. It is suggested that the increasing desire of people to live in cities, and the expected increase in efficiency (and well-being) provided by setting up of clusters of cities, may provide an opportunity to consider associating such a city cluster with a collider that could ultimately deliver interactions at a center-of-mass energy of 1 PeV, the Pevatron.

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