Chapter III.1

Particle accelerators, instruments of discovery in physics

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The idea of this seminar stemmed from questions by JUAS students who were trying to understand the links between the developments in accelerator science and technology and the advances in nuclear and particle physics that they permitted or conversely that stimulated them. It is by no means an exhaustive history of any of these fields, but rather the presentation of a few selected cases of didactical interest to non-experts in particle or nuclear physics (more information can be found in the bibliography, see Refs. [1–8]).

III.1.1 Introduction

Particle physics started with the discovery of the first particle, the electron (J.J. Thomson, 1897). Nuclear physics started with the discovery of the nucleus by the scattering experiment (E. Rutherford, H. Geiger and E. Marsden, 1911). The first of these discoveries was made using an elementary particle accelerator, the Crookes tube, the second one using a radioactive source. The Rutherford *et al.* experiment pioneered an essential method in particle physics, namely scattering, which allows to reconstruct the fine structure of the scattering centres from the observed angular distribution of scattered particles.

Soon after this, Rutherford advocated the use of particle accelerators instead of radioactive sources to reach higher intensities and momenta with different types of particles, in a controlled way. At the Anniversary Address of the Royal Society in 1927, he writes: *It has long been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of the α and β-particles from radioactive bodies. I am hopeful that I may yet have my wish fulfilled, but it is obvious that many experimental difficulties will have to be surmounted before this can be realised on a laboratory scale.*

Since then, particle accelerators have become the workhorses of particle and nuclear physics, and more recently of condensed matter physics as sources of synchrotron radiation and spallation neutrons. This symbiotic relation has developed under the pull of science and the push of technology (see Fig. III.1.1). In the following we illustrate this by a few salient cases.

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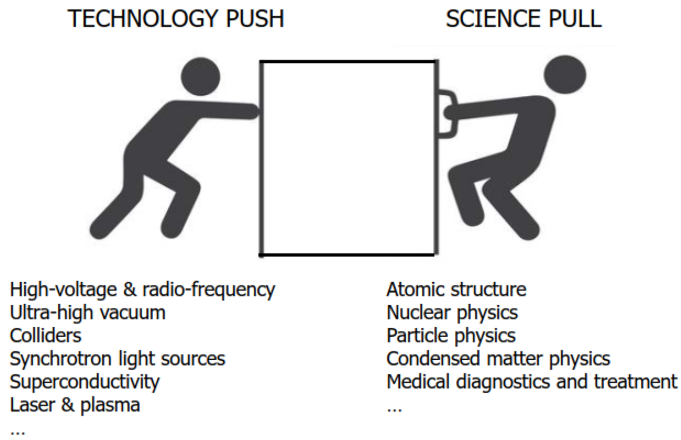


Fig. III.1.1: Science pull and technology push in particle accelerators.

III.1.2 Breaking the nucleus with electrostatic accelerators

In the 1920s, J.D. Cockcroft and E.T.S. Walton in Cambridge developed a high-voltage generator based on a ladder of capacitors connected by diodes, fed from a low-voltage AC transformer (see Fig. III.1.2): the conversion to DC and voltage multiplication were achieved by charging the capacitors in parallel and discharging them in series, allowing us to reach several hundred kV. With N stages, the theoretical maximum voltage is

$$\mathrm{V_{DC}} = 2\mathrm{N}\mathrm{V_{AC}} \quad . \tag{III.1.1}$$

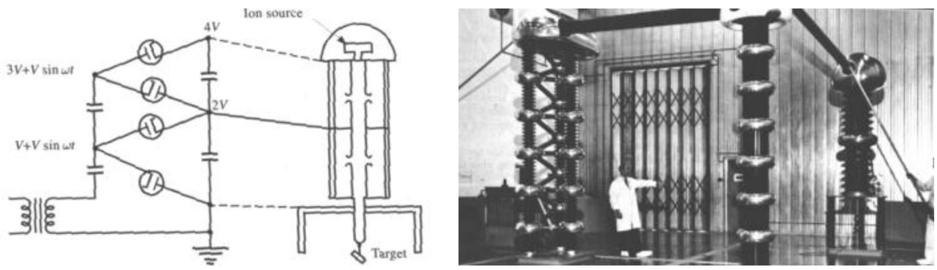


Fig. III.1.2: Cockcroft and Walton electrostatic accelerator (Courtesy Rutherford Appleton Laboratory).

In 1932, Cockcroft and Walton first broke the atomic nucleus by shooting protons accelerated to 125 kV onto a lithium target, following the reaction

$$\mathrm{Li}_3^7 + \mathrm{p} \rightarrow \mathrm{Be}_4^8 \rightarrow 2\mathrm{He}_2^4 + 17.2\ \mathrm{MeV} \quad . \tag{III.1.2}$$

They received the Nobel Prize in Physics for this in 1951.

III.1.3 Beyond electrostatics: linacs and the structure of the proton

Electrostatic accelerators are limited in voltage by electrical breakdown. Acceleration to higher energies could be achieved by having the charged particles passing several times through the accelerating structures. However, flux conservation in a time-independent electrostatic field limits acceleration to single pass. Multiple-pass acceleration thus requires time-varying fields (radio frequency, RF).

In 1924, G. Ising proposes time-varying fields across "drift tubes": with the proper phase, the particles are accelerated in the first gap between the tubes and drift inside the tubes, during which the field alternates so that it becomes accelerating again in the next gap (see Fig. III.1.3). In this way, the particles can reach energies above that given by highest voltage in the system.

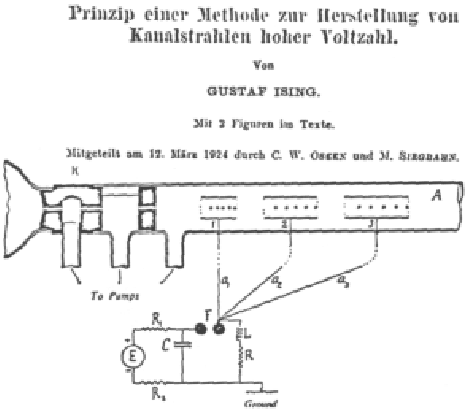


Fig. III.1.3: Principle of Ising's linear accelerator [9].

In 1928, R. Widerøe built the first demonstration linac (linear accelerator) using Ising's principle (see Fig. III.1.4): *Particles with a positive electric charge are drawn into the first cylindrical electrode by a negative potential; by the time they emerge from the tube the potential has switched to positive, which propels them away from the electrode with a second boost. Adding gaps and electrodes can extend the scheme to higher energies.*

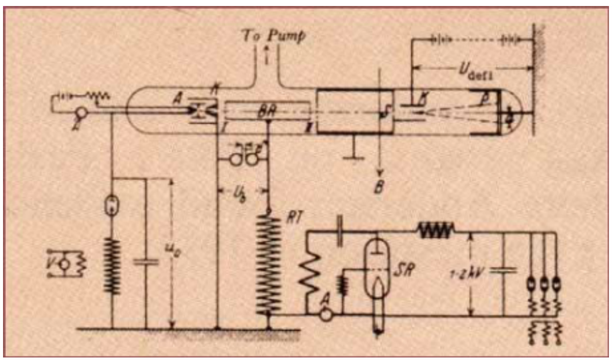


Fig. III.1.4: Widerøe's first linear accelerator [10].

Acceleration occurs in the gaps between the drift tubes, the length L of which is then "useless". As the velocity v of the (non-relativistic) accelerated particles increases, the drift tubes must become longer in order to fulfil the synchronism condition: assuming the length of the gaps is small as compared to that of the drift tubes, one can write

$$L \approx v\frac{T_{\mathrm{RF}}}{2} = \frac{v}{2f_{\mathrm{RF}}} \quad . \tag{III.1.3}$$

To limit L one must increase the RF frequency f_{RF}, which also increases electromagnetic losses. They can however be contained by enclosing the accelerating structures in a resonant cavity.

In 1946, L. Alvarez built a first linac in Berkeley along these principles. It accelerated protons to 32 MeV with a RF frequency of 200 MHz. The RF power sources were klystrons, recently invented (1939) by S. and R. Varian in Stanford, which soon became the centre for electron linacs built by W. Hansen from 1947 (see Fig. III.1.5).

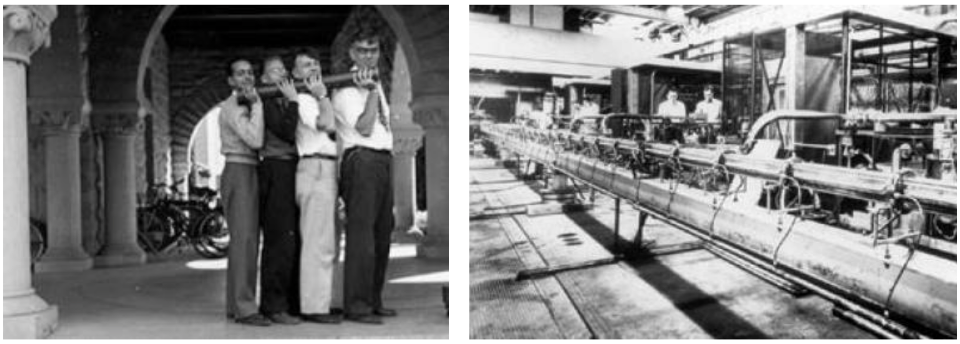


Fig. III.1.5: Stanford electron linacs: Mark I, 6 MeV, and Mark III, 75 MeV (Courtesy SLAC Archives).

In 1957, R. Hofstadter used 75 MeV electrons from the Mark III linac to probe the structure of the proton by scattering. Similar to Rutherford's experiments half a century earlier, scattering experiments at Mark III showed an excess of electrons at large angles: this is a sign of finite size and a hint of some internal structure of the proton. R. Hofstadter was awarded the Nobel Prize in Physics 1961 for this work. Following this, a 20 GeV electron linear accelerator, 3 km long, was proposed in 1957 to explore further this structure with "harder" probes, and built in the early 1960s in a dedicated laboratory: Stanford Linear Accelerator Centre (SLAC), see Fig. III.1.6.

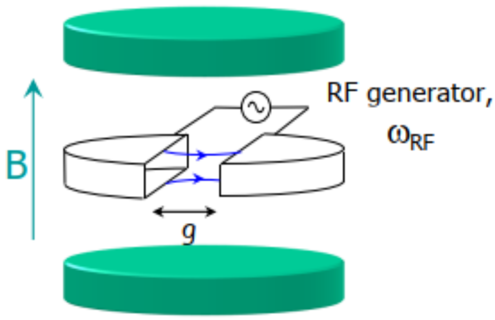
Using this accelerator in 1968, J. Friedman, H. Kendall, and R. Taylor discovered an excess of scattering at large transverse momentum transfer. R. Feynman explained the results as produced by point scattering from individual "partons" inside the proton. This later validated the theory of quarks developed by M. Gell-Mann, J. Friedman, H. Kendall, and R. Taylor were awarded the Nobel Prize in Physics 1990.

III.1.4 Circular accelerators and the discovery of the antiproton

In Berkeley in 1930, E.O. Lawrence was getting interested in particle accelerators, and tried to read R. Widerøe's paper. He writes: *"Not being able to read German easily, I merely looked at the diagrams and photographs of Widerøe's apparatus . . . and readily understood his general approach to the problem, i.e. the multiple acceleration of the positive ions by application of radio-frequency oscillating voltages to a series of cylindrical electrodes"*.

Fig. III.1.6: The 20 GeV, 3 km electron linac at SLAC (Courtesy SLAC Archives).

Using an external magnetic field, he had the idea to fold the beam of a linac in a circular pattern, with multiple pass between two D-shaped electrodes: the cyclotron was born (see Fig. III.1.7).



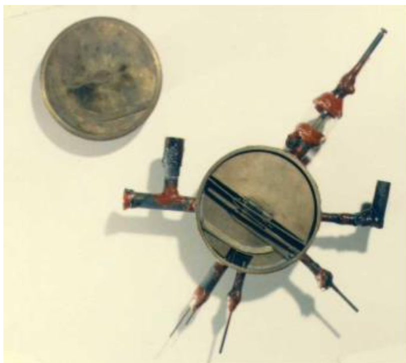


Fig. III.1.7: Principle of the cyclotron and 4.5-inch beam chamber of the first 80 keV cyclotron (1931) [11].

Orbits are spirals as particles, injected close to the centre of the machine, gain energy at each gap crossing. The synchronism condition is

$$2\pi\rho = vT_{\mathrm{RF}} = \frac{v}{f_{\mathrm{RF}}} \quad , \tag{III.1.4}$$

where ρ is the radius of curvature of the trajectory and v is the velocity of the particle. The cyclotron frequency is then

$$\omega_{\mathrm{RF}} = \frac{eB}{\gamma m_0} \quad , \tag{III.1.5}$$

where e and m_0 are the charge and rest mass of the particle, B is the magnetic field and γ is the relativistic factor. For a constant magnetic field, the cyclotron frequency is constant for non-relativistic particles ($\gamma = 1$), irrespective of the radius of their trajectory. The whole acceleration can thus be achieved with a constant RF frequency, injecting the particles close to the centre of the machine and extracting them on the outside.

Following the first 4.5-inch diameter machine (January 1931), cyclotrons of increasing size and energy were built in Berkeley: 11-inch in summer 1931, 27-inch in summer 1932, 37-inch in 1937, 60-inch in 1939, 184-inch with a 4'000-ton magnet in 1946. The world record is held by the Gatchina (Russia) cyclotron, built in 1957 to accelerate protons to 1 GeV, equipped with a 10'000-ton magnet. The invention and development of the cyclotron earned E.O. Lawrence the Nobel Prize in Physics 1939 and the cover of Time magazine on 1st November 1937!

Cyclotrons face two types of limitation at higher energy, namely the loss of isochronism in the relativistic regime, and the large size of the magnet. Synchro-cyclotrons, in which the RF frequency is decreased as the particle gains momentum, are a solution to the loss of isochronism. Another approach is to vary the magnetic field with the radius of the trajectories, using sectored magnets of the correct geometry (see Fig. III.1.8); the edge effect of the sectors also provides focusing. To contain the size of the cyclotron, using a superconducting magnet allows operating at higher field and thus accelerating to higher energy for a given radius.

Fig. III.1.8: 520 MeV proton sector cyclotron, Vancouver (Courtesy TRIUMF); 600 MeV ion superconducting cyclotron, Catania (Courtesy INFN).

In spite of these developments, high-energy cyclotrons are plagued by the large width of the magnet poles that have to cover the whole area of the spiralling trajectory. In 1943, M. Oliphant proposed the synchrotron, a circular accelerator in which the particles orbit the same trajectory at all energies (see Fig. III.1.9), later developed by E. McMillan and V. Veksler. Multi-pass acceleration is done by a RF cavity (or a set of RF cavities) located at one point of the circumference. The toroidal vacuum chamber and the gaps of the guiding and focusing magnets along the circumference of the machine tightly fit around the beam.

To maintain a constant-diameter orbit during acceleration, the magnetic field must increase with

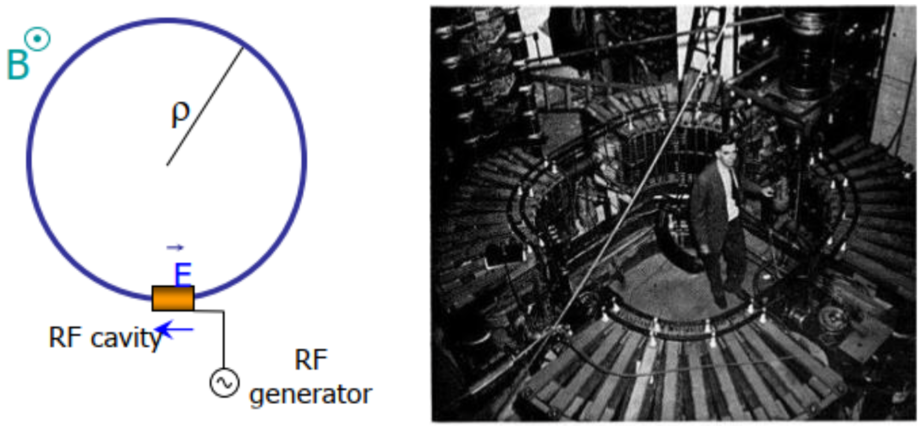


Fig. III.1.9: Principle of the synchrotron and early 300 MeV electron synchrotron at U. Michigan (1949) (Albert J. Forman, Public domain, via Wikimedia Commons).

time. With v the velocity and f the revolution frequency of the particles, the synchronism condition is

$$\frac{1}{f} = T = \frac{2\pi\rho}{v} \quad . \tag{III.1.6}$$

The RF frequency f_{RF} must be a multiple of the revolution frequency f

$$f_{\mathrm{RF}} = hf \quad , \tag{III.1.7}$$

where h is called the harmonic number.

An essential discovery made with a synchrotron – built *ad hoc* – is that of the antiproton in 1955. Putting this in perspective, one must get back to 1928, the year theoretical physicist P.A.M. Dirac derived his relativistic quantum wave equation, the first successful attempt to unify relativity and quantum mechanics. The Dirac equation implied the existence of a new form of matter, "antimatter". This forecast triggered the experimental search for antiparticles, the first of which, the positron, was discovered in cosmic rays by C.D. Anderson in 1932. Discovering the antiproton would then be a further confirmation of Dirac's theory. The antiproton, if it existed, must have had the same mass as the proton, i.e. close to 1 GeV/c^2, and would need to be produced by the collision of very energetic protons onto a hydrogen (i.e. proton) target.

Let us estimate the minimum energy of the incident proton beam. The nuclear reaction is

$$\mathrm{p}^+ + \mathrm{p}^+ \rightarrow \mathrm{p}^+ + \mathrm{p}^- + \mathrm{p}^+ + \mathrm{p}^+ \tag{III.1.8}$$

in order to conserve the baryonic number. In particle physics, the baryonic number is a strictly conserved additive quantum number of a system. It is defined as $B = \frac{1}{3}(n_q - n_{\bar{q}})$ where n_q is the number of quarks and $n_{\bar{q}}$ is the number of antiquarks. Baryons (three quarks) have a baryonic number of +1, mesons (one quark, one antiquark) have a baryonic number of 0, and antibaryons (three antiquarks) a baryonic number of -1. The baryonic number was defined long before the quark model was established, so rather than changing the definitions, particle physicists simply gave quarks one third the baryonic number. Nowadays it might be more accurate to speak of the conservation of quark number.

In the laboratory frame of reference, let us call p_1 the momentum of the incident proton, of energy $E_1 = mc^2 + K$, and $p_2 = 0$ the momentum of the target proton, of energy $E_2 = mc^2$ (m being the rest mass of the proton). Considering that the minimum incident kinetic energy K is just sufficient for the four reaction products to be all at rest, the relativistic mass invariant $(\Sigma m)^2c^4 = (\Sigma E)^2 - (\Sigma p)^2c^2$ can be written as

$$16m^2c^4 = (E_1 + mc^2)^2 - p_1^2c^2 \quad . \tag{III.1.9}$$

Remembering that $m^2c^4 = E_1^2 - p_1^2c^2$, one finds the minimum value for the kinetic energy

$$K = 6mc^2 \approx 5.6 \text{ GeV} \quad . \tag{III.1.10}$$

On this basis, a 6.2 GeV synchrotron called the Bevatron was built in Berkeley in 1954 (see Fig. III.1.10), enabling O. Chamberlain, E. Segrè, C. Wiegand and T. Ypsilantis to observe the first antiprotons in 1955, for which they received the Nobel Prize in Physics 1959.

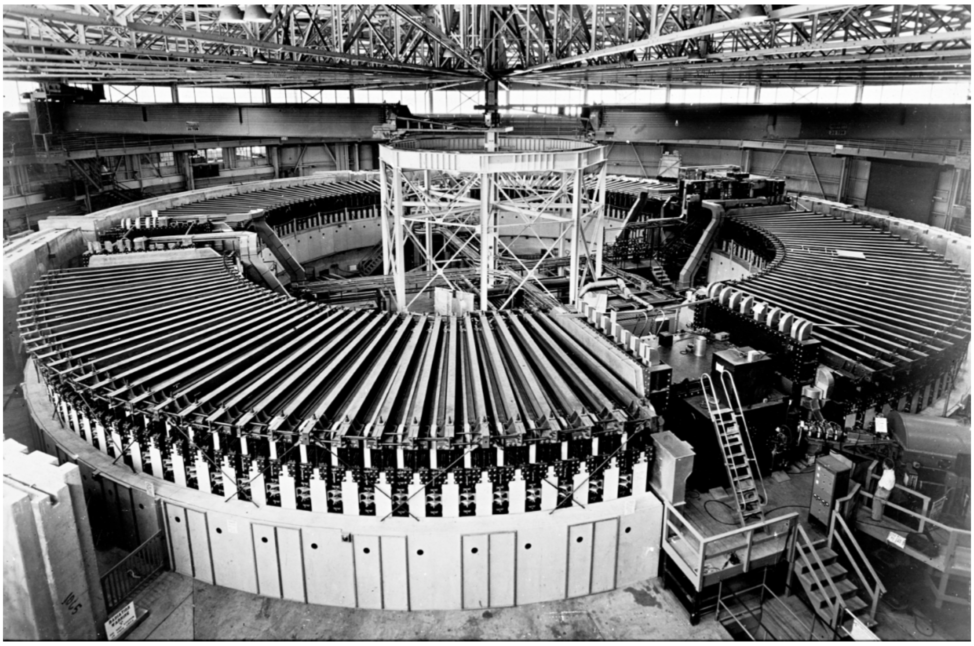


Fig. III.1.10: The Bevatron at Lawrence Berkeley Laboratory circa 1954 (LBNL, courtesy of AIP Emilio Segrè Visual Archives).

A major technical progress in accelerators came from the invention of alternating-gradient focusing by E. Courant, S. Livingston and H. Snyder, and independently by N. Christofilos in the early 1950s. Focusing the beam can be done by superimposing a field gradient in the bending magnets, i.e. a quadrupole field. The magnetic field in the current-free region of the magnet aperture satisfies $\vec{\nabla} \times \vec{B} = 0$ implying in the transverse (x, z) plane $\frac{\partial B_z}{\partial x} = -\frac{\partial B_x}{\partial z}$. A quadrupole field is focusing in one plane, defocusing in the other. However, a string of alternately focusing and defocusing quadrupoles of equal or similar gradient is globally focusing. In this fashion, strong focusing can be achieved in both horizontal and vertical planes, resulting in smaller beams, hence smaller electro-magnets with lower mass, lower cost and reduced power consumption. The PS at CERN, starting to operate in 1959, was the first strong-focusing synchrotron: its combined-function C-shaped magnets feature a gap varying across the aperture, thus adding a quadrupole term to the main dipole field. The magnets, powered in series, are installed with the opening of the C alternatively to the inside and outside of the ring (see Fig. III.1.11). Modern synchrotrons rather use separated-function magnets, i.e. dipoles, quadrupoles, sextupoles, higher-order multipoles, providing better flexibility in adjusting the focusing independently of the bending (see Fig. III.1.12).

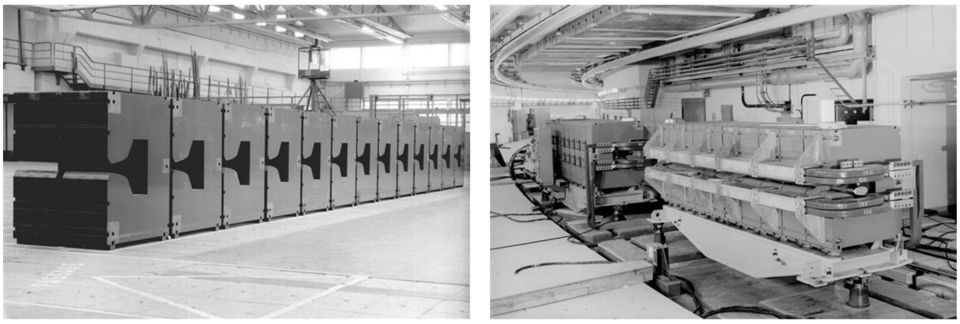


Fig. III.1.11: CERN PS magnets: combined-function yoke blocks and installed magnets.

Fig. III.1.12: The CERN SPS, an alternating-gradient focusing synchrotron with separated-function magnets.

III.1.5 Colliding beams and the discovery of weak vector bosons

In the collision of an accelerated particle A with a fixed (in the laboratory frame of reference) target particle B, only part of the energy of the incoming particle is available in the centre of mass, the rest is taken away in kinetic form with the outgoing reaction products. Assuming particles of equal mass m, one can write the relativistic invariant in the laboratory frame

$$4m^2c^4 = (E_\mathrm{A} + E_\mathrm{B})^2 - (\overrightarrow{p_\mathrm{A}} + \overrightarrow{p_\mathrm{B}})^2c^2 \quad . \tag{III.1.11}$$

Let E^* and $\overrightarrow{p^*}$ be the total energy and total momentum in the centre-of-mass frame, i.e. those available in the collision. Then $\overrightarrow{p^*} = \overrightarrow{p^*_\mathrm{A}} + \overrightarrow{p^*_\mathrm{B}} \equiv 0$ and the relativistic invariant is simply $4m^2c^4 = E^{*2}$. Consequently,

$$E^{*2} = (E_\mathrm{A} + E_\mathrm{B})^2 - (\overrightarrow{p_\mathrm{A}} + \overrightarrow{p_\mathrm{B}})^2c^2 \quad . \tag{III.1.12}$$

In a fixed-target collision, $p_\mathrm{B} = 0$ and $E_\mathrm{B} = mc^2$, which leads to

$$E^{*2} = 2m^2c^4 + 2E_\mathrm{A}mc^2 \approx 2E_\mathrm{A}mc^2 \quad , \tag{III.1.13}$$

and therefore

$$E^* \approx \sqrt{2E_\mathrm{A}mc^2} \quad . \tag{III.1.14}$$

Considering now the head-on collision of two accelerated particles

$$E^* = E_\mathrm{A} + E_\mathrm{B} \quad . \tag{III.1.15}$$

As soon as the acceleration energy becomes significantly higher than the rest mass of the particles, the energy available in the collision gets much larger in a head-on than in a fixed-target collision (see Fig. III.1.13). This is the driving concept of particle colliders, pioneered in Frascati where the first electron-positron collider, ADA was built in 1961, opening the way for a long series of machines colliding beams of particles (electrons, protons, ions) and antiparticles. The first proton collider, the Intersecting Storage Rings (ISR) at CERN, started operation in 1971 (see Fig. III.1.14).

As compared to fixed-target accelerators, particle colliders face several types of challenges. The density of particles in a beam being many orders of magnitude lower than in condensed matter, colliding beams must have a high intensity and a small transverse size to obtain sufficient “luminosity”, i.e. number of interactions per unit of cross-section. This requires accumulating particles and maintaining the beams in circulation for long periods, up to tens of hours, which sets tight demands on the quality of the magnets, power supplies and ultra-high vacuum system, as well as on the acceptable level of ground vibration and electrical noise. At each crossing, only a small fraction of the particles effectively collide, but they all feel electromagnetic interactions which tend to disrupt the circulating beams. The particle detectors must be designed and built around the collision points (and not downstream as in fixed-target physics).

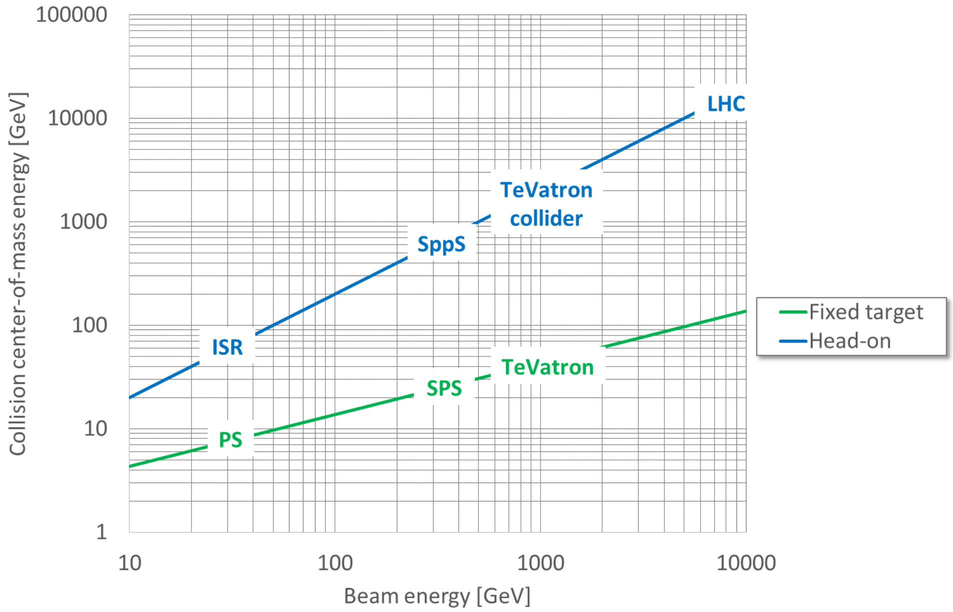


Fig. III.1.13: Fixed-target vs. head-on beam collisions.

D. Kerst and G.K. O'Neill identified the need of accumulating particles to obtain beams of sufficient intensity and invented the concept of colliding storage rings in 1956. A further development in colliders was the invention of "insertions", i.e. sets of strong focussing quadrupoles reducing the transverse size of the beam to increase luminosity at the collision points. The first high-luminosity insertion equipped with superconducting quadrupoles operated at the CERN ISR in 1980.

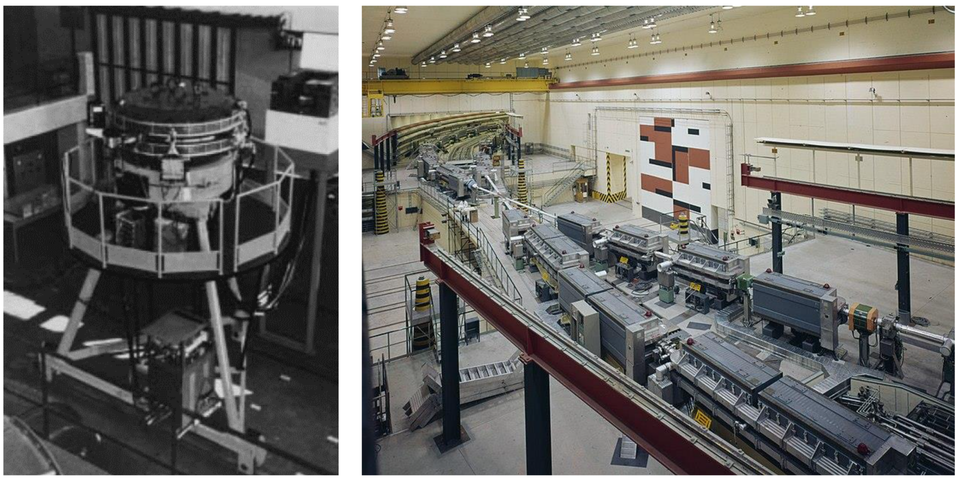


Fig. III.1.14: The first lepton collider ADA, Frascati National Laboratory (Courtesy INFN), and the first hadron collider ISR, CERN (Photo: 1970-11_X_CERN_14240_0059).

Following the development of the Standard Model of particle physics, the weak nuclear interaction is expected to be mediated by dedicated vector bosons. The short range of the weak interaction imposes large masses for the weak vector bosons W^+, W^- and Z, previously estimated at 60 to 80 GeV for the

W, and 75 to 92 GeV for the Z. The ideal machine to produce W and Z bosons would have been an electron-positron collider of sufficient centre-of-mass energy, unavailable in the 1970s. They could also be produced in hadron collisions at a p-p or p-$\bar{p}$ collider. In 1978, C. Rubbia proposes to convert the CERN SPS fixed-target proton synchrotron into a p-$\bar{p}$ collider, to search for the weak vector bosons.

He writes

> The production of W and Z bosons at a $\overline{\rm p}$p collider is expected to occur mainly as the results of quark–antiquark annihilation $\overline{\rm d}$u $\rightarrow$ W^+, d$\overline{\rm u}$ $\rightarrow$ W^-, u$\overline{\rm u}$ $\rightarrow$ Z, d$\overline{\rm d}$ $\rightarrow$ Z. In the parton model $\sim$ 50% of the momentum of a high-energy proton is carried, on average, by three valence quarks, and the remainder by gluons. Hence a valence quark carries about 1/6 of the proton momentum. As a consequence, W and Z production should require a $\overline{\rm p}$p collider with a total centre-of-mass energy equal to about six times the boson masses, or 500–600 GeV. The need to detect $Z \rightarrow e^+e^-$ decays determines the minimal collider luminosity: the cross-section for inclusive Z production at $\sim$600 GeV is $\sim$1.6 nb, and the fraction of $Z \rightarrow e^+e^-$ decays is $\sim$3%, hence a luminosity $L = 2.5 \times 10^{29}$ cm^{-2}s^{-1} would give an event rate of $\sim$1 per day. To achieve such luminosities one would need an antiproton source capable of delivering daily $\sim 3 \times 10^{10}$ $\overline{\rm p}$ distributed in few (3–6) tightly collimated bunches within the angular and momentum acceptance of the CERN SPS.

Before accelerating them, one must produce antiproton beams of sufficient intensity meeting the SPS acceptance. This requires accumulation for several hours and “stochastic cooling”, a technique invented by S. van der Meer to reduce emittance by acting statistically on the circulating beam. The Z and $W^\pm$ weak bosons were detected in 1982 at two detectors, UA1 and UA2 located, at two collision points around the SPS collider. In both cases, they were identified by their leptonic decays:

- Z, Z$\rightarrow$ e^+e^- and Z$\rightarrow$ $\mu^+\mu^-$, the characteristic signal being a pair of electron and positron (or muons) with high transverse momentum (see Fig. III.1.15).
- $W^\pm$, $W^\pm \rightarrow e^\pm\nu_e(\bar{\nu}_e)$, the characteristic signal being a high transverse-momentum electron (or positron) opposite to a high “missing” transverse momentum corresponding to the (unobserved) neutrino or antineutrino (see Fig. III.1.16).

C. Rubbia and S. van der Meer were awarded the Nobel Prize in Physics 1984, soon after the discovery of the Z and $W^\pm$ bosons.

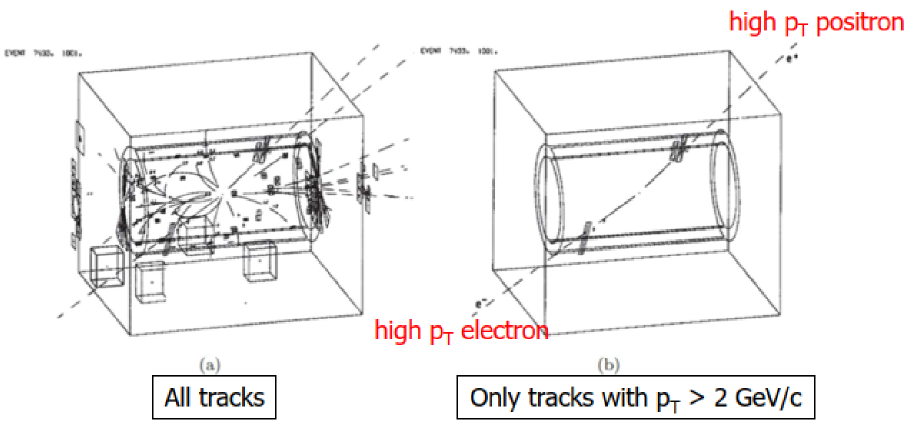


Fig. III.1.15: Detection of the Z boson at the CERN SPS collider, UA1 detector [12].

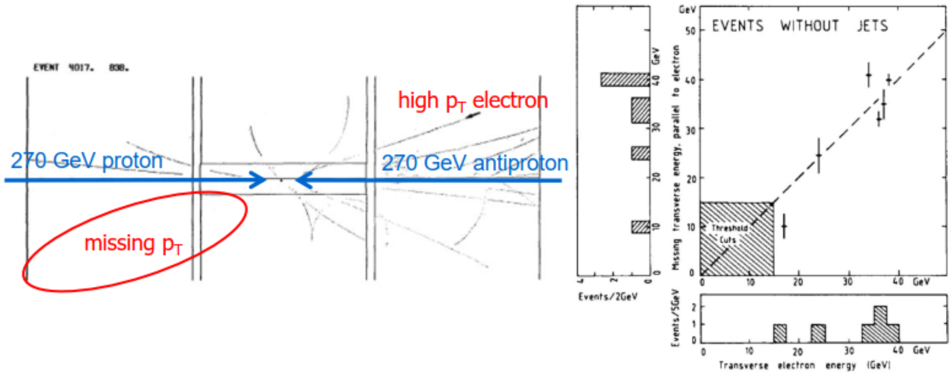


Fig. III.1.16: Detection of $W^{\pm}$ boson at the CERN SPS collider, UA1 detector [13].

III.1.6 Superconductivity to access the TeV scale: the top quark and the Higgs boson

Superconductivity, the ability of some materials to transport electrical current without losses in DC or with reduced losses in AC, has been considered for a long time a solution to sustain their development to higher beam energy and intensity, by enabling the generation of stronger electric and magnetic fields with reduced power consumption. The first practical superconductors, operating at liquid helium temperature, were invented in the 1960s, and it took almost two decades to see the first superconducting devices, magnets and RF cavities, operating in accelerators.

The first large superconducting synchrotron is the Tevatron, built in the 1980s at Fermilab, with a circumference of 6.3 km (see Fig. III.1.17). It accelerated protons up to 980 GeV and, like the CERN SPS, was later turned into a proton-antiproton collider, giving access for a few years to the highest attainable centre-of-mass energy.

Fig. III.1.17: The Tevatron at Fermilab (The photo is in the public domain).

In 1995, this enabled the discovery of the top quark, the heaviest particle known today: with a mass of 175 GeV, it "weighs" more than a gold nucleus. In proton-antiproton collisions, the top quark is produced together with its antiparticle: this requires a minimum energy of 350 GeV in the centre of mass. Since the colliding proton and antiproton are composite particles, they need to be accelerated close to the TeV to provide the needed energy per elementary constituent. The top and antitop quarks, having a short lifetime, are identified by their decays (see Fig. III.1.18).

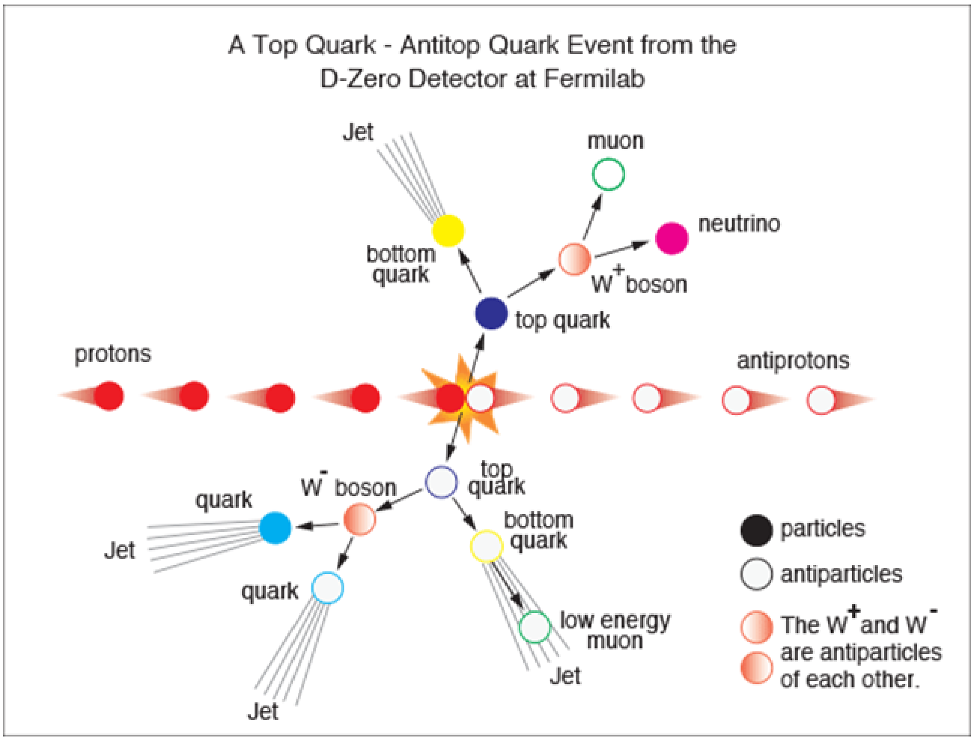


Fig. III.1.18: A top quark – antitop quark event from the D0 detector at Fermilab.

The last addition to the Standard Model is the Higgs boson, theorized by P. Higgs, R. Brout and F. Englert in 1964 to explain the electroweak symmetry breaking mechanism responsible for the masses of the vector bosons. Since then, the Higgs boson has been searched without success at different particle colliders. Its mass range, derived from theoretical and indirect experimental considerations, set a minimum value of about 1 TeV per elementary constituent for its production in proton collisions, though with a specific cross-section ten orders of magnitude below the total cross-section. Producing and detecting the Higgs boson needs not only a proton collider of very high energy and luminosity, but also very powerful and selective detectors and an unprecedented data processing system, to find what looks like a needle in a haystack.

In 1996, after some ten years of R&D on the key technologies of high-field superconducting magnets and superfluid helium cryogenics, CERN decided to build a 14 TeV centre-of-mass proton collider in the 26.7 km of the former LEP tunnel: the Large Hadron Collider LHC (see Fig. III.1.19). The two proton beams collide in four points around the perimeter of the machine, housing two large, general-purpose and two specialized particle detectors: ATLAS, CMS, ALICE and LHCb.

The Higgs boson, a neutral particle with a short lifetime, cannot be observed directly, but rather

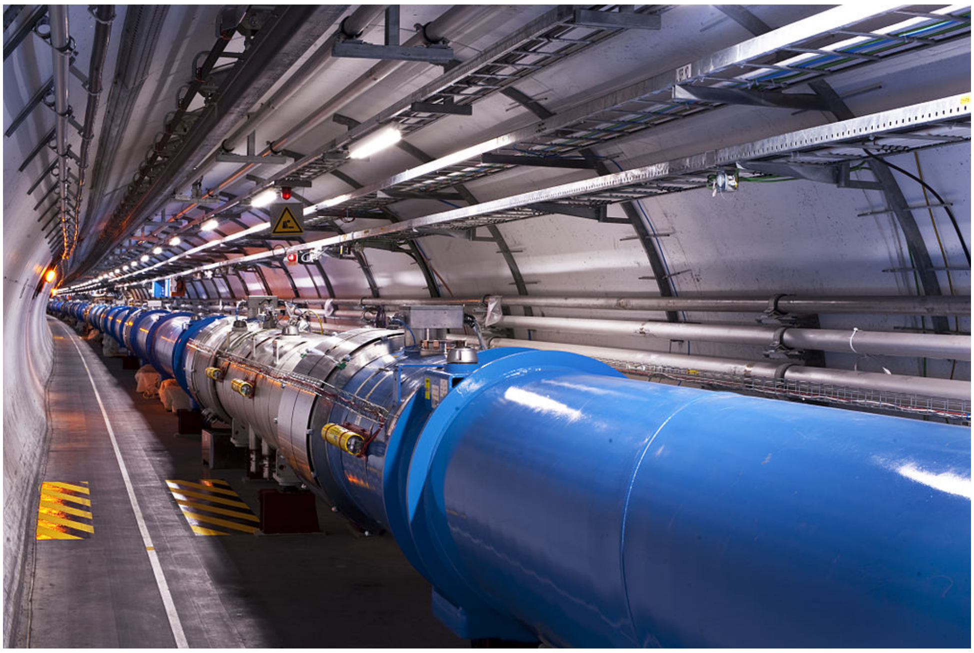


Fig. III.1.19: The Large Hadron Collider in the 26.7 km tunnel (Photo: CERN-AC-0910152-02).

by its decays. Two decay processes (among several) were used for the 2012 discovery in the ATLAS and CMS detectors (see Fig. III.1.20):

1. $H \rightarrow \gamma\gamma$, the signature being two energetic photons flying in opposite directions;
2. $H \rightarrow ZZ \rightarrow$ four leptons, the signature being the emergence of four muons (two $\mu^+\mu^-$ pairs) or one $\mu^+\mu^-$ pair and one e^+e^- pair.

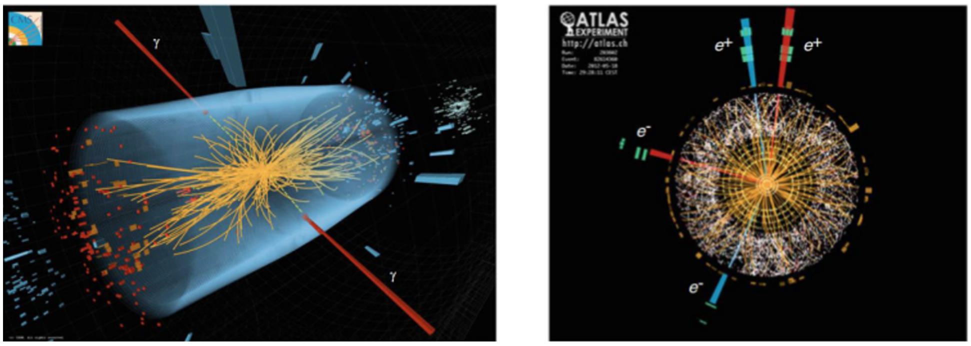


Fig. III.1.20: $H \rightarrow \gamma\gamma$ event at the CMS detector (left), and $H \rightarrow ZZ \rightarrow$ four leptons event at the ATLAS detector (right).

The LHC is today the particle collider producing the highest centre-of-mass collisions in the world: it was built to (successfully) discover the Higgs boson and complete the Standard Model, but also to resolve the structure of matter and the forces that hold it together on an unprecedentedly fine level. In spite of its success to explain nature, the Standard Model is however not a complete theory, and does not account for all observed processes. To gain another order of magnitude in centre-of-mass energy, CERN is now considering building a larger proton collider with a perimeter of about 90 km, using higher-field magnets based on advanced superconductor technology: the FCC (Future Circular Collider).

III.1.7 To conclude

This brief overview addressed only some of the symbiotic relations between particle accelerators and nuclear or particle physics, historically the most important sciences at the root of their development. Over the years, particle accelerators have colonized many other fields of science, technology and medicine. Out of some 50'000 accelerators operating in the world today, those used for basic science account for less than 1 %. Most accelerators serve applications in industry and medicine. Several chapters of this book address such applications.

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