Chapter III.2

Particle accelerators in the XXI century

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Particle accelerators are sophisticated instruments designed to concentrate energy at atomic and subatomic scales and use it to explore matter, generate secondary beams, or drive industrial processes. Their impressive evolution over the last century has been driven by a series of innovations, the last one being the widespread introduction of superconductivity at the end of the XX century. In this XXI century, the demand for more scientific discoveries and for a wider use of accelerators for societal applications is high, but to sustain their growth accelerators need to increase their performance while meeting new sustainability goals. In this dynamic landscape, new innovative technologies are appearing and are competing with traditional technologies pushed at their extreme limits. Particle accelerator research is a very dynamic interdisciplinary field that provides excellent opportunities for young creative students.

III.2.1 Accelerators as instruments to concentrate and deliver energy

We usually associate particle accelerators with the huge machines used for research in particle physics, of which the largest is the world-famous Large Hadron Collider (LHC) at CERN near Geneva. With its 27 km circumference and 17 km of injectors and beam transport lines, this accelerator is the biggest machine ever built by humankind. But although large in size, in terms of number accelerators for particle physics are only a small fraction of many accelerators devoted to scientific research, which in turn are only a tiny minority of about 40 000 particle accelerators in operation worldwide. Most of the accelerators built so far are smaller units used in medicine, where more than 15 000 particle accelerators are used to produce X-rays for cancer therapy, or in industry, where more than 12 000 units are used for ion implantation in semiconductors [1].

What makes particle accelerators so successful in many different fields? The first perception that we have of accelerators is that they are instruments made to accelerate particles, that is to transfer large amounts of energy to a structured "beam" of subatomic particles. A closer look at the numbers shows however that in this context energy alone is not the most important feature. Taking as an example the most energetic particle delivered by an accelerator, a 7 TeV proton coming out of the LHC, when converting its kinetic energy from electron-volts (eV) to the standard unit for energy, the Joule, we obtain only 1.1×10^{-6} J, a value extremely small by all standards—to give an idea, this is about one-millionth of the energy required to lift an apple to the height of 1 m ($1\,\text{J} = 1\,\text{N} \cdot \text{m}$). Only when we calculate the energy of a full bunch of protons out of the LHC (1.1×10^{11} particles) we come to a more respectable value

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for the total beam energy, 1.3×10^5 J. This might look large but is only, for example, the amount of the (chemical) energy contained in just 3 grams of diesel fuel.

Instead, the usefulness of the energy delivered by a beam of particles is not related to the amount of energy, but to the huge and unique density of this energy. Dividing the energy of our 7 TeV proton by the classic proton radius, we obtain the frightening number of $5.3 \times 10^{38}\ \mathrm{J/m^3}$—many orders of magnitude higher than the energy density of chemical compounds ($3.7 \times 10^{10}\ \mathrm{J/m^3}$ for the diesel fuel), macroscopic physical objects ($1.4 \times 10^9\ \mathrm{J/m^3}$ for a rifle bullet), or even laser beams (up to few times $10^9\ \mathrm{J/m^3}$). More standard but still higher than all the examples above is the energy density of an entire bunch of particles, $5 \times 10^{11}\ \mathrm{J/m^3}$ corresponding to the physical dimensions of the LHC bunch at the interaction point (30 cm in length, $16 \times 16\ \mu\mathrm{m}^2$ transverse dimensions).

As these simple calculations show, particle accelerators are instruments that have the unique quality of being able to concentrate energy at subatomic scale, where it can be used to interact with the atom and its components. When a particle beam enters a piece of matter—a metallic target, a semiconductor, an organic compound, a bacterium, or even a human tissue—it will very precisely deliver its energy to the atoms and to their constituents, electrons and nuclei. Depending on the type and energy of the particle, this may result in electron excitations (ionisation) that may induce molecular breaking or production of X-rays when the electron returns to its original status, or in phenomena involving the nuclei, from simple heating to nuclear reactions. In the extreme case of head-on collisions with other subatomic particles at sufficiently high energy, the energy developed in the collision may generate a new subatomic particle.

Thanks to their properties, accelerators are the only instruments giving us access to the atomic and subatomic world, realising the double goal of investigating its structure and properties, and of exploiting atomic processes for our needs. The small size of the particle beam allows one to deliver this energy very precisely, in some cases even at a well-defined depth inside the material without interacting with its surface layers. This gives us unique opportunities for research on subatomic particles, nuclei, atoms, and molecules, and for exploiting processes at the atomic level in medicine and industry. For industrial applications, however, the usefulness of particle accelerators is limited to small-scale processes requiring high precision. This is due to the relatively small total energy carried by the particle beam and to the high cost for producing it, in terms of infrastructure and of energy from the electricity grid.

III.2.2 Innovation in particle accelerator technologies

The development of particle accelerators has been a formidable adventure that took almost a century to advance from the early pioneering systems to the complex accelerators of today. The driving force behind it was without doubt the excitement of both scientists and non-scientists for the exceptional discoveries of atomic particle properties made possible by accelerators. During the early accelerator years, the interest came from nuclear physics, where breaking nuclei with accelerators allowed transforming elements into one another, thus making real after many centuries the dreams of medieval alchemists. Even more excitement came from the following dream made real, that of creating matter itself—not from nothing, but transforming the high-density energy carried by the particle beam into new subatomic particles like the elusive Higgs boson. Being able to fulfil two ancient dreams of humanity was an incredible achievement for particle accelerator technology. This attracted enormous interest and considerable funding, leading to a strong demand for technological innovation to reach increasingly higher energies at affordable cost. As for any other technology, the accelerator evolution was not linear, but relied on a series of innovations that progressively enabled technological leaps improving accelerator performance and making new ambitious goals possible.

Surprisingly enough, the first and one of the most outstanding of these innovations, at the basis of modern particle accelerator technology, was the result of the work of a PhD student. Rolf Widerøe was a Norwegian doctoral student at the Aachen University in Germany when in 1928 he published a thesis that contained not only the principle of acceleration using radio-frequency waves, but also its brilliant practical demonstration on a small laboratory device [2, 3]. It is interesting to look in more detail at how this innovation developed. At the time, the development of early accelerators went in the direction of electrostatic devices, intrinsically limited in energy by the sparking occurring when pushing the electrodes to very high voltages. Widerøe started from a paper by G. Ising, a Swedish professor who proposed to accelerate particles with "voltage pulses" between "tubes" but did not consider how to put this in practice [4].

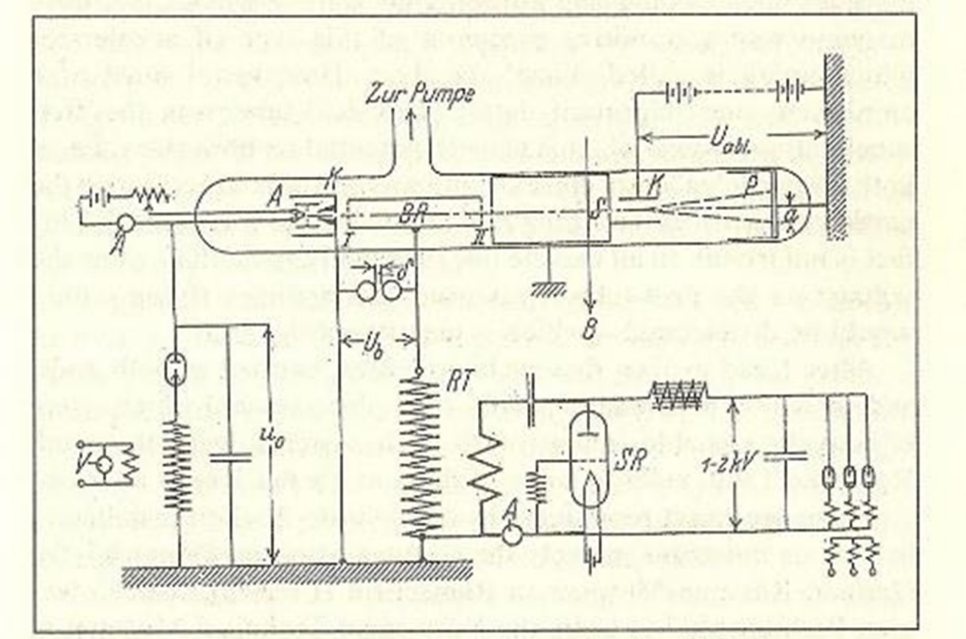

Fig. III.2.1: The Widerøe device (figure taken from Ref. [2])

Widerøe, who was a radio amateur at a time when radio broadcasting was just starting, had the brilliant idea of connecting to these tubes a simple radio generator, inducing between them a sinusoidal voltage at a frequency in the kHz range. In this way, the tubes were alternately at positive and negative voltage with respect to ground, and a particle (or a bunch of particles) crossing a tube at the correct phase with respect to the wave would be accelerated entering the tube and accelerated again by the same value exiting the tube, provided that the time to cross the tube is equal a half period of the frequency used. The result was accelerating twice with the same voltage, as Widerøe demonstrated with the device shown in Figure III.2.1, taken from his thesis. Adding more tubes to the system would allow reaching higher and higher energies.

What were the main ingredients in Widerøe's innovation? First, driven by his curiosity he was able to advance accelerator technology by *connecting experience from different fields*, particle acceleration and radio technology, and second, he went all the way from *enunciating a principle to its practical demonstration*—according to a standard definition, innovation is not only an idea but "the implementation of a new or significantly improved product or process" [5].

This first innovation in accelerator technology was followed by many others, characterised by the introduction of more sophisticated technologies often borrowed in other environments, making the construction of larger and more powerful accelerators possible. Soon after Widerøe came the invention of the cyclotron at Berkeley by E.O. Lawrence, a young and ambitious professor who after reading Widerøe's thesis had the idea of putting his device between the poles of an electromagnet. By replacing the tube with two half disks (the "Dees") he defined the basic structure of the cyclotron, introducing the concept of cyclic acceleration on a circular trajectory that enabled most of the major physics discoveries of the 1930s—and accessorily allowed Lawrence to be remembered as the inventor of "Big Science", the complex and lasting connection between large scientific infrastructure, industry, and government [6].

The next technological leap came after World War II, when innovation in the accelerator field stemmed from the sophisticated radar technology developed during the war. This led to the first high-frequency linear accelerators (with different contributions by Slater, Hansen, and Alvarez) and the related high-power sources (by the Varian brothers). At this point, technology was ready for the next major step, the development during the 1950s of the theoretical and technological expertise required to manage large amounts of particles within circular accelerators of increasing size, the synchrotrons, culminating in the independent invention of strong focusing by Courant, Livingston, Snyder, Blewett, and Christophilos [7]. This achievement made the construction of the large synchrotrons of the 1960s and 1970s possible, paving the way for an enormous increase in accelerator energy and for a wealth of scientific discoveries. To further increase centre-of-mass energy, next came the idea of converting fixed target synchrotrons into proton-antiproton colliders, following a direction already taken by electron-positron colliders. This technology made another leap in energy possible, eventually celebrated with the Nobel Prize in Physics attributed to C. Rubbia and S. van der Meer in 1984. Finally, the advent of superconductivity allowed the construction in the 1990s and 2000s of powerful radiofrequency accelerating systems and high-gradient dipole magnets with affordable cost and limited power consumption. CERN's LHC as the largest superconducting particle collider is the pinnacle of this evolution spanning exactly 80 years, from Widerøe's invention to the LHC initial operation.

This amazing progress can be visualised in the so-called "Livingston diagram", where M.S. Livingston, who developed the cyclotron with Lawrence, plotted in logarithmic scale the energy reached by different types of accelerators as a function of time. Figure III.2.2 shows a typical Livingston diagram for the period 1930–2010.

In the diagram is reported the increase of maximum energy for different types of accelerators. It is striking that all technologies follow a very similar trend. Each new accelerator technology allows reaching a higher energy than the previous generation, but after some years the progress is slower and eventually reaches some limitations. This is the moment when another technology comes to maturity, making further progress possible. Remarkably, the maximum energy for collisions shows an almost

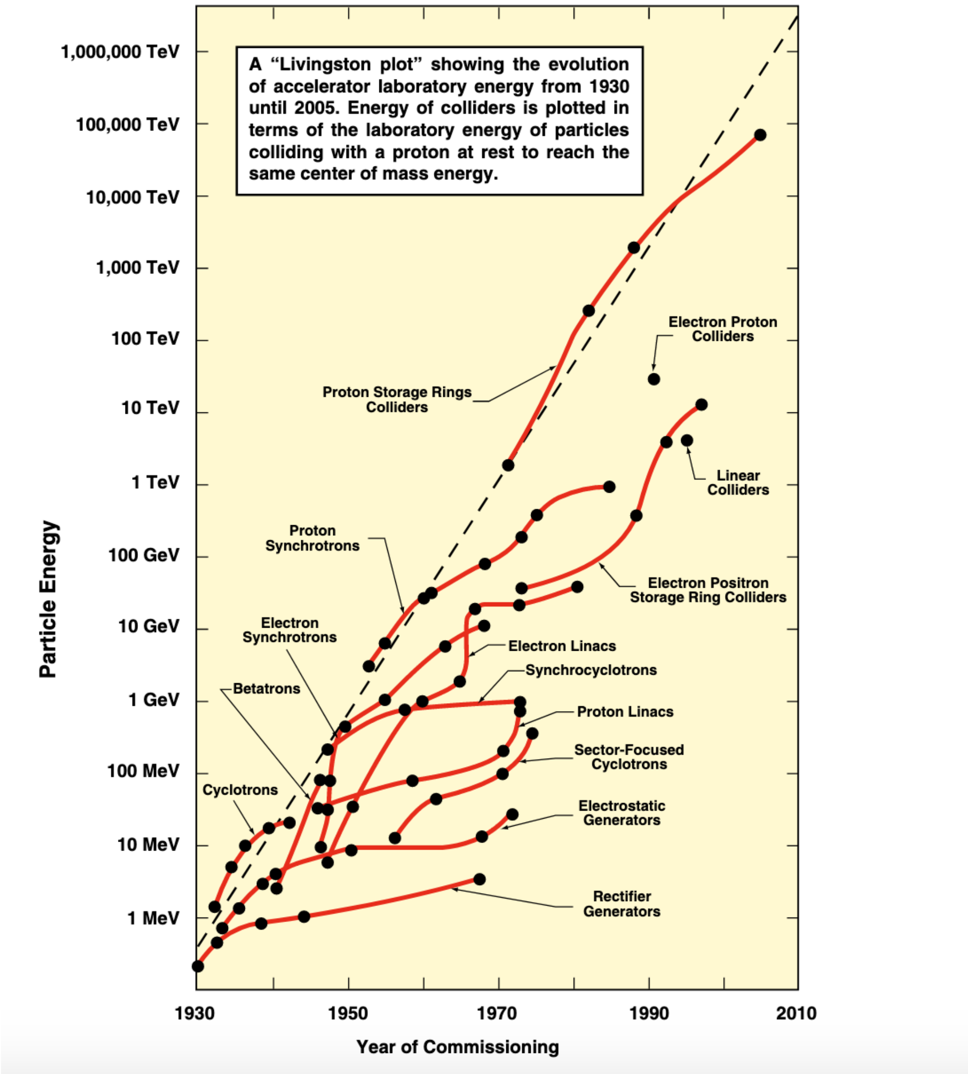

Fig. III.2.2: Livingston diagram illustrating the rapid increase in accelerator energy over the period 1930–2005 (from Ref. [8]).

constant exponential increase with respect to time, which is practically independent from the type of accelerator. This “Moore’s law” of accelerator science is valid from the early accelerators of the 1930s, up to the highest point on the plot of Fig. III.2.2, the Large Hadron Collider. While the dashed line in Fig. III.2.2 represents the “Moore’s law” for high energy hadron accelerators, a similar curve can be traced to represent a parallel exponential increase in the energy of lepton accelerators.

III.2.3 Particle accelerators in the XXI century

The Livingston curve is a clear visualisation of the successful evolution of particle accelerators, but as all exponential growths it cannot be sustainable over a long period. Indeed, the final commissioning of the LHC in 2008 was not followed by another accelerator project with the scope to reach yet higher energies, and if we would continue drawing the Livingston curve to present days, the last section (> 2008) would be dramatically flat. New high-energy accelerators are proposed and will likely be built in the future but considering that decades will be needed for their detailed design, approval, and construction, the slope of the Livingston curve will never look as in the past.

Is this the end of the evolution of particle accelerators? Of course not, and there are some considerations to be made at this point. The first is that energy and particle physics are no longer the only driving forces for accelerator development. The last decades have seen an impressive number of large accelerator construction projects, out of which only a minority is devoted to particle physics. Out of the 50 large projects worldwide for construction or upgrade of accelerators listed in a summary report published in 2017 [9], the majority is aimed at a wide range of scientific communities that includes photon-based research, material research, energy research, and low and medium-energy nuclear physics. For all these applications energy is not the main parameter, the challenge being instead on intensity, brightness, and time structure of the particle beam. In parallel, recent years have seen a rapid growth in the number of accelerators used for applications outside of scientific research, in fields as varied as medicine, industry, environment, security, etc. Although their dimensions are small, medical, and industrial accelerators are reaching a high level of complexity that is mobilising a large R&D community and creating a remarkable number of job positions for accelerator experts. An estimate made in 2012 evaluated the annual market for all medical and industrial accelerators to be US$ 5.0 billion/year and growing at $>5\%$ per year [10].

The second consideration is that indeed increasing the energy of particle beams beyond the present LHC record is an extremely complex endeavour, since after almost a century of development both the radio-frequency (RF) technology introduced by Widerøe, and the magnet technology introduced by Lawrence are meeting severe technological limitations. Moving the technological boundaries to reach the energies needed to observe new physics phenomena requires a considerable R&D effort. Developing the next high-energy machines is a formidable challenge, which is attracting talents and investments and will likely contribute to the development of new accelerator concepts and technologies with a positive impact on all types of accelerators, even those more distant from the energy contest.

Looking at the general trends, we can easily conclude that despite the saturation in the Livingston curve, accelerator science has never been as flourishing as today. But at the same time, we must consider that since the start of LHC operation, accelerator science and technology have entered a new critical phase, corresponding to the transition from rapid growth to sustainable development. This transition is as usual multi-faceted, covering several directions. The first is the transition towards sustainable technologies in terms of use of natural (energy, but not only), human, and financial resources, and of reducing the overall impact on the environment (emissions, land occupation, etc.). The second is the transition from an environment where basic science was the main technology driver for accelerators, to a multiple system where basic and applied science, medicine and industry are together driving accelerator development. The third trend goes in the direction of decentralisation: from a scheme where accelerator technology relied almost exclusively on a few large national laboratories in highly developed countries, we are moving towards a distributed configuration where new actors are appearing, in particular in countries that are still developing a technological infrastructure. Large projects are increasingly structured in the form of clusters involving consortia of large and small laboratories and industry, spanning countries and continents.

The priority of the accelerator R&D community in this century will be to accompany and favour these transitions, with a particular focus on the directions of improving the sustainability of particle accelerators and of increasing their impact on both science and society.

III.2.4 Pushing the limits of accelerator technologies

In a commonly accepted definition, sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs [11]. When we come to large technological infrastructure like the ones needed by particle accelerators, this requirement translates into considering from an early design phase the fact that resources are finite and the need to use them conservatively and wisely with a view to long-term priorities, considering the entire life cycle from construction to decommissioning and final reuse, recycling or disposal. The "footprint" of particle accelerators is significant, since they are major consumers of energy, as well as of environmental, financial, and human resources. What can be done to reduce this footprint?

Energy consumption of present and future accelerators is a major concern, and increasing energy efficiency is a formidable challenge for accelerator designers. CERN's yearly average electricity consumption is 1.2 TWh, equivalent to about one third of the electricity consumption of the entire Canton of Geneva, with the LHC and its injectors needing about 122 MW when in operation—and 89 MW in stand-by. In comparison, future projects for high-energy physics will need even larger power. The $>$ 500 MW consumption foreseen for the proton version of Future Circular Collider [12] corresponds to about one half of the production of a large-scale nuclear reactor. To produce this energy in a greener way, a wind farm made of 400 large windmills (80 m diameter, 2.5 MW, 50% efficiency) would be needed. Installing them in a line at the recommended distance of 1 km, the farm would extend over 400 km.

Unfortunately, improving energy efficiency of particle accelerators is a delicate issue that meets some fundamental limitations. As discussed in Section III.2.1, particle accelerators are huge "energy concentrators" that, going through several steps, transform energy from the electricity grid into the very high-quality energy stored in the particle beam. To achieve this goal, an accelerator system will go through many energy transformation processes. In the case of radio-frequency acceleration, these include energy storage in large capacitors, transformation from DC to high voltage, conversion to high-frequency waves, and generation of electromagnetic field configurations from which the particles can extract energy. Adding the magnetic fields needed to guide the particles in their trajectories means that additional large amounts of energy will be dissipated in the coils of the magnets required to sustain the fields. And even if some elements generating the electric and magnetic fields are made superconducting, to reduce their energy dissipation, additional energy and energy transformations will be needed to power the cryogenic system keeping them cold. To any transformation is associated some loss of energy, simply related to thermal dissipation effects in the components, or originating from some more fundamental entropy-related considerations. Whatever the technical configuration, the overall energy efficiency of a particle accelerator is the product of several individual efficiencies, all lower than one. The main contributions to the efficiency come from fundamental processes, as the Carnot efficiency limiting the performance of cryogenic systems, or the RF efficiency limiting the amount of energy that can be converted into electromagnetic waves. These are intrinsic limitation originates from physics processes. To these fundamental losses must be added the usual energy transformation losses, and the consistent amount of energy required to keep in operation the accelerator ancillary systems like vacuum, ventilation, instrumentation, etc.

The result is that in a large accelerator complex most of the energy will be finally dissipated in the cooling water used to remove heat from the components. As an example, Fig. III.2.3 shows the overall energy flow in the PSI cyclotron for production of neutrons and muons.

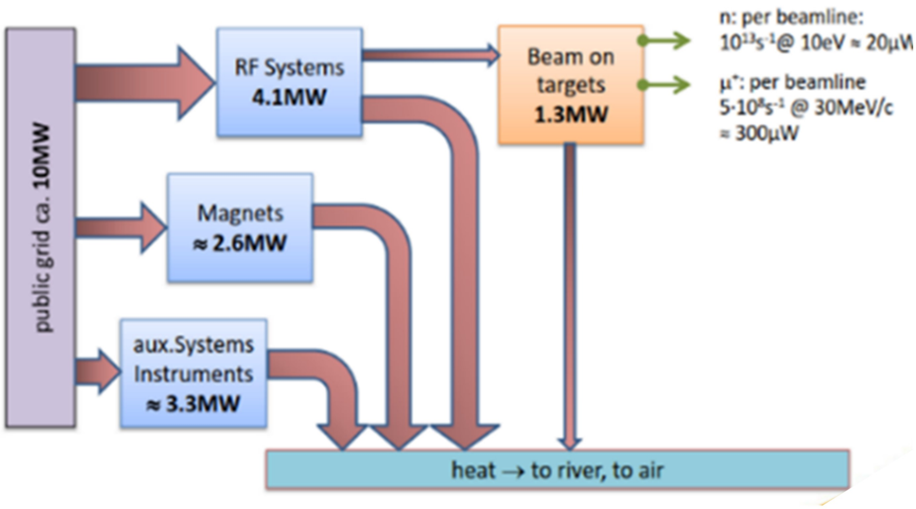

Fig. III.2.3: Energy flow in the PSI cyclotron-based accelerator complex (from Ref. [14]).

The overall grid-to-beam efficiency is 13%, meaning that as much as 87% of the energy extracted from the electricity ends up in heat, dissipated in the nearby river or in air. Accelerators operating for particle physics have even lower efficiencies, related to the higher quality of the beam required to produce the collisions. Only specially designed superconducting linac systems for high-intensity beams are expected to reach, in some specific energy ranges and operating conditions, efficiencies close to 50% [13]. In general terms, concentrating energy into a particle beam creates a drastic local reduction in entropy, that must be paid for with a strong energy dissipation.

Some improvements in energy efficiency are however possible, and many initiatives are ongoing to improve accelerator subsystems, for gains in efficiency going from few percent to some 10–20%. RF power sources have margins for improvement, in particular klystrons where more sophisticated beam transport designs can provide an increase in efficiency, at the price of increased complexity and cost. Another important trend is replacing wherever possible conventional electromagnets with permanent magnets made of rare-earth materials. Permanent magnets do not consume electrical power, but their mechanically defined magnetic field cannot be adjusted during operation. Permanent magnet systems with some level of field tuning are under development in many laboratories. Other important initiatives to improve the overall energy management for large accelerators consist in finding ways to recover and reuse the heat deposited in the cooling water, for example for household heating. The economic viability of these systems is however limited since the water comes out of the accelerator at relatively low temperature and must be transported over long distances. Additionally, the operating times of the accelerator often do not coincide with the periods when heating is required.

Together with increasing efficiency, another major challenge consists in finding ways to reduce the overall dimensions of the accelerator. Smaller dimensions lead to savings in construction and material costs, reduce the impact on the environment, and might pave the way to an easier and wider use of accelerator technologies outside scientific laboratories. Reducing accelerator dimensions is therefore a priority direction towards lower carbon emission. Presently, the carbon footprint of accelerator facilities is dominated by the carbon content of the energy used for operation. For future facilities increasingly relying on decarbonized energy, carbon emission generated by concrete production during construction is going to be the prevailing term, although reduced by the ongoing decarbonization effort of construction industry. Technically, the challenge of reducing accelerator dimensions can be brought back to two very specific challenges. In a linear accelerator, for example of the Widerøe-type where acceleration is provided by electric fields, reducing length requires to increase the average electric field gradient (in terms of V/m). In a circular accelerator, where particles are bent in a circular path, reducing the diameter requires to increase the average field in the accelerator magnets. In linear accelerators, the electric field gradient is limited by sparking between electrodes, and the challenge of accelerator designers consists of finding geometries and materials that can sustain higher fields. Here as well fundamental limitations come into play, related to the unavoidable field emission, the extraction of electrons from a high-voltage surface. For room-temperature accelerating systems made of copper, gradients as high as 100 MV/m have been achieved. For superconducting accelerating systems (cavities), maximum achievable electric fields are of the order of 40–50 MV/m for operational multi-cell systems and 60 MV/m for single cells, limited by the presence of impurities in the superconducting material. To extend the reach, several techniques are being tried, going in the direction of reducing the presence of impurities on the surfaces and of testing new materials and material processing techniques. Nitrogen infusion processes and other doping techniques are providing major improvements to larger gradients for superconducting systems as well as in their power efficiency, while coating niobium or copper with thin layers of different superconducting materials are another promising direction to further increase achievable gradients. The long-term goal in this regard is to bring superconducting systems close to the 100 MV/m limitation of normal-conducting systems. This appears as a technological limit ultimately related to the RF critical magnetic field, above which the superconducting phase can no longer exist. Presently, achievable gradients are limited by thermal instabilities related to material defects and by field emission of electrons from the surfaces operating at high voltages [15].

In circular accelerators, dimensions are defined by the maximum achievable magnetic field in the magnets, with the conductor material defining the maximum achievable current density and magnetic field. The standard superconducting technology that allowed reaching dipole fields up to 8 T in the LHC consists of using wires made of a niobium-titanium alloy, aided by operating at temperatures below 2 K in superfluid helium. Large investments have been recently made in developing superconducting magnets using a new type of superconductor made of niobium-tin (Nb_3Sn), with the short-term goal of reaching 12 T for the high-luminosity LHC upgrade and an ultimate target of 16 T for future colliders. A major step forward is nevertheless needed to reach higher fields, an opportunity that might be provided by exploiting another superconductor technology slowly coming to maturity, High Temperature Superconductivity (HTS). High temperature superconductors are in the form of rare-earth powders and have critical temperature above 77 K, the boiling point of liquid nitrogen. The most used HTS material for accelerator magnets is yttrium barium copper oxide (YBCO). Dipole magnets with an HTS insert reaching 20 T have been conceived, but their practical realisation is still under research. The main problems to be solved with HTS materials is the realisation of sophisticated multi-layer tapes that can support the HTS material, providing the required homogeneity and mechanical properties, at an affordable cost. Alternative iron based HTS materials are being intensively studied, to produce superconducting wires with high mechanical properties at lower cost than YBCO tapes.

III.2.5 New trends and directions

We have seen that particle accelerators are based on few basic principles that have not changed for almost a century: transport beams of stable charged particles using magnetic fields and progressively increase their energy using electric fields generated by electromagnetic waves. But since we are reaching the limits of these technologies, then comes quite naturally the idea of trying to extend the reach of particle accelerators by introducing new technologies that might challenge these basic principles, moving from "incremental" innovation to "disruptive" innovation.

In this sense, the main disruptive acceleration technology under development is the use of plasma as the medium to generate intense electric fields. Within a plasma, electric fields up to three orders of magnitude higher than in conventional copper or niobium accelerating cavities can be in principle achieved. The power required to excite the plasma waves generating the electric fields might come either from an intense bunched beam of electrons or protons produced in a conventional way (plasma wakefield acceleration, PWFA), or from a high-power laser pulse (laser wakefield acceleration, LWFA). In these schemes, drive beams and lasers replace the traditional radio-frequency systems, and a plasma cell replaces the usual resonant accelerating cavities. From the initial formulation of the basic concepts in the late 1970s, plasma technologies have progressively evolved and acceleration of electrons with gradients 500 times higher than in conventional linear accelerators has been demonstrated in dedicated test facilities [16]. Although very successful, these tests are limited to acceleration of electrons over short distances, in a single plasma cell. Since in a plasma the mobility of ions is much lower than that of electrons, acceleration of positive particles is extremely difficult, making the realisation of a plasma-based collider a complex endeavour. Other challenges being progressively addressed are the coupling of several plasma cells over long distances, the inherent limitations on the quality of the beam accelerated in the plasma, and the low energy efficiency characteristic of laser-based systems. Most of the open issues are related, for a first validation of the technology, to the realisation of a traditional electron-positron collider, hence applications based on electron acceleration are being proposed, such as the compact PWFA-based Free Electron Laser EuPRAXIA, intended to be the first user facility based on plasma technology [17]. Similarly, a new design for a plasma-based collider (Higgs factory) has been recently proposed adding to PWFA acceleration of electrons a conventional acceleration of positrons for an asymmetric configuration of colliding beams at different energies. The HALHF concept, presented in Fig. III.2.4, shows the vitality and creativity of the plasma accelerator community [18].

In parallel to the development of electron accelerators and colliders, also protons and ions are expected to profit from the remarkable progress of laser technologies. Experiments are ongoing in several laboratories to produce intense proton or ion beams generated by the impact of high-power laser pulses on a metallic target.

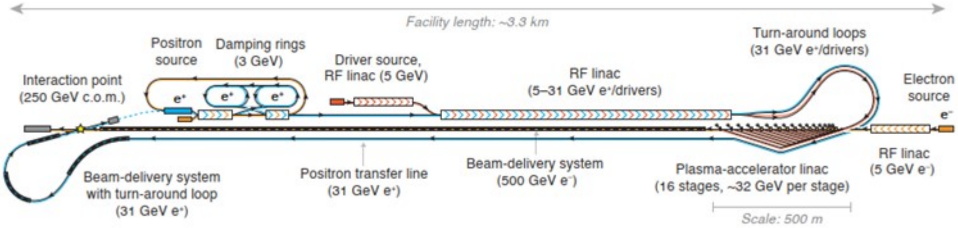

Fig. III.2.4: The HALHF (Hybrid, Asymmetric, Linear Higgs Factory) concept (from Ref. [18]).

While plasma technologies challenge traditional acceleration techniques, another interesting option consists in challenging the type of particle, moving to acceleration of an unstable particle like the muon. Muons are “heavy electrons”, negatively charged unstable particles with a mass 207 times higher than electrons. The main advantage of accelerating muons in a high-energy circular collider is that they lose only a negligible amount of energy because of synchrotron radiation, which is the main limitation to the compactness and efficiency of circular electron colliders. There are however some challenges to be faced, the first being the production of the muon beam, since these particles are generated by the decay of pions produced in the collision of energetic protons with metallic targets. On top of achieving sufficient proton energies and intensities, the process of collecting, transporting, and cooling the muons until they reach sufficient phase-space density to be captured and accelerated in the following accelerator is an extremely complex and low-efficiency process that has still to be demonstrated on a large scale. Similarly, muon acceleration requires many non-conventional solutions to speed up the process since mean lifetime of muons at rest is only 2.2 μs. The original idea of a muon collider dates from the early 1980s and since these times the analysis of the accelerator configuration has progressed, highlighting the technical challenges and the need for original solutions in terms of particle production, magnetic systems, background radiation, etc. To advance towards a first proof-of-principle muon system, preliminary to a possible collider, large investments are needed for dedicated test stands and prototyping of major components. International collaborations are being formed, to gather the required resources to advance the R&D towards a future muon collider [19].

III.2.6 Accelerators for society

Traditionally, the quest to reach higher and higher energy in the accelerators for particle physics has been the driving force for the development of accelerator technologies. This continuous effort to innovate however has not only profited the large scientific accelerators but has been successfully translated into a wealth of accelerator applications for the benefit of society, particularly in medicine and industry. Estimating about 40 000 accelerators in operation worldwide, less than 1% are devoted to scientific research [1]. The remaining ones are small low-energy accelerators, based on sophisticated technologies developed in scientific laboratories, and used outside of the traditional field of scientific research. The best example in this respect are definitely the nearly 15 000 radiotherapy accelerators, small radiofrequency units used to produce X-rays for cancer treatment that are installed now in all major hospitals worldwide. They are all based on the efficient and reliable side-coupled linac technology developed at the end of the 1960s for the Los Alamos Meson Factory project [20]. In medicine, accelerators are also used to directly treat cancer with beams of protons or ions, and to produce many types of radioisotopes commonly used for imaging, for cancer therapy, and for the combination of the two – theragnostics. In industry, accelerators are largely used for precise doping of semiconductors (more than 12 000 low-energy electrostatic accelerator systems), for food and equipment sterilisation, for cross-linking of polymers, and for other precision treatments of materials.

New emerging accelerator applications are aimed at solving environmental problems, as the elimination of sulphur and nitrogen pollutants from flue gases produced by fossil fuel power plants or from the exhaust of large marine diesel engines. In all these applications, compact low-energy electron accelerators are used to break large oxide molecules that can then be removed by more classical systems. Applications of accelerators to the energy domain are also under study, to treat long-lived radioactive waste, to sustain the reaction in subcritical nuclear reactors, or to analyse the resistance of materials used in fusion reactors. Surface analysis with low-energy ion beams is another increasingly popular application, for scientific research but also for analysis of artwork, where accelerator-based systems can precisely and non-destructively determine the chemical composition of materials or painting. In this case too, modern accelerator technologies derived from scientific accelerators can help in reducing the dimensions of the systems, as is the case of the recent MACHINA transportable system for analysis of artwork, based on a compact high-frequency radio-frequency quadrupole shown in Fig. III.2.5 [21].

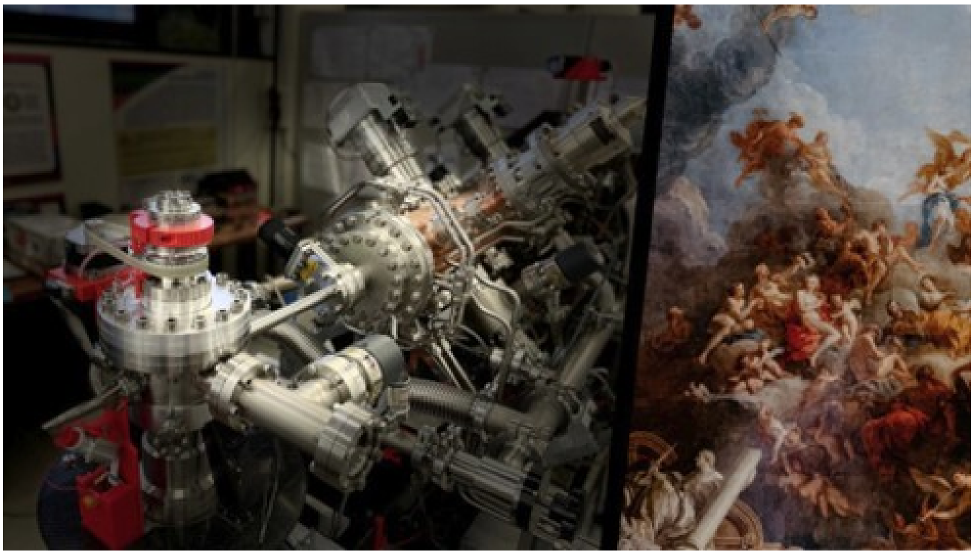

Fig. III.2.5: Left: The MACHINA accelerator (INFN, 2023); Right: A representational picture of an art piece. (Image credit: CERN)

These applications are only a small example of what can be done outside of the scientific field by exploiting the potential of accelerators in precisely interacting with atomic and molecular systems. Many other applications are being explored that might progressively become commercial products. The limitation however is not given by the ideas, but by the time and investment required to go from the original idea to a fully tested and reliable pre-commercial prototype. Translation of accelerator technologies to society is a long and expensive process that requires constant support from public bodies or from private investors and usually needs decades before coming to an exploitable commercial product.

III.2.7 Conclusions: at the roots of innovation

Particle accelerators are fascinating instruments that are facing a critical moment in their evolution. Expectations from basic and applied science and from medicine and industry are growing but most of our key technologies are still those developed almost 100 years ago. This environment offers unique opportunities for innovation, providing stimulating research topics for young people joining the accelerator field. From the example of Rolf Widerøe's invention, they should remember what the roots of innovation are: merge inputs from different science and technology fields (look around you), challenge the established traditions (but respect experience), and take risks (but foresee mitigations).

We have the privilege of contributing to a vibrant and growing field, in full transition from basic science to applied science and to wider societal applications. But to drive this transition and to push further the frontiers of accelerators we need fresh ideas, technology jumps, and perhaps some change in paradigm. As usual, the secret for success is novel ideas developed in a collaborative environment, jumping across borders between different scientific fields. To achieve these goals, we need multinational research programmes with wide support from governments and scientific communities, but above all we need the energy and motivation of young people, with ideas and the ability to transform these ideas into innovations. And especially we need places like JUAS, where young researchers can meet and get a global overview of accelerator technologies and how they are correlated, starting to acquire the knowledge and the connections that will accompany them throughout their careers.

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