Chapter 14
Technical Challenges for Future Accelerators

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Accelerators have accompanied the development of nuclear and particle physics in the last ninety years. From first cyclotrons to the LHC and the discovery of the Higgs boson, throughout the collider concept demonstrated first by Bruno Toushek, accelerators have been instrumental for the discovery of new fundamental particles and mechanisms, thanks to an undeniable progress in performance supported by a continuous technical development. Now for the after-LHC era even larger challenges have to be faced, pushing existing technologies much beyond their present limits and pursuing until practical demonstration new technologies and concepts.

14.1 Introduction

The potential of accelerators as engines of discovery was clear since Lawrence, in collaboration with Livingstone, in Berkeley built the first accelerators capable to go well beyond a few MeV energy, i.e., the classical cyclotron for which he was credited with the Nobel Prize in 1939. Actually we like to cite the prophetic words used by Lord Rutherford in his opening speech at the 1927 Royal Society, in his capacity of President: "*The advance of science depends to a large extent on the development of new technical methods and their application… From the purely scientific point of view interest is mainly centred on the application of these high potentials to vacuum tubes in order to obtain a copious supply of high-speed electrons and high-speed atoms. This would open up an extraordinarily interesting field of investigation which*

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could not fail to give us information of great value, not only in the constitution of atomic nuclei but in many other directions" [1].

Already in the '40s and the '50s accelerators were a key tool for physics. But it was after two main breakthroughs: the proposal of the phase stability by Mc Millan and Veksler and the invention of the strong focusing by Christofilos, Courant, Livingstone and Snyder, applied to synchrotrons, that accelerators started rivaling with the cosmic rays for the discovery of new fundamental particles and mechanism. By providing copious flux of particles at the highest energy in a repeatable and predictable way, the increase in energy of the accelerated particle has accompanied the all new discoveries of fundamental particles from the sixties, as shown in the schematic of Fig. 14.1.

Accelerators are very complex instruments, with a variety of components, many of them having a strong influence on the performance of the accelerators. However, certainly the most significant components determining the performance of an accelerator are the accelerating structure, usually a cavity where an e.m. field with frequency ranging typically from the 30 MHz up to 30 GHz (for historical reason called radiofrequency, RF resonator) and the magnetic system providing the bending strength. Therefore in this paper we will discuss mainly the challenges for making progress in these two systems. However we will discuss also new accelerator schemes like the muon collider and the plasma acceleration.

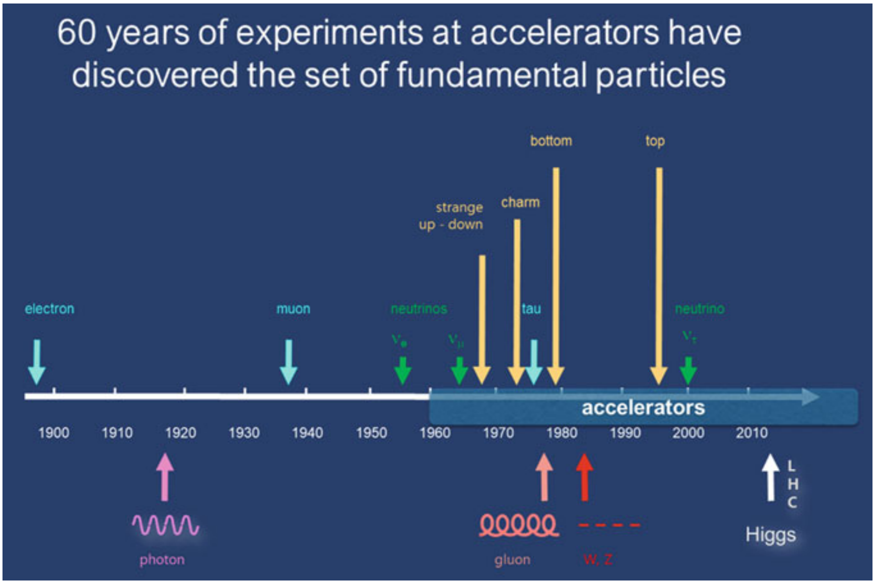


Fig. 14.1 Schematic of the timeline of discoveries of the fundamental particles with in evidence the ones discovered by accelerators (figure by L. Rossi)

14.2 The Accelerator Frontiers

14.2.1 The Energy Frontier

The first and most important parameters of an accelerator is the maximum kinetic energy attained by the particle beam. The energy gain is given almost invariably by the electric component of an electromagnetic (e.m.) field resonating in a cavity. The energy gain in a single cavity or in a gap between two electrodes of the cavity varies typically from about 100 keV to about 10 MeV. Considering here single charged particle, 1 MV voltage translates into a 1 MeV energy gain. We need to sum up the voltage of about ten thousands of cavities to reach the regime of hundreds GeV. Another way to express this is referring to the electric field. The highest performance RF cavities can provide, in pulsed operation mode, $E_{acc} \approx$ 30–50 MV/m if superconducting and $E_{acc} \approx$ 100–150 MV/m if high frequency normal conducting. Let's take the 100 MV/m, which is the baseline for the ee Clic collider, and clearly a length $L =$ 10 km of RF field is necessary to reach 1 TeV. The Energy in a linac (linear accelerator) is simply given by: $E_{beam} = G \times L$ where G is the electric field (mostly referred as the potential gradient) and $L = \sum l_i$ with l_i being the length of a single cavity ($i = 1 \ldots N =$ total number of cavities). Of course the actual physical length of the whole accelerator needs to be multiplied by almost a factor two to account for all the space which is not covered by the accelerating field. To make just a 2 TeV c.o.m. collider with 100 MV/m cavity we need about a 2 × 20 km long infrastructure, considering that electron and positrons accelerators are independent and collide head-on. So the limit to the particle energy is feasibility and cost of the infrastructure, which scales with the accelerator length, and the technology limitation on the attainable electric field.

Another way to accelerate is of course based on the original idea that brought Lawrence to invent the cyclotron: recirculate the beam in the same cavity (ies) such as to use the same accelerating structure many times. To keep the particle in orbit a perpendicular magnetic field, that we call dipolar field, is needed. In theory we can pass the particles through the accelerating cavity as many times as we want and sum up energy without limitation. Of course this is not true since the increase in energy or momentum entails an increase of the magnetic field strength necessary to keep the particle in orbit; due to the barrier of the speed of light, speed is almost constant $v_{particle} \approx c$. So, as soon as we leave the favorable territory of the classical regime, where the magnetic force increases at constant field with velocity of the particle, the limit to the maximum attainable energy is the centripetal force we can provide through the magnetic field to keep the orbit. In relativistic approximation, for single charged particles, the relation turns to be quite simple: $E_{beam} \approx 0.3\ B \times \rho$ with E_{beam} in GeV, magnetic field B in tesla and ρ is the curvature radius inside the -uniform- magnetic field in meters. To reach the 7 TeV proton beam energy in the LHC in the 26.7 km long tunnel, considering that approximately only 2/3 of the tunnel length can be covered with dipoles, we need 8.3 T dipoles, a huge field that requires superconductivity. Therefore for circular accelerators, the maximum attainable energy is determined by cost and feasibility of infrastructure, i.e., the accelerator length or radius, and by the technological challenge, i.e., the maximum field intensity B we can generate perpendicularly to the particle trajectory.

In both cases, linear or circular, infrastructure and technology contribute with the same weight to the performance of the accelerator: technology is not all, after all! However, cost and size are of course limited, even for a community, like the one of high energy physics (HEP) that is used to large projects. Therefore pushing the technology is the way to secure progress of the so-called energy frontiers.

One can note that the equation $E_{beam} \approx 0.3\ B \times \rho$ does not contains the rest mass, due to relativistic conditions, so it applies both to electrons and protons. However, beyond certain energy the electron dynamics in a synchrotron is dominated by the energy loss by radiation, due to centripetal acceleration, which is not called synchrotron radiation for nothing. This is the main reason why electron synchrotrons have an energy reach much less than for protons or other heavy particles, being the synchrotron energy loss proportional to $(E/E_0)^4$, where E_0 is the rest energy of the particle. It is clear that relativistic beam of electron radiates $\cong 10 \times 10^{12}$ times more power than protons with the same energy! Indeed the kinetic energy of the electron beam in the LHC tunnel, called LEP tunnel at the time, was limited at 100 GeV not by the magnetic field (just a very modest 0.2 T versus the 8 T used for the LHC) but the fact that at that beam energy the power loss by radiation was equal to the power transferred to the beam itself by the accelerating structure.

The complex rush toward high beam energy is depicted in Fig. 14.2, [2] which needs some explication. The graph, maximum beam energy versus time, is called Livingston plot, and is used to show the exponential increase of energy versus time. To make compatible in terms of physics reach the most recent accelerators, all of collider type, with the previous generation (fixed targets), the energy is reported as equivalent beam energy on a fixed target. Such a graph shows that the colliders, first realized by Touschek in Frascati, were essential to support the exponential growth, that otherwise would have stopped already in the sixties. Another factor that helped to support the exponential growth was the introduction of superconducting magnets for hadron colliders, in the late eighties. The graph of Fig. 14.2 shows clearly that even in the case the next projects would be timely realized: Fcc-ee and/or FCC-hh, ILC and/or CLIC, we are almost in a saturation regime. Since we cannot grow only by size, as mentioned before, this graph makes evident the urgency of a technology jump or of novel ideas in our field.

14.2.2 The Luminosity Frontier

For new discovery and studies, energy is not enough. Any energy increase must be accompanied by a consequent increase of the luminosity to compensate the decrease of cross section with energy. Luminosity is a fundamental parameter for measuring a collider performance, right after its beam energy, and is defined as: $L = \dot{n}/\sigma$ where $\dot{n}$ is the collision rate and σ the cross section of a particular event (or the

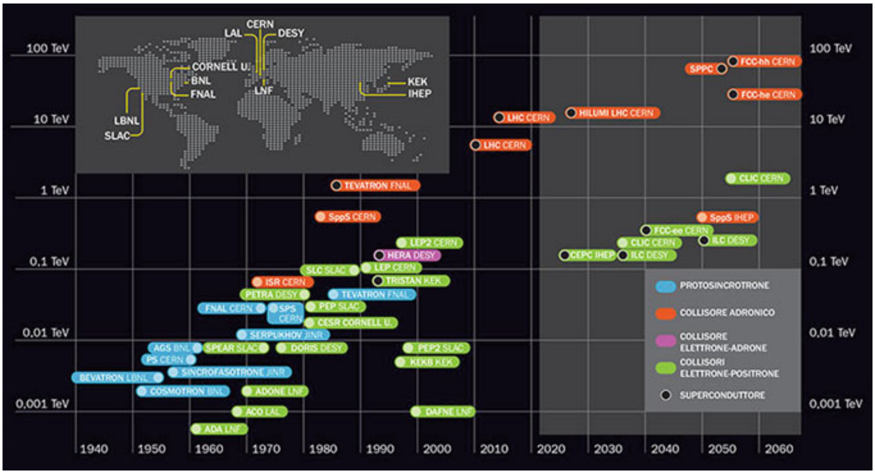


Fig. 14.2 Energy versus time for a compilation of accelerators (Livingstone plot). In grey background, on the right, the future accelerators under construction or under study (figure by L. Rossi published in Asimmetrie, INFN)

sum of cross sections). Even more interesting for physics reach is the concept of integrated luminosity over a period of time, that can be one year or the full span life of an accelerator: $L_{int} = n/\sigma$, where n is the total number of collisions over the time interval considered.

For a circular collider the luminosity depends: i) on the square of the bunch population, N^2 (we assume the colliding bunches have both the same population, N); ii) on the collision frequency, which means increase as much as possible the number of bunches; iii) on the inverse of the beam transverse size at collision point $\sigma_{xy} = \varepsilon \cdot \beta *$, where ε is the transverse emittance and $\beta *$ is the optical function at the collision point. In many case a machine, after a first phase at maximum energy and at a certain luminosity, undergoes an important upgrade concerning mainly increasing the luminosity by a factor 3 to 10, with change in hardware limited to a few components and cost of a fraction, 10–25%, of the initial machine: a way to double the lifetime of a machine without spending too much, leveraging the initial investment.

In Fig. 14.3 the luminosity reached by various machines is plotted versus time, mixing lepton and hadron colliders. It is worth noticing that now SuperKEK overshadows the performance of any previous lepton (e^+e^-) while LHC the one of previous hadron (pp or pp_{bar}) colliders.

14.2.3 *The Intensity Frontier*

Another frontier is the one of beam intensity. Intense beams are necessary also in a collider for HEP, in order to increase the luminosity. However here we refer more

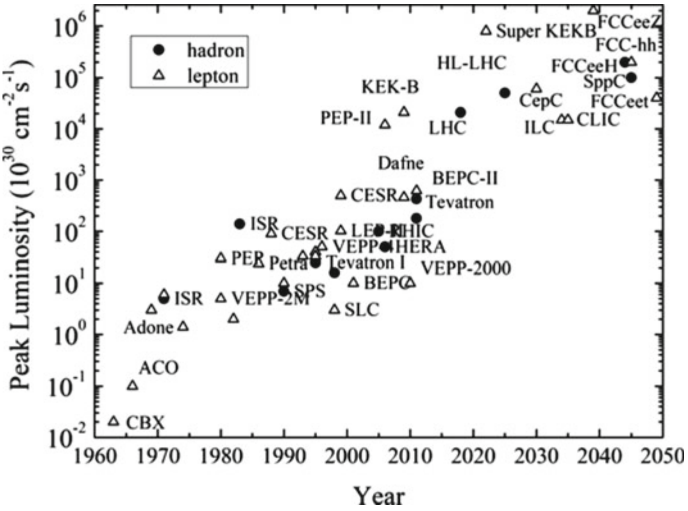
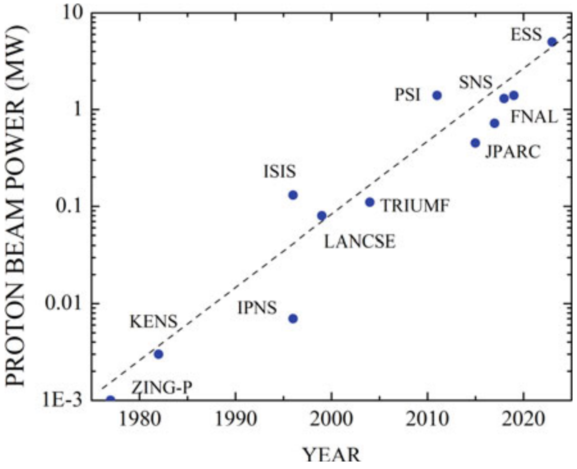


Fig. 14.3 Luminosity performance for a vast compilation of machines. HL-LHC us under construction, all other machine on the right are just in design study phase. Courtesy of V. Shiltev, FNAL

to beam used on targets. Demand of intense proton beams comes from neutron spallation sources, like SNS in the US, JPARC in Japan and ESS in Sweden. Intense proton beams are required also by neutrino sources, like JPARC, again, and FNAL in the US. In Fig. 14.4 we plot the beam intensity of the proton sources versus time.

Fig. 14.4 Beam power for proton accelerators versus time (compilation by V. Shiltev, FNAL)



14.3 Technology Advance: Superconducting Magnets for h–h and RF Cavities for e-e

As mentioned before the progress of the energy frontier is linked to the progress of the superconducting magnet (SM) and of accelerating structures, both superconducting rf (SRF) or normal conducting. We will try to go over the main advance and the progress needed for the next generation colliders.

14.3.1 Superconducting Magnets

The LHC superconducting magnets are the summit of a 30 year-development for hadron colliders. The 8 T used in the LHC main dipole, see Fig. 14.5, is more or less the maximum that can be reached by using the superconducting Nb-Ti alloy.

To go beyond the limit of Nb-Ti new more advanced superconductors need to be employed, like the A3 compound Nb_3Sn. The situation is depicted in the graph of Fig. 14.6, reporting the performance of superconductors, in terms of engineering current density J_E, as a function of magnetic fields. As it can be seen, since magnets needs to operate in the region $J_E \approx 500$ A/mm^2, below 8–9 T Nb-Ti will be the

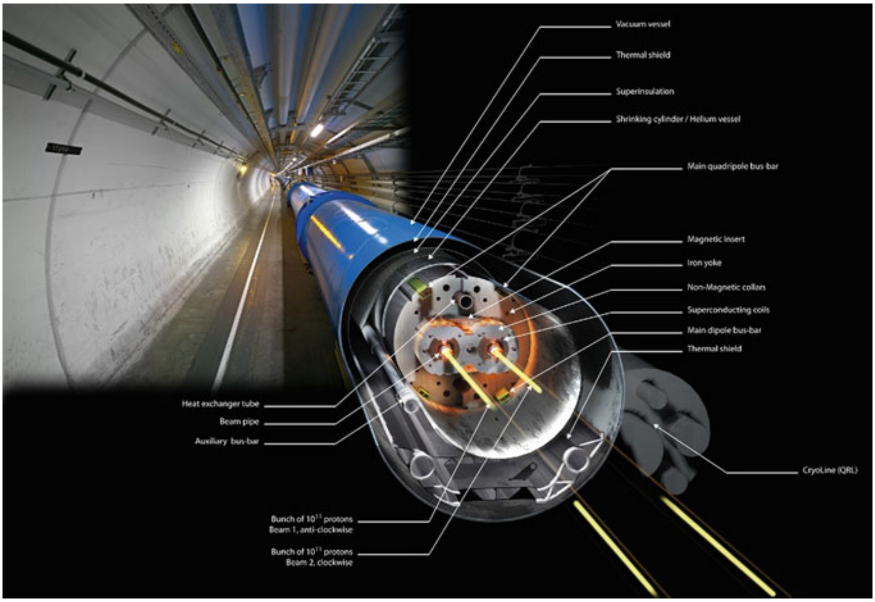


Fig. 14.5 The LHC main dipole: picture with opened cross-section superimposed. Yellow lines represent the two counter-circulating proton beams (not in scale). The superconducting coils is the crescent around the yellow beams (CERN Archive)

invariable choice, given its low cost and easy manufacturability, like the LHC magnets as indicated in Fig. 14.6; between 9 and 15 T Nb_3Sn is the suitable material, like it is used for HL-LHC (in the Fig. 14.6 a cross section of an HL-LHC dipole is shown for the Nb_3Sn regime); above 16 T the only choice is use of HTS (high temperature superconductor), either in form of YBCO (yttrium barium copper oxide) or bismuth based superconductors (Bi-2212 or Bi-2223). For various reasons REBCO (where RE stays for rare earth, since yttrium can be substitute partially or totally by gadolinium) is in this moment more favorite but the community has not yet made a clear decision. In Fig. 14.6 the use of HTS is depicted by a cross section of a dipole studied for the first idea of an HE-LHC [3].

Since a few years, and following the development of very high current density Nb_3Sn for accelerator magnets, there is a strong effort by CERN and by US laboratories (FNAL, LBNL, and BNL) to produce magnet suitable for accelerators. Magnets for colliders are the most difficult application of superconductivity because they need a very high current and a very precise field. The requirements translate into severe requirements on superconductors. The effort started some 20 years ago and is oriented to make magnets for the High Luminosity LHC project, of a level of 11–12 T [4]. It has been a huge effort, to overcome the difficulty due to the characteristics of Nb_3Sn: it requires a thermal treatment at 650–700 ºC of the whole coils, which poses technical challenges for the insulation, and the brittleness of Nb_3Sn when in superconducting state implies a complex mechanical structure with tight control of the tolerances. For the High Luminosity LHC (HL-LHC) project two types of high field superconducting magnets in Nb_3Sn are required: about 30 units of the inner

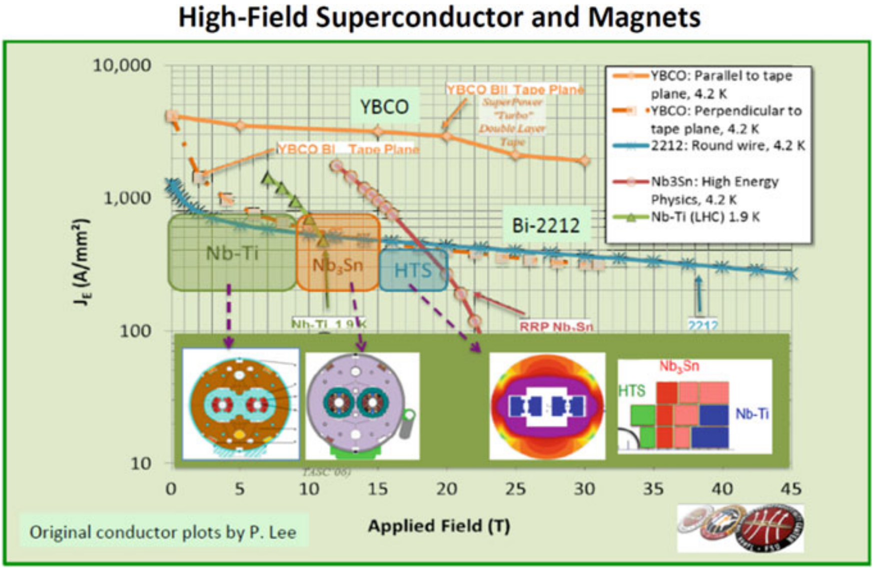


Fig. 14.6 Engineering critical current density for the practical superconductors and regime of application for various magnetic field level (figure by L. Rossi)

Fig. 14.7 Pictures of the two Nb3Sn magnets for the HL-LHC project at CERN (photo CERN Archive)

triplet (IT) quadrupole, with a very large aperture and 11.5 T peak field, 4.2 and 7.15 meters of length, and eight dipoles rated for 11 T and 5.5 m long. Despite the difficulties various short model magnets (1 m long) have been successfully manufactured and tested [5]. The passage to long magnets has been more painful than anticipated. However now there is a number of long magnets that have successfully reached the nominal field value, especially for the IT quadrupole that are the backbone of the project [6]. Their installation is foreseen in the period 2025–2027. In Fig. 14.7 the picture of the two among the first long prototypes for HL-LHC, an 11 T dipole and a IT quadrupole are shown.

In Fig. 14.8 the progress for magnetic field reached by magnets in various hadron colliders is shown. Blue dots refers to operating magnets in real accelerators. For Nb_3Sn this will happen at around 2027 (orange dot) at the commissioning of the HL-LHC magnets. The clouds of orange circles in the Nb_3Sn band of Fig. 14.8 indicates the number of R&D magnets for HL-LHC.

Beyond High Luminosity LHC we have the objective of the next hadron collider: FCC-hh, which is based on a tunnel of 100 km that would first host the lepton collider, FCC-ee and then the hadron collider, very much like the LEP/LHC tunnel. FCC-hh is designed for the CERN area, and the today baseline foresees the use of 16 T dipole magnets in Nb_3Sn. The possibility of going above, about 20 T is left open if HTS would be possible. The two green diamonds and the brown one in Fig. 14.8 refers to initial R&D for the FCC-hh: green refers to the baseline 16 T in Nb_3Sn and brown refers to a hybrid solution with HTS boosting the performance of a 15 T Nb_3Sn dipole.

In the period 2013–2018 a 16 T design was extensively investigated and about four magnet layouts were produced. First a classical $cos\vartheta$ design, by INFN Genova and Milano-LASA team, which has been chosen as baseline for the FCC-hh technical design report. Another design makes use of rectangular coil block, by CEA-Saclay, while the Spanish CIEMAT of Madrid ended up with a design called common coils, where the two apertures for the counter circulating beam are placed vertically, one on the top of the other, rather than side-by-side as in all other solutions. In Fig. 14.9 we report the cross section of these main dipoles proposed for FCC-hh.

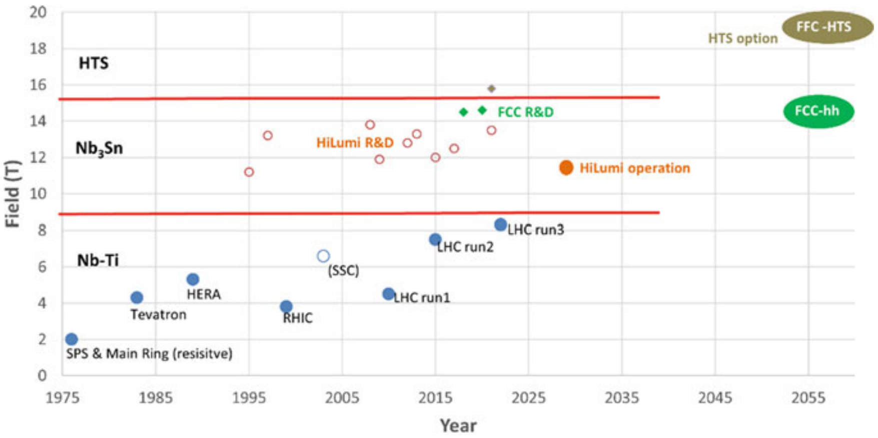


Fig. 14.8 Progress in time of the magnetic field for hadron collider magnets until HL-LHC (figure by L. Rossi)

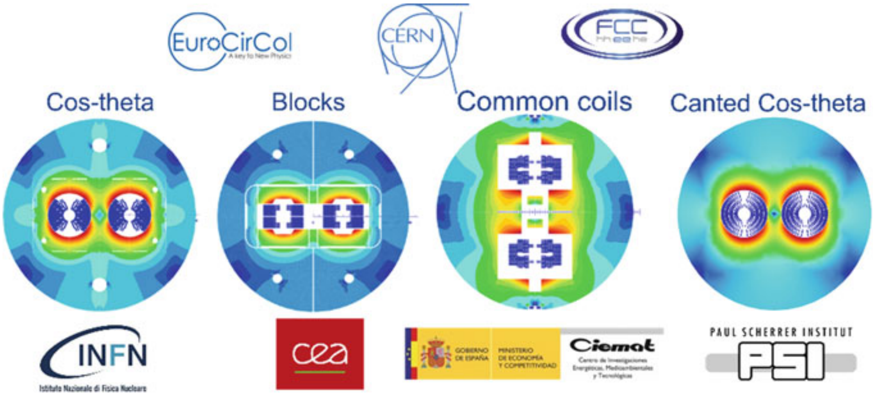


Fig. 14.9 Various magnet cross section studied in the H2020-Eurocircle project for FCC-hh by various Institutes under the guidance of CERN (figure by L. Rossi)

However, following the difficulties encountered in the HL-LHC for long magnets, now the community has made a step back and the idea is to produce magnets of 12 T with more robust characteristics with respect to the pioneering HL-LHC magnets. The jump from the 11–12 T level of HL-LHC, that has required about 20 year of development, see Fig. 14.8, up to the 16 T level seems now quite big, indeed. For FCC-hh almost 5000, 15 m long, magnets would be needed, versus the few tens of 4 to 7 m long magnets for HL-LHC. Therefore, demonstrating the manufacturability of 12 T long magnets in Nb3Sn seems a necessary intermediate step, which may take all the present decade. Then the solution is either to use it to built a 12 T based FCC, with an energy reach of 70–75 TeV c.o.m., or to continue an R&D for reaching the ultimate limit of Nb_3Sn. However, we are not sure that the limit of 16 T given by Nb_3Sn conductor performance can be actually attained: maybe mechanical degradation will impose a lower limit at 14 or 15 T. In such a case FCC-hh would need, if the final goal of 100 TeV performance remains important, the use of HTS superconductor.

As shown in the graph of Fig. 14.6, HTS may boost performance up to 20 T and beyond, being 25 T maybe the upper limit of such material. HTS materials, in particular REBCO, are mechanically robust: they can withstand stresses of up to 400 MPa versus the 150 MPa that can be applied to Nb3Sn. However they come in form of coated flat tape instead of multi-filamentary round wire, like the classical superconductors. This means that the field quality is today a serious issue for which there is no solution, yet. The second big issue with HTS is the difficulty in making a sound protection following a quench (quench being the sudden transition from the superconducting state to the normal conducting state). Because of the high transition temperature HTS have a huge stability margin, measurable in tens of joules rather than *mJ* typical for the classical superconductors. However, this stability margin entails that a quenched zone would propagate very slowly making a detection very difficult, with consequent possible irreversible damage of the coils. We have devised a strategy to limit this effect [7, 8], based on current redistribution, and demonstrated it in a small demo magnets of about 3–4 T. However a long R&D remains for introducing these features in a real accelerator magnet.

In Fig. 14.10 we show a compilation of the performance of the small HTS magnet built so far [9], with also a figure of the CERN small HTS dipole (35 mm free bore, 700 mm in length) holding the record dipole field of 4.5 T in standalone and having made a record of nearly 16 T when inserted in a high field facility (brown diamond in the plot of Fig. 14.8).

In conclusion we believe that for Nb_3Sn the 12 T level would be a sound field and to go beyond the 12 T is probably better to use HTS, if its cost decreases by at least a factor 3 to 5, since today is too expensive. Another possibility, also based in case of cost reduction, is to use HTS magnets for 12–16 T operating at higher temperature,

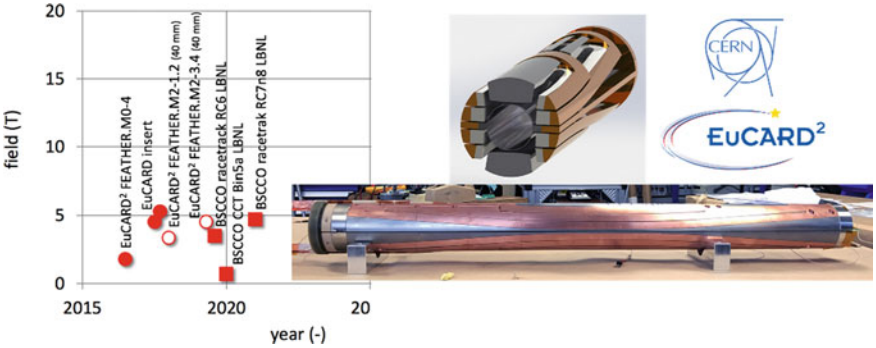


Fig. 14.10 Left: compilation of field result for various HTS racetrack coils (no bore) or dipole magnets (with an accessible bore); right: picture (bottom) and rendering (top) of the CERN dipole for Eucard2 program holding the record field for HTS dipoles (figure by L. Rossi)

e.g., 20 K instead of the 1.9 K necessary for Nb_3Sn. The 20 K operation temperature could save some 200 MW or more in the powering of the cryogenic plants, which is a very important goal both for environmental reasons and for cost reasons.

14.3.2 Superconducting RF Development

While for magnets the choice of superconductivity is very well established, the use of SRF or of normal conducting RF (NCRF) is not so straightforward. Indeed despite the better global energy efficiency in case of SRF the highest attainable gradients are still in the camp of NCRF, i.e., of copper cavity. Therefore the choice of using one or the other technology depends on the structure of the beam and on various considerations, not last also political ones.

In Table 14.1 we report a summary of the main points for the two technologies and in Fig. 14.11 is depicted the progress of SRF in the L-band (1.3 GHz, the most used for electron acceleration) both for single cell and for multicell cavity. In all cases we refer to Nb bulk cavities. As can be observed in Fig. 14.11 multicell performances have progressed steadily and have attained nearly 50 MV/m. Taking into account the inevitable contingency for operation in a cryomodule and for the fluctuation of a large production, which in case of X-FEL showed a variance of about 5 MV/m, we can say that the SRF technology is mature to go beyond the 30–35 MV/m of the ILC design, as indicated by the 45 MV/m indicated in parentheses in the RF performance table.

Normally linacs work with duty cycle. However the need of continuous (CW) beam is becoming high. For HEP machines in particular the FCC-ee, as well as its Chinese counterpart CepC, both e^+e^- machines at some 250–350 GeV c.o.m. collider would requires a large numbers of CW cavities. In such case the electric field is lower about 20 MV/m but the request on the Q_0 is very high, to limit the cryogenic losses. It is worth noticing the remarkable progress in Q_0 at moderate electric fields thanks to infusion and at higher gradient thanks to doping with nitrogen, as clearly shown in Fig. 14.12. This rather recent development shows that there is still a lot of room to improve in this technology [10].

A different interesting developing line is the study for using A15 compounds, namely Nb_3Sn as superconducting material for the SRF cavity: Nb_3Sn would allow operating the cavity in the 4.2 K or higher temperature, rather than the 2 K required by niobium bulk. This would result in a considerable saving on the electric bill and in increased cavity stability (heat capacity increases cubically at these temperatures so the same temperature margin gives eight time largest energy margin, very much like superconducting magnets). Recent result are very encouraging, [11] and alternative methods for coating like sputtering are being investigated, see Fig. 14.13. A similar line is pursuing the use of HTS thin films, opening the way to high temperature operation, even more than Nb_3Sn, as suggested in [12] on bulk Nb_3Sn cavity and an interesting development on Nb_3Sn coating on a copper cavity. If successful this last

Table 14.1 Comparison between normal and superconducting RF systems (*Source:* A. Yamamoto, KEK)

Parameters	Normal conducting (CLIC)	Superconducting (ILC)
Electric Field (MV/m)	70–100 Higher energy or shorter accelerator	30–35 (45) Higher efficiency, steady state beam power from RF input
RF frequency f (GHz)	12 High efficiency peak power Need precision alignment and stabilization for wake filed compensation	1.3 Large aperture  small wakefields
Quality factor Q0	$<10^5$ Resistive wall losses compensated by strong beam loading	$\cong 10^{10}$ Small losses Losses at cryogenic temperatures (250–500 factor)
Pulse structure	180 ns/50 Hz	700 μm 5 Hz
Fabrication issue	μm level mechanical tolerances	Material quality (purity) and complex clean room chemistry
Efficiency considerations	High-efficiency RF peak power production through long-pulse, low freq. klystrons and two-beam scheme	High-efficiency RF also from long-pulse, low-frequency klystrons

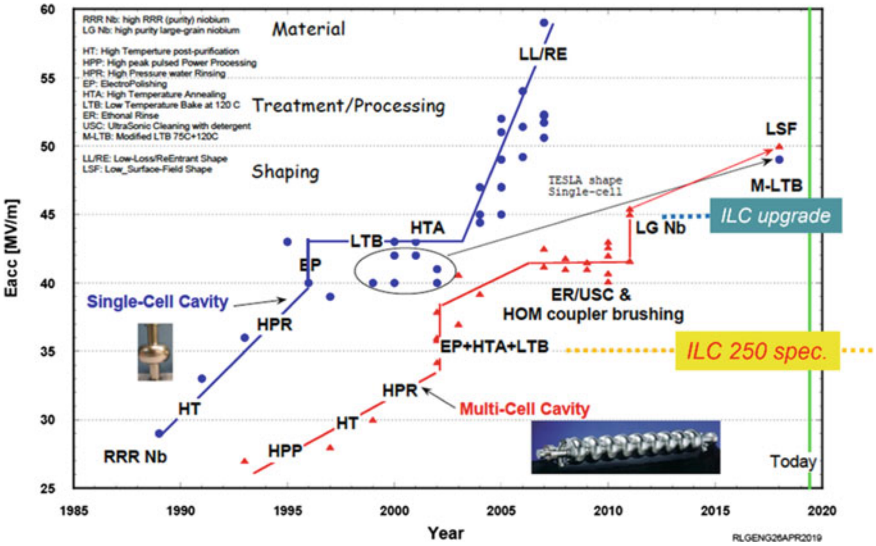
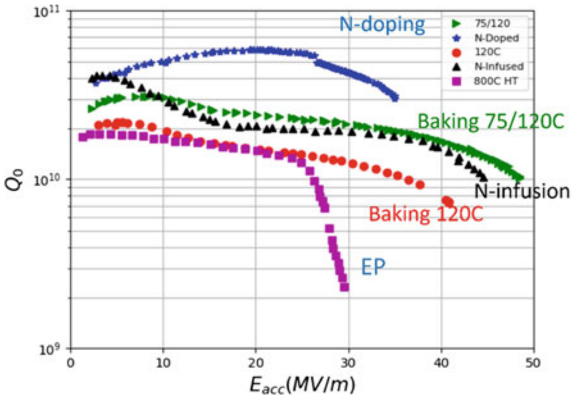


Fig. 14.11 Progress of the performance in SRF gradient for 1.3 GHz electron cavities (figure by CERN Courier, adapted by L. Rossi)

Fig. 14.12 Infusion & doping Q0 (Ref. [11])



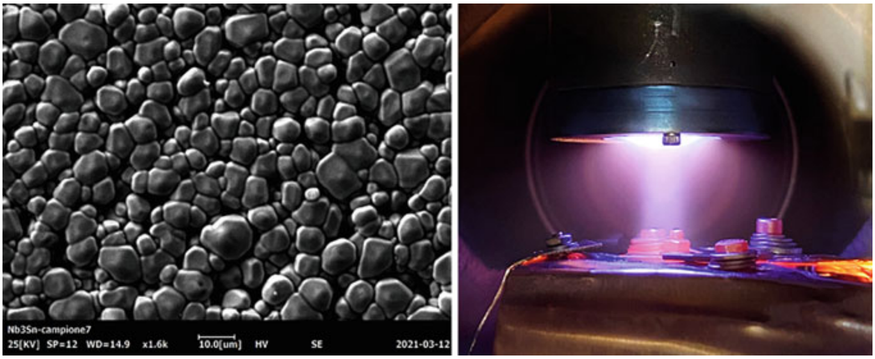


Fig. 14.13 Nb_3Sn thin film deposited on high conductivity Cu substrate for cavity R&D via sputtering (left) and picture of the sputtering process (right), Ref. [12]

development could open the way to higher gradient, with reduced cryogenic power and very high stability since the substrate would be high conductivity copper.

14.4 Beyond Superconducting RF Cavities and Superconducting Magnets

From what said in the previous sections, increasing basic performance, the fields in magnets or in cavities, takes a very long time constant: one can see a doubling each 20–25 years, and maybe more in the future.

An electric field two times larger than the one of SRF cavities is offered already now by CLIC technologies working at 12 GHz, as mentioned in the SRF section. We refer to specific paper on this [13].

Anyway, we think that apart from the incremental gain offered by continuous R&D along the routes previously described, we have two alternative routes:

The muon-collider, that holds the promise of accelerating leptons in a circular accelerator, where the luminosity is better controlled than in a linear collider, at energy of 3 TeV and then up to 10 TeV. At 10 TeV a lepton collider can claim a physics reach similar to the FCC-hh, but with an infrastructure size much smaller, comparable to the present LHC one. A muon-collider specificity is presented in [14].

Plasma acceleration. A lot is going on at present on this rather novel technology. This technology that holds the promise of reducing the infrastructure, for the same energy, by a factor of ten or so, thanks to electric field that in plasma can be as higher as tens of GV/m. While it looks like that for smaller size applications, like FEL, medicines, etc.… this technology may be a real game changer, the usefulness for colliders, also in view of the power consumption, is still to be demonstrated also in principle. But the challenge is one of the most interesting in all accelerator sectors. The plasma acceleration is discussed in Chap. 13 of these Proceedings and in R. Assman's contribution to the Symposium.

14.5 Conclusions

Accelerators have been a drivers of technology innovations. The use of NMR for spectroscopy and especially for MRI has been made possible by the development of the superconductors and superconducting magnets of the Tevatron. Now various machines for hadron therapy employ superconducting magnets. Use of superconducting magnets for cyclotrons and of superconducting cavities for CW linacs are essential for transmutation and efficiency improvement of nuclear power plants. Also CLIC technologies are being used for new type of flash-therapy with electron beams.

The request for new development in accelerator technology to face the challenges posed by the future HEP colliders will certainly profit the fundamental knowledge itself but will also certainly result in new interesting—maybe unexpected- societal applications.

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