



Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Future colliders for particle physics—“Big and small”

Frank Zimmermann

CERN, Geneva, Switzerland

ARTICLE INFO

Keywords:

Crystal acceleration
Future circular collider
Gamma factory
Muon collider
Particle colliders
Synchrotron radiation

ABSTRACT

Discoveries at high-energy particle colliders have established the standard model of particle physics. Technological innovation has helped to increase the collider energy at a much faster pace than the corresponding costs. New concepts will allow reaching ever higher luminosities and energies throughout the coming century. Cost-effective strategies for the collider implementation include staging. For example, a future circular collider could first provide electron–positron collisions, then hadron collisions (proton–proton and heavy-ion), and finally the collision of muons. Cooling-free muon colliders, realizable in a number of ways, promise an attractive and energy-efficient path towards lepton collisions at tens of TeV. While plasma accelerators and dielectric accelerators offer unprecedented gradients, the construction of a high-energy collider based on these new technologies still calls for significant improvements in cost and performance. Pushing the accelerating gradients or bending fields ever further, the breakdown of the QED vacuum may set an ultimate limit to electromagnetic acceleration. Finally, some ideas are sketched for reaching, or exceeding, the Planck energy.

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1. Introduction

In January 1932 the first practical cyclotron of E.O. Lawrence with a diameter of 23 cm accelerated protons to a kinetic energy of 1.22 MeV. The beam current was about 1 nA [1]. Almost 90 years later the Large Hadron Collider (LHC) at CERN, with a diameter of 9 km, accelerates protons to an energy of 6.5 TeV with a beam current of the order of 1 A. Therefore, over about a century, the accelerators became 3×10^4 larger and now achieve close to 10^7 times higher energy than 100 years ago. While a large part of this energy rise was accomplished by an increase in size, two to three orders of magnitude were gained by technological improvements.

At the same time, the technology advances have also dramatically reduced the specific construction cost, i.e. the cost per centre-of-mass (c.m.) energy, from about 60 MCHF/(GeV c.m.) for the CERN Proton Synchrotron (PS), first operated in 1959, to 0.3 MCHF/(GeV c.m.) for the Large Hadron Collider (LHC), in operation since 2008, with both prices expressed in 2008 Swiss francs [CHF] [2,3] — a cost reduction by a factor 200 over 40 years.

The colliders, which could be realized thanks to this advancing technology, have proven powerful instruments for discovery and precision measurement. All the heavier particles of the standard model were produced at colliders: the tau lepton and charm quark at SPEAR, the top quark at the Tevatron, the gluon at PETRA, the W and Z bosons at the SpS collider, and the Higgs boson at the LHC. These and other colliders appear in Fig. 1.

The past progress was enabled by the introduction of new concepts (e.g., strong focusing, separate function magnets, colliding beams) as much as by the emergence of new technologies, in particular ones based on superconductivity. PETRA, TRISTAN and LEP-II started the massive use of superconducting radiofrequency (rf) systems. The Tevatron was the first accelerator based on superconducting magnets. HERA, RHIC, and the LHC used, or use, both superconducting magnets and superconducting rf.

In addition to energy and specific cost, also the accelerator performance was tremendously improved over time: Every year the LHC delivers more luminosity than all the previous hadron colliders together had accumulated over their entire operating history.

2. Pushing the energy frontier in the 21st century

A very large circular hadron collider appears to be the only feasible approach to reach 100 TeV c.m. collision energy in the coming decades. Such collider would offer access to new particles through direct production in the few-TeV to 30 TeV mass range, far beyond the LHC reach [6]. It would also provide much-increased rates for phenomena in the sub-TeV mass range and, thereby, a much increased precision compared with the LHC [6].

The centre-of-mass energy reach of a hadron collider is directly proportional to the maximum magnetic field B and to the bending

E-mail address: frank.zimmermann@cern.ch.

<https://doi.org/10.1016/j.nima.2018.01.034>

Received 17 December 2017; Received in revised form 29 December 2017; Accepted 11 January 2018

Available online xxxx

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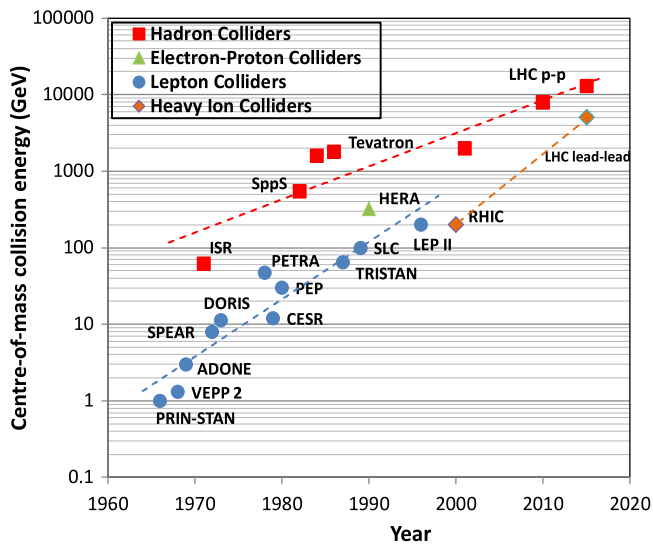


Fig. 1. Centre-of-mass energy of particle colliders versus year [4,5].

radius ρ :

$$E_{c.m.} \propto \rho B. \quad (1)$$

Therefore, an increase in the size of the collider compared with the LHC by a factor of about 4 and an approximate doubling of the magnetic field yields almost an order of magnitude increase in energy.

Such approach was first suggested in the year 2010 during the High-Energy LHC (HE-LHC) workshop [7]. Now it is the focus of the Future Circular Collider (FCC) study [8], which was launched in response to the 2013 Update of the European Strategy for Particle Physics: 16 T magnets in a 100 km ring will result in a centre-of-mass energy of 100 TeV. This goal defines the overall infrastructure requirements for the FCC accelerator complex. The FCC study scope also includes the design of a high-luminosity e^+e^- collider (FCC-ee), as a possible first step (with a remarkably rich physics programme [9]), as well as a proton-electron collision option (FCC-he) at one interaction point, where a 60 GeV electron beam from an energy recovery linac is collided with one of the two 50 TeV proton beams circulating in the FCC-hh. The design of a higher-energy hadron collider in the LHC tunnel based on FCC-hh magnet technology – the so-called High-Energy LHC (HE-LHC) – is yet another part of the FCC study.

As of June 2017, 111 institutes and 25 companies from 30 countries are participating in the FCC study effort. The near-term goal is to deliver a conceptual design report of all FCC collider options, including technologies, detector design, and physics goals, before the end of 2018,

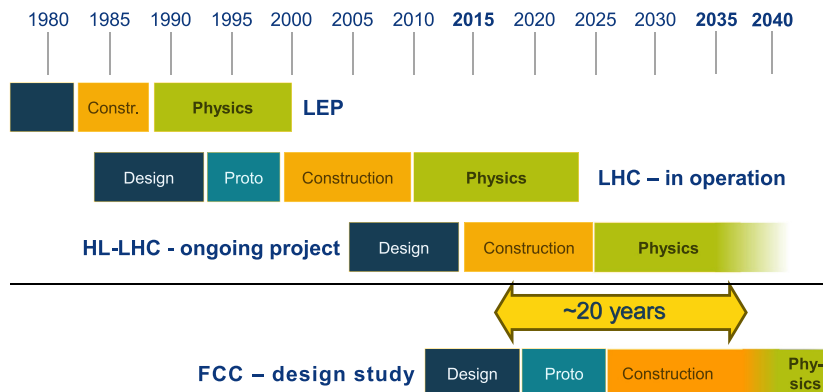


Fig. 2. Time lines of several past, present and future circular colliders at CERN, distinguishing periods of design, prototyping, construction, and physics exploitation.

as input to the next European Strategy Update process expected for 2019/20.

Fig. 2 compares the time lines of various past and present circular colliders at CERN with a projected time line for the FCC, indicating a need for fast progress.

CEPC and SppC are two colliders similar to FCC-ee/FCC-hh, which are being studied by another international collaboration, centred at IHEP Beijing [10]. These two machines have a similar circumference of about 100 km. Several possible locations in China are under study. The e^+e^- collider CEPC is designed with a maximum centre-of-mass energy of 240 GeV, and a 3 or 200 times lower luminosity than FCC-ee, at the Higgs production peak and on the Z resonance, respectively. The SppC hadron collider relies on 12 T (later 24 T) iron-based high-temperature superconducting magnets, which could be installed in the same tunnel as the CEPC.

Table 1 shows key parameters of FCC-hh, SppC, and HE-LHC, together with the design values of the present LHC and its luminosity upgrade (HL-LHC). Table 2 compares parameters for FCC-ee and CEPC at different operating energies with those of LEP-2 and SuperKEKB.

Construction cost of future projects can, and should, be minimized by [11,12]: (1) reducing the cost of the components, e.g., superconductor and high-field magnet for the hadron colliders; (2) building on a site with an existing infrastructure and injector complex, e.g., on the CERN site; and (3) staging, e.g., FCC-ee followed by FCC-hh, and possibly by a muon collider FCC- $\mu\mu$ (see below).

3. Mitigating synchrotron radiation

Synchrotron radiation (SR) is an obstacle on the path to higher energy, as the resulting energy loss per turn increases with the fourth power of a charged particle's energy. For FCC-ee, synchrotron radiation limits the maximum attainable c.m. energy to about 400 GeV since at higher energy the required rf voltage could no longer be provided by conventional rf technology. Also, by design, the FCC-ee beams emit a total of 100 MW SR power at all energies.

However, synchrotron radiation does not only afflict the electron and positron machines. The synchrotron radiation of the FCC-hh hadron collider amounts to about 5 MW, emitted inside the cryogenic arcs. The power consumption of the FCC-hh hadron collider is likely to be dominated by the effects of this synchrotron radiation. Namely, the heat extraction from the beam screen inside the cold magnets and from the cold bore itself requires well above 100 MW of electric power for the cryogenics plants. In addition, of order 10 MW electric power is required for the rf system to maintain the energy of the stored beams.

Several possible approaches exist for eliminating, avoiding, or at least reducing the synchrotron radiation:

- suppression of synchrotron radiation for circular e^+e^- and hadron colliders by (1) shaping the beam: classically a time-invariant beam – like a constant-current loop – does not radiate,

Table 1
Parameters of future hadron colliders, the LHC and its HL-LHC upgrade.

Parameter	FCC-hh	SppC	HE-LHC	(HL-)LHC
c.m. energy [TeV]	100	75	150	27
Dipole field [T]	16	12	24	16
Circumference [km]	97.8	100	26.7	26.7
Beam current [A]	0.5	0.77	–	1.12
Part./bunch [10^{11}]	1	1.5	–	2.2
Bunch spacing [ns]	25	25	–	25
Norm. emittance [μm]	2.2 (1.1)	3.16	–	2.5 (1.25)
IP beta function [m]	1.1	0.3	0.71	–
Lum. [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	5	30	10	25
Events per crossing	170	1000	~300	–
SR power/beam [kW]	2400	1130	–	100
Longit. damp. time [h]	1.1	2.4	–	3.6
Init. burn-off time [h]	17	3.4	13	–
			3.0	(15) 40

Table 2
Parameters of future e^+e^- colliders, LEP-2 and SuperKEKB.

Parameter	FCC-ee	CEPC	LEP-2	SKEKB
Beam energy [GeV]	45.6	120	182.5	45.5
Circumference [km]	97.8	100	26.7	3.0
Beam current [mA]	1390	29	5.4	19
Part./bunch [10^{11}]	1.7	1.5	2.8	0.1
h. emittance [nm]	0.3	0.6	2	0.2
v. emittance [pm]	1	1	3	0.9
h. IP beta [m]	0.15	0.3	1	0.17
v. IP beta [mm]	0.8	1	2	2
Lum. [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	>200	>7	>1.3	1.1

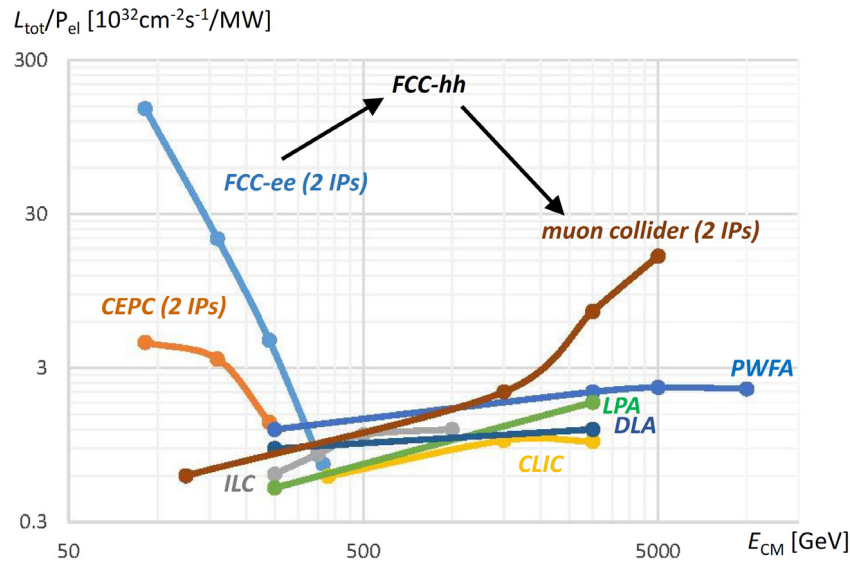


Fig. 3. Lepton-collider luminosity per electrical power for different accelerator projects and technologies, hinting that the staged approach FCC-ee (\rightarrow FCC-hh) \rightarrow FCC- $\mu\mu$ would deliver highest possible luminosity at c.m. energies from 91 GeV to >5 TeV in the most efficient way [23,25].

i.e., it does not emit any electromagnetic waves; for the same reason a quieter beam or a crystalline beam would radiate less [13,14]; and/or by (2) tailoring the beam-pipe boundary: a large bending radius ρ combined with a small chamber suppresses SR emission at long wavelengths; specifically, radiation is shielded at wavelengths $\lambda \geq 2\sqrt{d^3/\rho}$, where d denotes the beam-pipe diameter [15];

- transiting from circular to linear e^+e^- colliders, such as the proposed International Linear Collider (ILC) [16] or Compact Linear Collider (CLIC) [17]; however, linear colliders are intrinsically inefficient, as the entire beam is disposed, and its energy lost, after only a single collision; on the other hand,

synchrotron radiation is still present during the collision (here called “beamstrahlung”), where it becomes a significant limitation at multi-TeV beam energies; future advanced variants of linear colliders with higher gradient, and therefore of smaller size, are proposed to be based on laser- or beam-driven plasma wake-field acceleration schemes (LPA [18] or PWFA [19–21]) or on dielectric laser acceleration (DLA [22]) schemes; at present such acceleration schemes, which promise 10–1000 times higher accelerating gradients than conventional rf structures, still tend to have a non-negligible specific cost, currently as high as the super- or normalconducting rf systems [11], if not higher; their luminosity per wall-plug power might also increase with beam

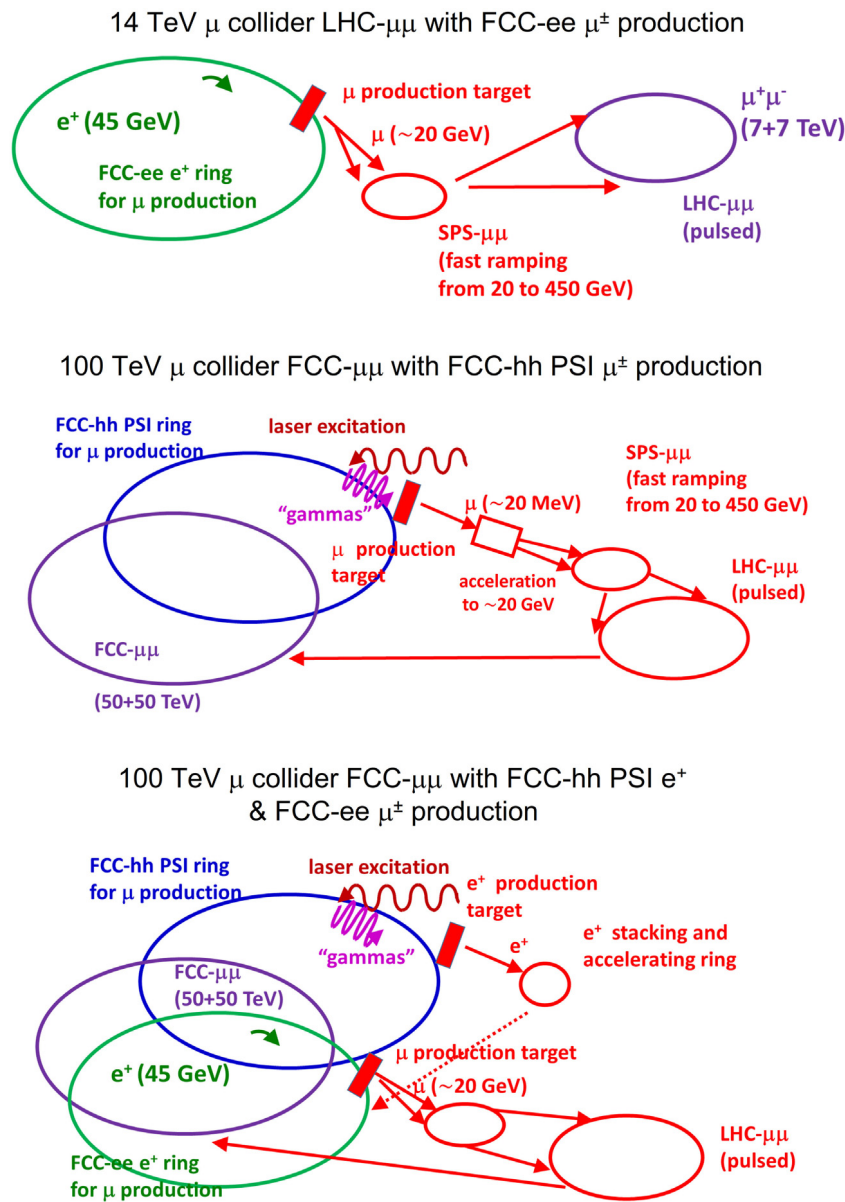


Fig. 4. Example variants of multi-TeV muon colliders based on the LHC/FCC complex.

energy less strongly than required by particle physics [23]; preserving the quality of a positron beam during plasma acceleration may prove yet another challenge [24];

- changing the particle type from e^+e^- to muons; indeed such muon-collider schemes [23] promise a high efficiency, as we will discuss in the following.

4. Maximizing efficiency

Fig. 3 demonstrates that up to the top quark threshold the circular collider FCC-ee offers by far the highest luminosity at the lowest electric input power, revealing the FCC-ee characteristics as a truly “green” accelerator. The FCC-ee would naturally be followed by FCC-hh, which spans a wide range of parton collision energies at high luminosity, for a total electric input power similar to the one of FCC-ee. A possible third stage would be a muon collider, the only lepton-collider approach which promises a high luminosity at higher energy [23], as is required for particle-physics explorations.

Fig. 4 sketches various example configurations for converting the LHC-FCC complex into a muon collider, using the concepts of low-emittance muon beam generation by positron annihilation in a ~ 45 -GeV storage ring [26] (which could be FCC-ee or its top-up booster, already optimized for Z pole operation at the same energy), and/or of either positron or muon production in laser-Compton collisions with a partially stripped heavy-ion (PSI) beam, the so-called Gamma Factory [27]. The muon beams would be collided in one of the two LHC or FCC rings, while the second ring (or the other one of the two accelerators, respectively) might potentially be used to store partially stripped heavy-ion beams for muon or positron production. Remaining issues, still to be tackled, include the muon stacking, rapid acceleration, muon synchrotron radiation and neutrino radiation.

5. Ultimate limits and outlook

An ultimate limit on electromagnetic acceleration may be set by the Sauter–Schwinger critical field, above which the QED vacuum breaks down. This critical field is equal to $E_{cr} \approx 10^{12}$ MV/m or $B_{ct} \approx 4.4 \times 10^9$ T. Assuming these fields, the Planck scale of 10^{28} eV can be reached by a

circular or linear collider with a size of about 10^{10} m, or about a tenth of the distance between earth and sun, for either type of collider (!). A solar-system Planck-energy linear collider was considered previously, and it was judged to be “not an inconceivable task for an advanced technological society” [28]. The presently studied FCC and CEPC/SppC colliders appear small if compared with a future solar-system collider at the Planck energy.

The future holds other tantalizing accelerator challenges, such as (1) the possible use of accelerators for the detection or generation of gravitational waves [29–31]; (2) the possibility of constructing a high-field crystal [4,32] or nano-tube [33] accelerator (for acceleration [4] or bending [32]); (3) the strategy for approaching (or exceeding) the Planck scale [34], and the possible acceleration beyond the Schwinger limit e.g., by developing a “quantum plasma accelerator” [35], or using techniques of entanglement [36].

Acknowledgements

I would like to thank the organizers of EAAC2017, especially Edda Gschwendtner, Ralph Aßmann, and Massimo Ferrario, for inviting my contribution and proposing the title.

This work was supported, in part, by the European Commission under the HORIZON2020 Integrating Activity project ARIES, grant agreement 730871.

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