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Future Highest-Energy Circular Colliders

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At present the Large Hadron Collider (LHC) pushes the energy frontier of accelerator-based particle physics. During its Run 1 (2010–2012) the LHC produced proton-proton collisions at centre-of-mass energies of 7–8 TeV. For Run 2, in 2015, this energy will be increased to 13 TeV. The exploitation of the LHC will continue until about 2035. In particular, around the year 2023 the LHC will be upgraded for ten times higher integrated luminosity ("High Luminosity LHC," or, short, HL-LHC), by means of a novel magnet technology based on Nb_3Sn superconductor, paving the way for future projects.
Indeed, in response to the 2013 Update of the European Strategy for Particle Physics, a design study for a future circular 100-TeV hadron collider (FCC-hh) has already been launched. This 100-TeV collider will exploit, and further advance, the HL-LHC magnet technology. In addition, the FCC-hh will require a new 100-km tunnel infrastructure in the Lake Geneva basin. As a potential intermediate step the same tunnel could host a high-luminosity circular e^+e^- collider (FCC-ee), serving as Higgs, Z, $t\bar{t}$, and W factory. A lepton-hadron collider option (FCC-he) is also being considered. Similar projects of large circular lepton and hadron colliders, called CEPC and SPPC, are being pursued in China.
The global FCC collaboration is evolving and expanding. Key parts of the hadron collider design study are now being co-funded by the European Commission in the frame of its HORIZON 2020 programme.
The FCC complex could deliver energy-frontier science through the end of the 21st century.

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1. Introduction

Today the Large Hadron Collider (LHC) at CERN represents the energy-frontier of accelerator based particle physics. The LHC, inlcuding its high-luminosity upgrade, will operate for another 20 years. After the discovery, in 2012, of the Higgs boson, by two of the LHC experiments, future large circular electron-positron and proton-proton colliders have been proposed as powerful tools to examine the nature of this unique particle, including its pointlikeness and its self-coupling, and to look for New Physics beyond the Standard Model. In this article we review the schedule for the LHC and HL-LHC, and then discuss plans for future hadron and lepton colliders, such as FCC-hh, FCC-ee, CEPC and SPPC.

2. Large Hadron Collider (LHC)

The LHC is installed in a tunnel of 26.7 km circumference, which has formerly housed the e^+e^- collider LEP. Figure 1 shows a schematic of the two counter-rotating LHC proton beams. These two beams intersect each other at four collision points, where the four particle-physics detectors are located: the multi-purpose experiments ATLAS and CMS, the B-physics experiment LHCb, and ALICE, mainly devoted to the physics of heavy-ion collisions.

The LHC design proton beam energy is 7 TeV, corresponding to a centre-of-mass (c.m.) energy of 14 TeV. The design proton-proton peak luminosity of 10^{34} cm^{-2}s^{-1} is obtained with about 2800 bunches per beam, each containing 1.15×10^{11} protons. The energy stored in each beam amounts to about 360 MJ. The design beam energy of 7 TeV is obtained for a field of 8.33 T in the superconducting Nb-Ti dipole magnets.

For LHC Run 1 (2010-2012) the strength of the magnetic field in the arc dipole and quadrupole magnets was restricted for reasons of machine protection. As a consequence the beam energy was limited to 3.5 TeV in 2010–2011, and later raised to 4 TeV in 2012. At 4 TeV, the LHC has reached a peak pp luminosity of 7.7×10^{33} cm^{-2}s^{-1} with 50-ns bunch spacing. In other words, at an energy approximately equal to half the design value about 80% of the design luminosity has already been attained. This is remarkable since, in first approximation, the luminosity scales with the square of the energy. At the Run-1 bunch spacing of 50 ns (twice the design) and close to the design luminosity, a large number of up to 40 events per bunch crossing ("pile up") were recorded by the LHC physics experiments.

During Run 1, the LHC delivered a total luminosity of about 30 fb^{-1} to the experiments ATLAS and CMS. As an example, Fig. 2 shows the accumulated luminosity for CMS. The integrated luminosity produced by the LHC so far is already larger than those from all previous hadron colliders (ISR, S$p\bar{p}$S, Tevatron, RHIC) together.

The target energy for LHC Run 2, starting in 2015, is 13 TeV c.m. In Run 2 the LHC will operate at the design bunch spacing of 25 ns (for reduced pile up), and aim at a peak luminosity of 1.3×10^{34} cm^{-2}s^{-1}. By the end of Run 2, around 2018, a total of 100–120 fb^{-1} should be accumulated [1]. Run 3, extending through 2022 will reach 300 fb^{-1}, a value which corresponds to the expected lifetime limit of the final-focus quadrupole magnets (also known as triplet quadrupoles) in view of their exposure to radiation from collision debris.

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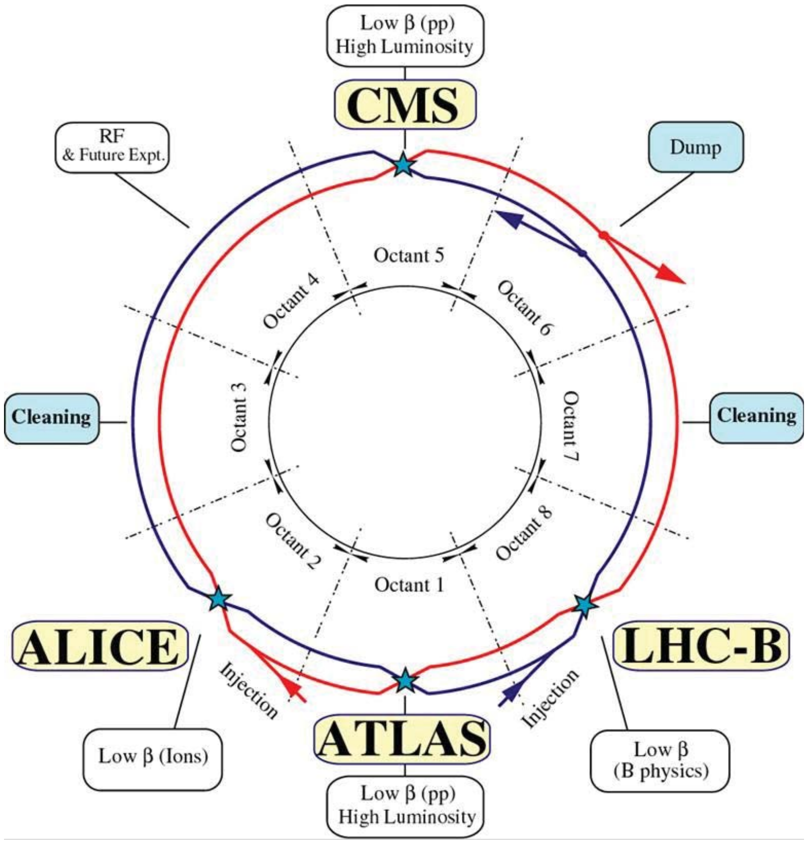

Figure 1: Schematic of the Large Hadron Collider with its four experiments (Courtesy CERN).

3. High Luminosity LHC

Figure 3 shows the 20-year roadmap for the LHC. The upgrade of the LHC to the HL-LHC is foreseen to occur around 2023.

The key part of the HL-LHC upgrade [2] is the replacement of the final quadrupole triplets by magnets of larger aperture, based on a novel technology. Namely, the new triplet quadrupoles will be made from Nb_3Sn superconductor. Figure 4 illustrates that the Nb_3Sn wire conductor can support up to a factor 2 higher field than a *Nb-Ti* wire at comparable current densities. With a design peak field at the coil of about 12 T [3], the new quadrupoles allow for three to four times smaller β^* and, thereby, for higher luminosity.

In addition, a few bending magnets in several of the so-called dispersion supressors, located between the arcs and the straight sections, will be replaced by shorter and stronger 11-T dipoles [4], so as to make space for additional collimators. These stronger and shorter dipoles will equally be based on Nb_3Sn technology.

In total the HL-LHC will feature a few tens of Nb_3Sn magnets, both dipoles and quadrupoles, operating at a field level of 11–12 T.

The HL-LHC upgrade contains many other elements. In its course the LHC accelerator will be modified over a total length of 1.2 km. Aside from the Nb_3Sn magnets, another key ingredient is the compact crab cavities, which will be installed around the Interaction Points (IPs) 1 and 5.

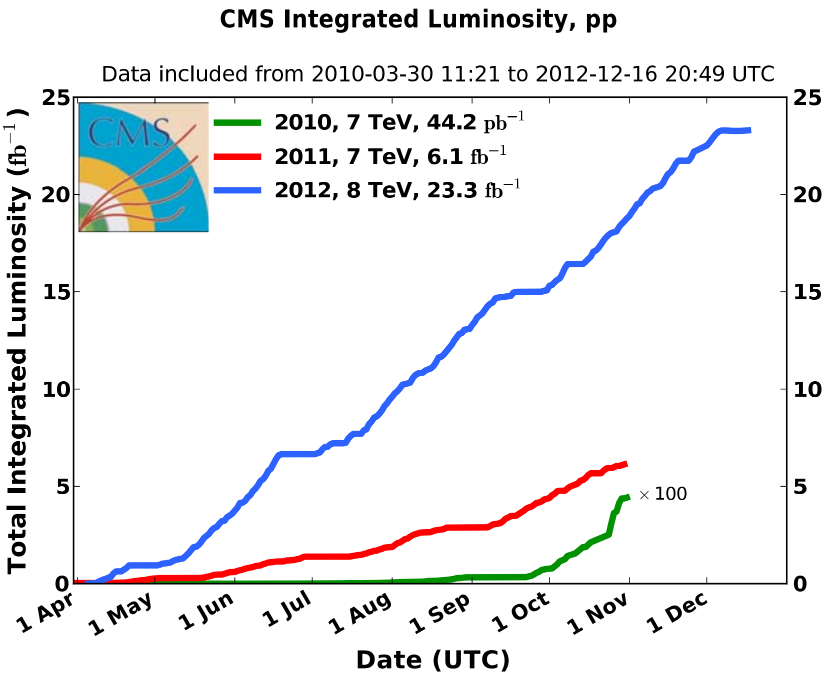

Figure 2: LHC Run-1 integrated luminosities, as recorded by CMS, for the years 2010, 2011 and 2012 (Courtesy CMS).

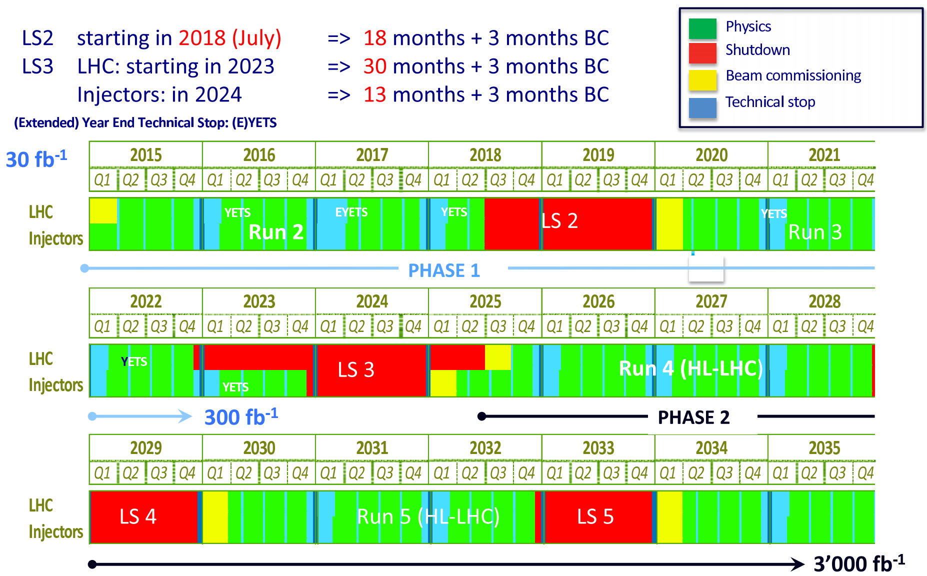

Figure 3: LHC 20-year roadmap (Courtesy F. Bordry).

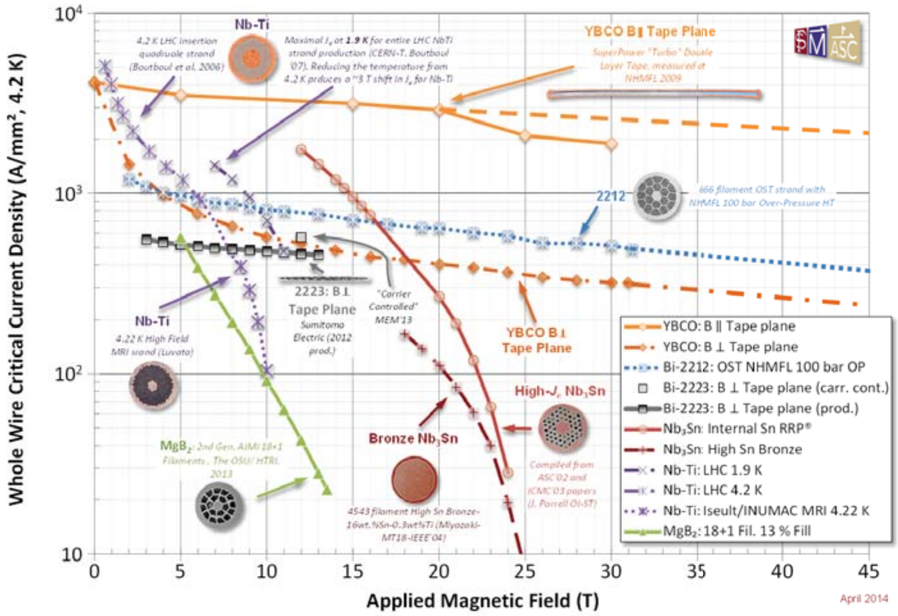

Figure 4: Engineering critical current density in various types of superconducting wire versus the applied field, as of 16 April 2014 [5], illustrating the transition from $Nb-Ti$ to Nb_3Sn (Courtesy P. J. Lee, NHMFL).

4. Future Circular Hadron Colliders (FCC-hh, SPPC)

The 2013 Update of European Strategy for Particle Physics has emphasized, as its second highest priority, after the full exploitation of the LHC, that "... to propose an ambitous post-LHC accelerator project..., CERN should undertake design studies for accelerator projects in a global context,... with emphasis on proton-proton and electron-positron high-energy frontier machines ..." [6]. In response to this demand, the global Future Circular Collider (FCC) design study was launched in a meeting at the University of Geneva in February 2013 [7, 8]. The goal of the FCC study is to complete a Conceptual Design Report (CDR) together with some preliminary cost estimates by the end of 2018, in time for the next European Strategy update, and by when physics results from the LHC Run 2 should be available.

The US P5 recommendations from 2014 include the observation that "a very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window [10–20 years] ..." [9].

Meanwhile, on the other side of the world, also in 2014, the Chinese High Energy Physics Association concluded that a "Circular e^+e^- Circular Higgs Factory (CEPC) together with a Super pp Collider (SPPC) is the first choice for China's future high energy physics accelerator" [10].

The long-term goal of the FCC study is a 100-TeV hadron collider (FCC-hh), which determines the infrastructure needs. With a target dipole field of 16 T, expected to be within the reach of Nb_3Sn technology (Fig. 4), the ring circumference must be about 100 km.

A schematic of the FCC tunnel is presented in Fig. 5. This new tunnel could also host a high-luminosity circular e^+e^- collider (FCC-ee), as a potential intermediate step. Concurrent operation of hadron and lepton colliders is not foreseen, however. The FCC study also considers aspects of *pe* collisions, as could be realized, e.g., by colliding the electron beam from an energy recovery linac (ERL) with one of the two FCC-hh hadron beams.

The focus of the Chinese project is on the e^+e^- Higgs factory (CEPC), whose tunnel could later host a hadron collider (SPPC) operating concurrently, and also allow for ring-ring hadron-lepton collisions [11]. The CEPC tunnel circumference has been chosen to be 54 km, i.e. substantially smaller than for FCC. For this reason, the SPPC necessitates higher dipole fields of 20 T in order to exceed a *pp* collision energy of 50 TeV in the centre of mass. Such a field cannot be realized with Nb_3Sn. Instead the SPPC magnets will be based on high-temperature superconductor.

Table 1 compares key parameters of FCC-hh with those of LHC, HL-LHC and SPPC. The FCC-hh design considers parameter sets for two phases of operation: Phase 1 (baseline) aims at a peak luminosity of 5×10^{34} cm^{-2}s^{-1}, delivering 250 fb^{-1} per year on average. In Phase 2 (ultimate) the peak luminosity is increased by a factor of five 2.5×10^{35} cm^{-2}s^{-1} and the average luminosity by a factor of four to 1000 fb^{-1} per year. The transition from FCC-hh Phase 1 to Phase 2 is realized without any increase in the beam current, by reducing β^* from 1.1 to 0.3 m, and by accepting a three times larger beam-beam tune shift ($\Delta Q_{\rm tot} = 0.03$ instead of 0.01; the larger value was already demonstrated at the LHC [12]. Taken together, the total FCC-hh luminosity will amount to a few 10's of ab^{-1} accumulated over about 25 years of operation. Synthesizing the discussions from several theory workshops, targeting an integrated luminosity goal of 10–20 ab^{-1} for the FCC-hh seems well justified [13].

Figure 6 shows the historical evolution of centre-of-mass collision energies extrapolated into the future. Figure 7 presents a similar graph for the ever increasing peak luminosity.

Table 1: Key parameters of LHC, HL-LHC, FCC-hh, and SPPC.

parameter	LHC (*pp*)	HL-LHC	FCC-hh	SppC
c.m. energy [TeV]	14	14	100	63.4
ring circumference [km]	26.7	26.7	100	54.4
arc dipole field [T]	8.33	8.33	16	20
number of IPs	2+2	2+2	2+2	2
initial bunch intensity [10^{11}]	1.15	2.2	1.0	2.0
beam current [A]	0.58	1.11	0.5	1.0
peak luminosity/IP [10^{34} cm^{-1}s^{-1}]	1	5 (levelled)	5–25	12
stored energy per beam	≈0.4	0.7	8.4	6.6
synchrotron radiation [W/m/aperture]	0.17	0.33	28.4	57.8
bunch spacing	25	25	25 or 5	25
IP beta function $\beta^*_{x,y}$ [m]	0.55	0.15	1.1–0.3	0.75
initial normalized rms emittance [μm]	3.75	2.5	2.2	4.1

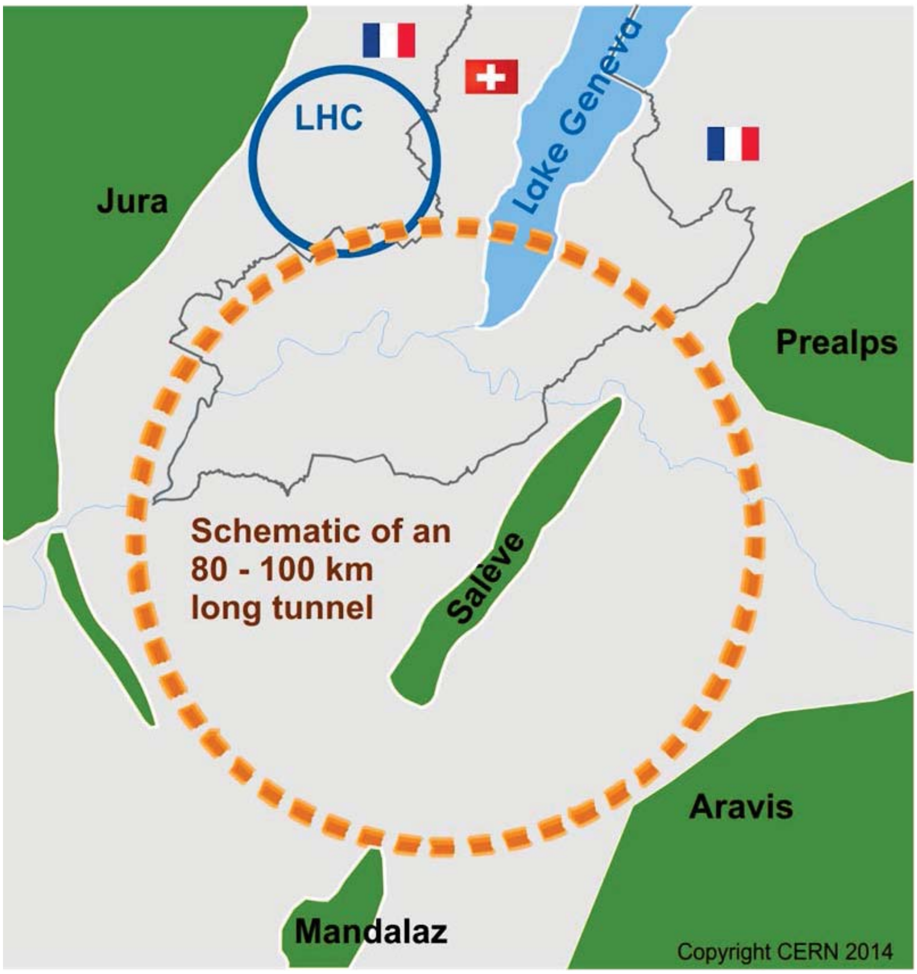

Figure 5: Schematic of a 100-km tunnel for a highest-energy circular collider in the Lake Geneva basin.

5. Future Circular Lepton Colliders (FCC-ee, CEPC)

Table 2 compiles a few key parameters of FCC-ee, CEPC, and the past LEP2 collider.

The range of values for FCC-ee reflects the various operating modes spanning from the Z pole at 91 GeV ("TeraZ factory") over the WW threshold at 160 GeV, the maximum Higgs production at 240 GeV (Higgs factory) to operation at or above the $t\bar{t}$ threhsold (top factory) [15]. Keeping the synchrotron radiation power constant, equal to 50 MW per beam, leads to greatly different beam currents at the various beam energies, i.e. a few mA (like LEP) for $t\bar{t}$ running and more than 1 A (resembling the B factories KEKB and PEP-II) at the Z pole. The bunch intensities and emittances can be adapted for the different modes of operation, e.g., through optics changes in the arcs, along with the collision scheme, so that the luminosity varies with the beam energy E roughly as $1/E^2$; see Fig. 8.

One of the limitations, especially at the lower energies, is the conventional beam-beam effect. This limit can be overcome by a crab waist scheme, as has been demonstrated at the DAFNE collider in Frascati [16]. Crab-waist collisions can increase the FCC-ee luminosity at the Z pole

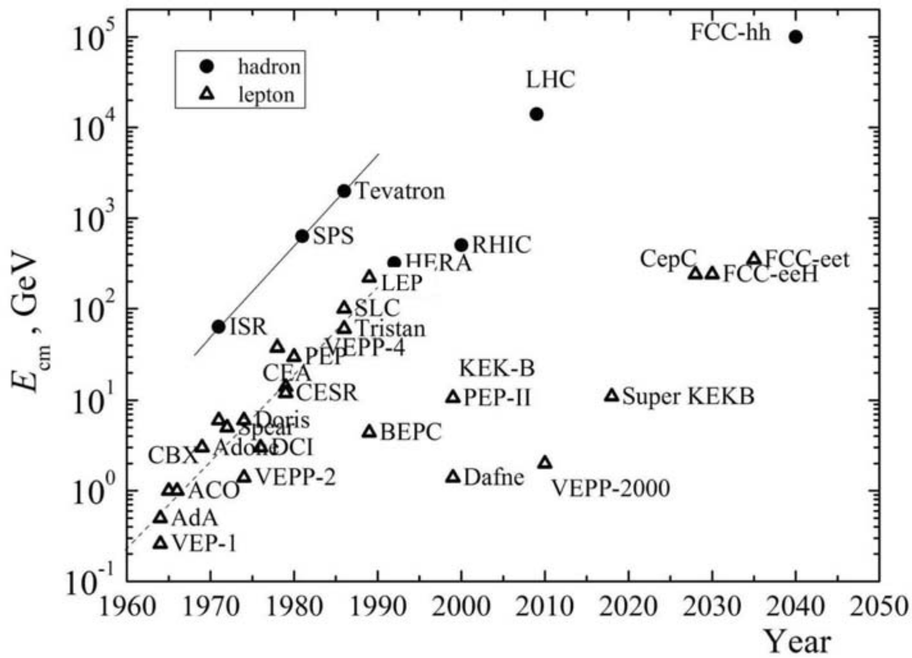

Figure 6: Collider energy vs. year including the proposed FCC hadron and lepton colliders [14] (Courtesy V. Shiltsev).

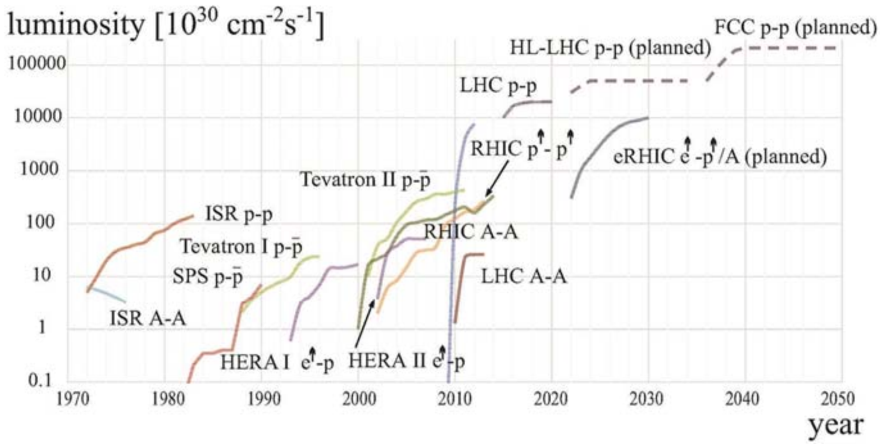

Figure 7: Past and future hadron-collider peak luminosity in units of 10^{30} cm^{-2}s^{-1} vs. year (Courtesy W. Fischer).

by an order of magnitude [17]. A new limit encountered at high energy is beamstrahlung [18], i.e. synchrotron radiation emitted in the field of the oppositing bunch during the collision. To mitigate the effects of beamstrahlung, the bunches need to be sufficiently long. Transversely they should be as flat as possible ($\varepsilon_y \ll \varepsilon_x$), to obtain the target luminosity at the top threshold with an adequate beam lifetime. At lower beam energy, the beamstrahlung does not affect the beam lifetime, but it increases the natural energy spread and bunch length, otherwise determined by regular synchrotron radiation in the collider arcs [19].

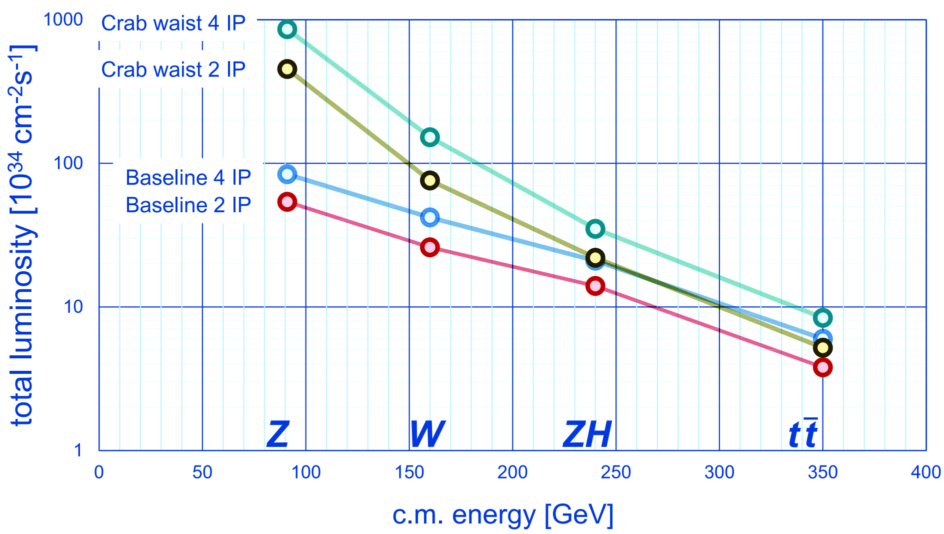

Figure 8: FCC-ee collider luminosity as a function of c.m. energy.

FCC-ee operation with monochromatization for direct Higgs production $e^+e^- \to H$ is also being considered. Monochromatization requires introducing (horizontal) dispersion at the colision point, of opposite sign for the two beams [20].

The CEPC design is optimized for operating as a Higgs factory at 240 GeV centre of mass [11]. It features a single beam pipe which severely limits the number of bunches per ring. As a consequence, the CEPC luminosity at lower energy (Z and WW operation) is likely to be orders of magnitude lower than the values forecast for the FCC-ee. Operation at the top threshold is also not presently considered for the CEPC.

Apart from the shorter-cell arc optics and the collision scheme, in particular the 50 times reduced vertical beta function at the collision point (β_y^*) contributes to the much higher luminosity of FCC-ee compared with LEP2. Figure 9 illustrates the history of β_y^* over the past several decades. Only at KEKB β_y^* was pushed below 1 cm. FCC-ee targets a tens timees lower value of 1 mm. It is interesting and reassuring that, long before FCC-ee, SuperKEKB will operate at an even lower β_y^* of 0.3 mm.

SuperKEKB, illustrated in Fig. 10, will start operation in 2016. It will not only aim for an unprecedentedly small beta function, but it also faces an even shorter beam lifetime (less than 5 minutes, dominated by Touschek scattering) than FCC-ee (around 30 min., due to radiative Bhabha scattering). Operating SuperKEKB requires an efficient top-up injection scheme, an adequate positron production rate, and a sufficiently large dynamic momentum acceptance. In short, all the key aspects of the FCC-ee design not already addressed by LEP2 or KEKB will be demonstrated at SuperKEKB.

6. Future Circular Lepton-Hadron Colliders (LHeC, FCC-he)

In 2012 a Conceptual Design Report was published for a Large Hadron electron Collider (LHeC) [22], where an electron beam from an energy-recovery linac collides with one of the proton beams circulating in the LHC, targeting a luminosity of 10^{33} cm^{-2}s^{-1}. Motivated by the dis-

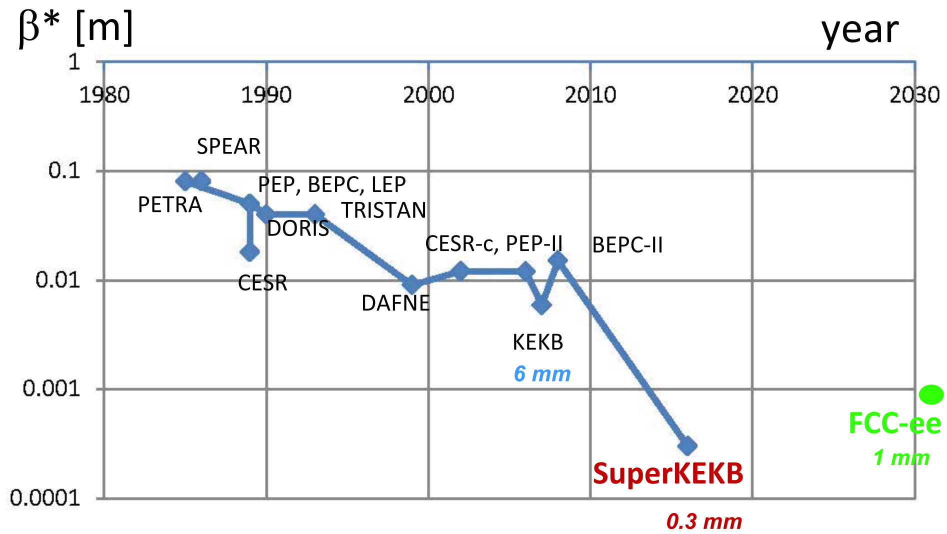

Figure 9: β^* at various e^+e^- colliders versus the calendar year, including a forecast to SuperKEKB and FCC-ee.

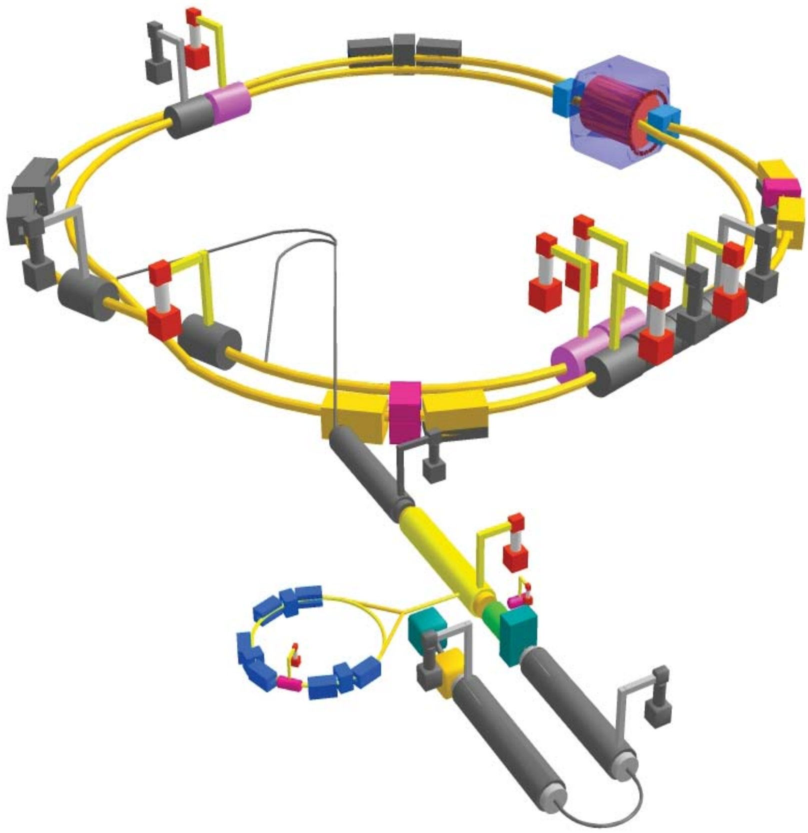

Figure 10: SuperKEKB – an FCC-ee demonstrator [21].

Table 2: Key parameters of LEP2, FCC-ee, and CEPC.

parameter	LEP	FCC-ee	CEPC
c.m. energy [GeV]	90–209	90–350	240
ring circumference [km]	26.7	100	54.4
arc dipole field [T]	0.11	0.014–0.055	0.066
number of IPs	4	2 or 4	2
bunches / beam	4	40–130,000	50
beam current [A]	0.003	0.007–1.5	0.017
peak luminosity/IP [10^{34} cm^{-1}s^{-1}]	0.0012	1.5–280	2.0
energy loss / turn [GeV]	3.34	0.03–7.55	3.11
synchrotron radiation power [MW]	22	100	100
vertical IP beta function β_y^* [mm]	50	1.0	1.2
horizontal geometrical rms emittance [nm]	22	1–30	6

covery of the Higgs boson at the LHC in the same year, and profiting from the HL-LHC upgrade, parameters for 10–20 times higher luminosity (“LHeC Higgs factory”) have also been developed [23]. Furthermore, the LHeC could be reconfigured and operated as a $\gamma\gamma$ Higgs factory, called SAPPHIRE [23, 24].

A configuration similar to LHeC is considered for the FCC, i.e., collisions between an electron beam from a recirculating energy-recovery linac (ERL) with one of the FCC-hh hadron beams (FCC-he). The ERL could be the one of the LHeC, with a bypass extension connecting it to the FCC tunnel infrastructure, or else a facilty built on purpose. The electron beam energy would be about 60 GeV as for the proposed LHeC, the proton beam energy 50 TeV as for the FCC-hh. The achievable lepton-hadron luminosity, determined by the hadron beam spot size and electron beam current, is of order 10^{34} cm^{-2}s^{-1} [25]. For the FCC design, the option of a ring-ring lepton-hadron collider, where the FCC-hh and FCC-ee would simultaneously occupy space in the 100-km tunnel, is not considered at present.

At the CEPC-SPPC electron-proton collisions may be obtained by colliding a lepton beam stored in one of the two CEPC rings with a SPPC hadron beam, either in parallel to pp collisions or in a dedicated mode of operation. The attainable ep luminosity ranges from 3 to 5×10^{33} cm^{-2}s^{-1}, respectively [11].

7. Global FCC Study

The FCC study is organized as an open international collaboration. It was launched, and is hosted by CERN, following the request of the European Strategy Update. The FCC collaboration is based on a general Memorandum of Understanding (MoU), complemented by specific addenda which describe activities and contributions from individual institutes. As of April 2015, 54 institutes from around the world have formally joined the FCC collaboration.

Part of the global study is co-funded by the European Commmission under a HORIZON 2020 grant (“EuroCirCol”). EuroCirCol addresses the core aspects of the hadron collider design, namely the arc and IR optics, as well as a feasibility study for two FCC-hh key technologies — the 16 T magnet program and the cryogenic beam vacuum system.

Figure 11 shows the top level breakdown structure of the FCC study, indicating the elements which are partly, or fully, included in EuroCirCol. Figure 12 presents the FCC 5-year study time line towards the CDR. The FCC Week 2016 will be organized in Rome from 11 to 15 April 2016.

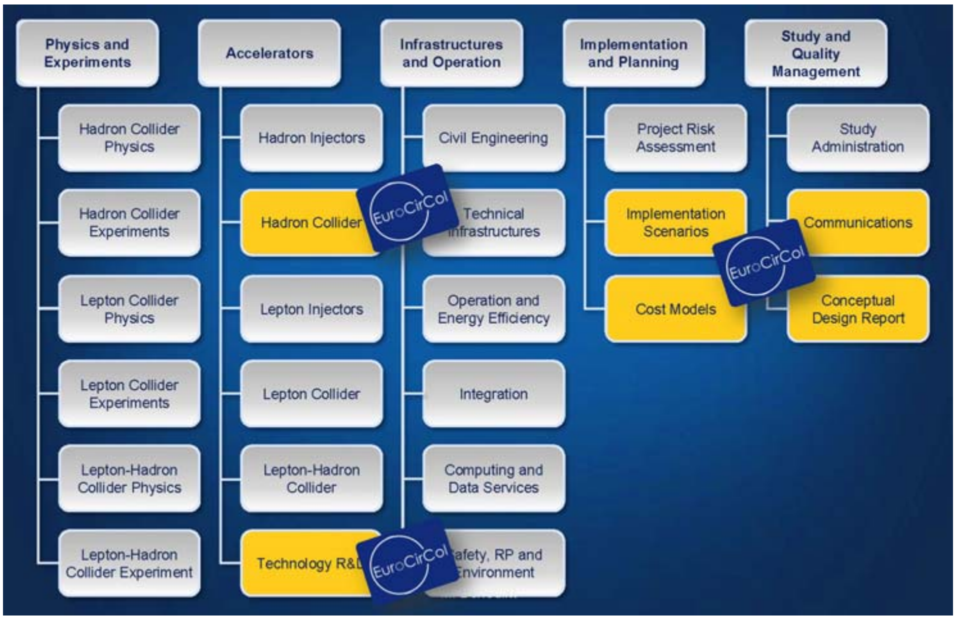

Figure 11: Work breakdown structure of global FCC study; highlighted in orange are the parts (partly) addressed by the HORIZON 2020 EuroCirCol project (Courtesy J. Gutleber).

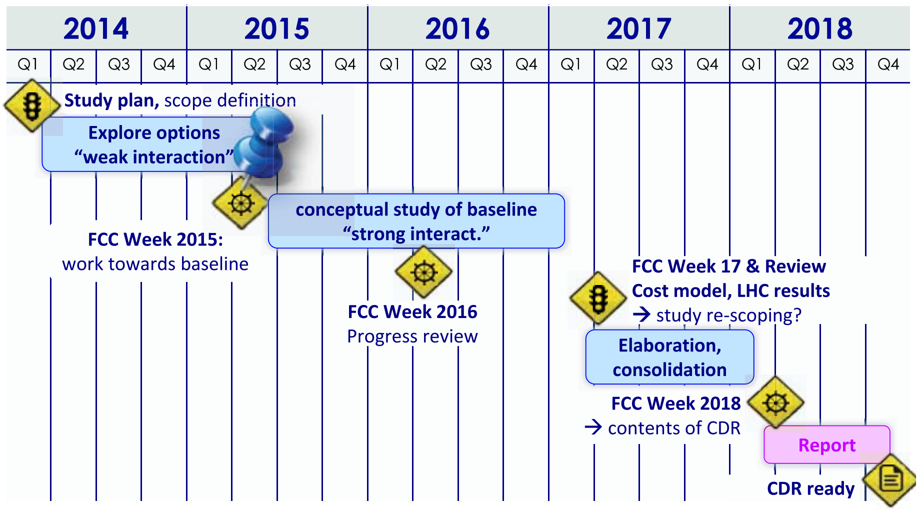

Figure 12: FCC 5-year study time line (Courtesy M. Benedikt).

8. Conclusions and Outlook

Since more than 50 years, circular colliders have been the primary tool for pushing the energy frontier on three continents. These colliders and their performances have been spectacularly successful.

From May 2015 onwards, the LHC, the present flagship collider, will deliver physics data at 13 TeV c.m. energy. Around 2023 the LHC will be upgraded for much increased luminosity. The HL-LHC upgrade aims at accumulating a total of 3000 fb^{-1} by about 2035. Given the extremely long lead-times and various historical examples, the preparation for the post-LHC period must start now.

An even more powerful circular hadron collider represents an attractive option. Indeed, it is the only path available in this century for accelerator based high-energy physics to explore energy scales of 10s of TeV.

The proposed future hadron collider, FCC-hh, exploits, and advances, the new Nb_3Sn magnet technology developed for the HL-LHC. The FCC-hh design study also promotes many other technological imnnovations, e.g., with regards to cryogenics. beam-vacuum system, etc. An alternative collider design in China, SPPC, assumes the use of higher-field (20-T) magnets based on high-temperature superconductor.

A future lepton collider, FCC-ee or CEPC, serving as Higgs, Z, W and top factory, represents an attractive intermediate step towards FCC-hh (or SPPC). and would be highly synergetic with FCC-hh, not only in terms of sharing a common tunnel infrastructure and cryogenics, or using similar superconducting radiofrequency (RF) systems and RF power sources, but also in view of the time required for the FCC-hh high-field magnet production and, perhaps, for sharpening the hadron physics program.

The suite of possibilities available at future circular colliders also includes heavy-ion collisions. and lepton-hadron collisions.

Figure 13 presents the possible evolution of the LHC/FCC complex, allowing for energy-frontier physics till the end of the 21st century, and Fig. 14 a tentative time line.

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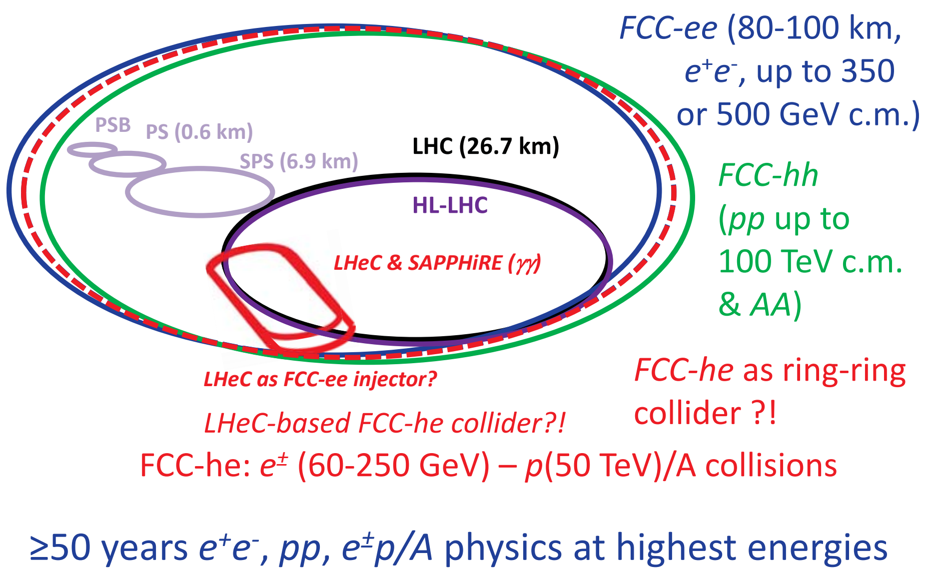

Figure 13: Possible evolution of the CERN–LHC–FCC complex.

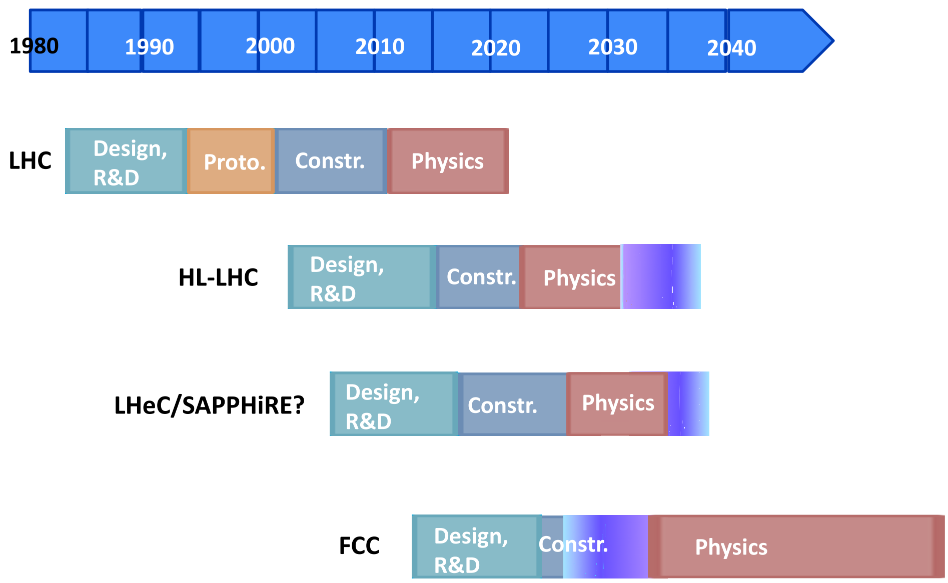

Figure 14: Tentative time line of future circular colliders at CERN.

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