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STATUS OF THE e^+e^- COLLIDER PROJECTS IN ASIA AND EUROPE: CEPC AND FCC-ee

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Abstract

Since the Higgs boson discovery at CERN, precision measurement of its properties has become the first priority in the field of High Energy Physics. Two laboratories, CERN from Europe and IHEP from China, are studying future large scale circular electron-positron colliders, namely FCC-ee and CEPC. Record luminosities are expected in the center of mass energy range from 90 to about 365 GeV. In this talk, the statuses of both projects are reviewed: Following the publication of the first CDR, FCC-ee and CEPC are entering the phase of consolidation and feasibility study. Special focus will be put on R&D plans, prototyping and key technologies.

SCIENCE MOTIVATION

The Higgs boson is a vital part of the Standard Model (SM). It is directly related to many mysteries that include the large hierarchy between the weak scale and the Planck scale, the nature of the electroweak phase transition, the origin of masses of fundamental fermions and the W, Z bosons, and the stability of vacuum. The Higgs can serve as an important portal to detect the dark matter and understand its nature. Precise measurements of the properties of the Higgs boson serve as probes of the underlying fundamental physics principles of the SM and beyond.

The discovery of the Higgs boson at the Large Hadron Collider (LHC) in July 2012 has created an excellent new opportunity for scientists to envision e^+e^- Higgs factories, by which millions of clean Higgs events and unprecedented high statistics Z, W bosons and top quark can be produced. At ~125 GeV, the Higgs boson mass makes it possible to design a Higgs factory based on the circular electron–positron collider with mature technology and high luminosity, and affordable power consumption.

TWIN PROPOSALS

Two future large circular e^+e^- colliders are being proposed, one on a greenfield site in China, the other linked to the existing CERN facilities. These are the Circular Electron Position Collider (CEPC) [1,2] and the Future Circular lepton Collider (FCC-ee) [3]. Both of these would serve as high-luminosity Higgs, precision electroweak and top factories. Either collider requires a roughly circular tunnel with a circumference of about 100 km. In a subsequent project stage, this same tunnel could later accommodate a high energy hadron collider, such as Super Proton-Proton Collider (SPPC) or FCC-hh, respectively.

Both CEPC and FCC-ee are conceived as double ring colliders, with 2 (or 4) interaction points (IPs), up to 2 radio-frequency (RF) system straights, and a tapering of the arc magnet strengths to match local energy. The two layouts are shown in Fig. 1. Both collider designs consider an asymmetric interaction region to limit SR of incoming beams towards detectors and to generate the required large crossing angle. Common use of RF systems for both beams at highest energy working points, starting from the ZH production mode. Each of the two machines is accompanied by a full-energy top-up booster ring situated in the same large tunnel.

FCC-ee

The FCC design efforts were launched and extended in response to the latest two Updates of the European Strategy for Particle Physics, in 2013 and 2020 [4, 5]. A comprehensive Conceptual Design Report (CDR) for the FCC was published in 2019 [3, 6, 7], reporting the physics cases, the design of the lepton and hadron colliders, along with the related technologies and infrastructures. The proposed FCC integrated project, consisting of FCC-ee followed by FCC-hh, is inspired by the successful past Large Electron Positron collider (LEP) and Large Hadron Collider (LHC) projects at CERN. It represents a comprehensive long-term programme maximising physics opportunities.

Following the 2020 European Strategy Update, in 2021 the CERN Council has launched the FCC Feasibility Study (FS), that will address not only the technical aspects of the accelerators, but also, and in particular, the feasibility of tunnel construction and technical infrastructures, and the possible financing of the proposed future facility. As requested by the European Strategy, the FCC Feasibility Study is organized as an international collaboration, with presently about 150 participating institutes plus 30 industrial companies.

The FCC shall be located in the Lake Geneva basin and be linked to the existing CERN facilities. The 2019 FCC CDR described an FCC design with a circumference of 97.75 km, 12 surface sites, and two primary collision points. In 2021, a placement optimisation resulted in a new circumference of about 91.1 km, and a configuration with only 8 surface sites, allowing for either 2 or 4 IPs. Re-optimization of the beam parameters is in progress, taking into account the new placement, the maximum number of 4 IPs, further beam dynamics studies, and a variety of machine errors.

The FCC-ee, as the first stage of the FCC integrated project, is planned to, at first, run on the Z pole, 91 GeV c.m., for 4 years, then on the W threshold, 160 GeV, for 2 years, later on the ZH production peak, 240 GeV c.m., for 3 years, and, after a full year of shutdown, at the $t\bar{t}$ threshold, 365 GeV, for another 5 years. Additional RF systems

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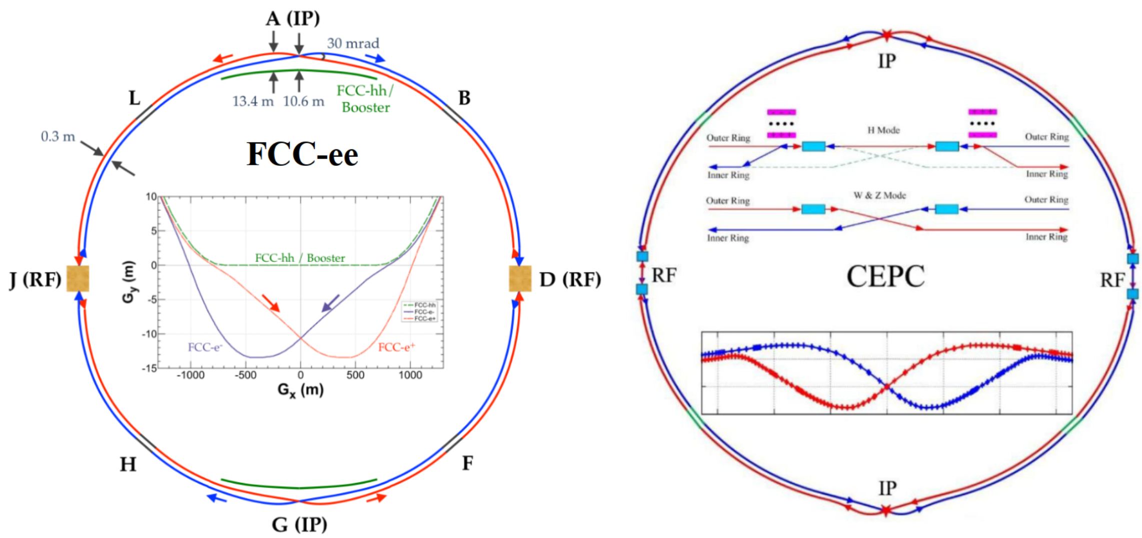

Figure 1: Layouts for FCC-ee (left) and CEPC (right).

are installed as the energy increases, and at the same time the beam current decreases. An additional optional run for direct Higgs production, 125 GeV c.m. with monochromatization is considered, and would require another couple of years of operation.

The FCC-ee luminosity ranges from ~ $2 \times 10^{36}\text{cm}^{-2}\text{s}^{-1}$ per IP on the Z pole, to ~ $1.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ per IP at the $t\bar{t}$ threshold. On the Z pole and at the WW threshold, resonant depolarisation of pilot bunches will enable an energy calibration down to 100 keV accuracy for m_Z and 300 keV for m_W , respectively. The FCC-ee parameters with two IPs are listed in the left-hand columns of Table 1.

A first beam optics was established in 2015 [8]. The optics varies with the beam energy so as to allow for a common IR layout at all energies. The crab-waist collision scheme has been chosen for the interaction region design [9]. One of the beam optics challenges for the collider is to provide an adequate dynamic aperture with small β-functions at the interaction point down to 0.1 m and 0.8 mm at the Z pole. These values, together with an ℓ^* of 2.2 m — the distance between the face of the the final quadrupole magnet to the IP —, lead to a vertical chromaticity around the IP as high as in modern B factories, that is corrected locally, by two sextupole magnets. At the $t\bar{t}$ energy, a very wide momentum acceptance is required due to the beamstrahlung emitted in the collisions. In addition, the transverse on-momentum dynamical aperture must be larger than ~ $12\,\sigma_x$ to enable top-up injection in the horizontal plane.

The beam lines in the interaction region are separated for the two beams, except for the common beam pipe over around ±2 m around the IP proper. There are no common quadrupoles in the IR. The full horizontal crossing angle is 30 mrad. The detector solenoid is 2 T and its effect on the stored beams is compensated by anti-solenoids, which cancel the $\int B_z dz$ between the IP and the faces of the final quadrupole. The flexibility of the IR optics is obtained by splitting the first quadrupole into three segments and by modulating their sign and strength according to the beam energy. One of the main guidelines for the IR design has been to keep the critical energy of the synchrotron radiation (SR) from bending magnets below 100 keV up to about 500 m from the IP for the incoming beam and to locate the last upstream dipole no closer than 100 m from the IP. These requirements stem from the LEP2 experience, where manageable detector backgrounds were obtained with a critical photon energy of at most 72 keV over the last 260 m from the IP. An asymmetric optics allows the beams to arrive from the inner ring to the IP, and to be then bent strongly after the IP to enter the opposing outer ring. Thereby, the critical energy requirement is met with a large crossing angle.

FCC-ee R&D on Key Technologies

The main technological systems required for the FCC-ee are the 400 and 800 MHz superconducting (SC) radiofrequency (SRF) systems, the energy efficient arc magnets, the arc vacuum system, a few special magnets for the interaction region, and the positron source [10]. The 400/800 MHz RF systems proposed for FCC-ee are state of the art. The 400 MHz Nb/Cu cavities are based on the technology developed for LEP and LHC. A first prototype of 5-cell 800 MHz bulk-Nb cavity constructed by JLAB met the design specifications. R&D is necessary to reduce cost and increase reliability of both the cavities and the RF power sources.

The FCC-ee arc vacuum system is based on a round copper vacuum chamber featuring winglets for photon stops, and ultra-thin NEG coating. Prototypes of the energy-efficient twin-aperture arc dipoles and quadrupoles were built and their field properties measured. A prototype of the SC canted-cosine-θ final focus quadrupole has also been built. The production rate required from the positron source is comparable to those achieved at the SLC and at SuperKEKB.

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Table 1: Preliminary key parameters of FCC-ee (left) as evolved from the CDR parameters, for scenarios with 2 IPs (K. Oide, 2021) and of CEPC (right). The beam lifetime represents the combined effect of radiative Bhabha scattering and beamstrahlung. For FCC-ee, an alternative scenario with 4 IPs is under study, with about 10-30% lower luminosity per collision point, 1.7–1.9 times higher expected total integrated luminosity, and a factor 1.7 shorter beam lifetime.

	FCC-ee				CEPC			
Running mode	Z	W	ZH	$t\bar{t}$	Z	W	ZH	$t\bar{t}$
Number of IPs	2				2			
Circumference (km)	91.2				100.0			
Beam energy (GeV)	45.6	80	120	182.5	45	80	120	180
Bunches/beam	12000	880	272	40	11951	1297	249	35
Beam current [mA]	1280	135	26.7	5.0	803.5	84.1	16.7	3.3
Lum. / IP [10^{34}cm^{-2}s^{-1}]	193	22.0	7.73	1.31	115	16	5	0.5
Synchr. Rad. Power [MW]	100				60			
Rms b. length (SR) [mm]	4.38	3.55	3.34	2.02	2.5	2.5	2.3	2.2
(+BS) [mm]	12.1	7.06	5.12	2.56	8.7	4.9	3.9	2.9
Rms en. spread (SR) [%]	0.039	0.069	0.103	0.157	0.04	0.07	0.10	0.15
(+BS) [%]	0.108	0.137	0.158	0.198	0.130	0.14	0.17	0.20
Rms hor. emit. ε_x [nm]	0.71	2.17	0.64	1.49	0.27	0.87	0.64	1.4
Rms vert. emit. ε_y [pm]	1.42	4.32	1.29	2.98	1.4	1.7	1.3	4.7
Hor. IP beta β_x^* [mm]	100	200	300	1000	130	210	330	1040
Vert. IP beta β_y^* [mm]	0.8	1.0	1.0	1.6	0.9	1.0	1.0	2.7
Beam lifetime rad. Bhabha & BS [min.]	35	32	9	16	80	55	20	18

The FCC-ee R&D aims at developing more efficient, novel technologies, which could decrease costs, lower the energy consumption, and reduce the environmental impact. Present R&D efforts towards these goals include high-efficiency continuous wave radiofrequency power sources, high-Q SC cavities for the 400-800 MHz range, and possible applications of HTS magnets.

As part of the FCC R&D plan, an arc half-cell mock up is foreseen to be constructed by 2025. It will include girder, a vacuum system with antechamber and pumps, dipole, quadrupole and sextupole magnets, beam position monitors, cooling and alignment systems, and technical infrastructure interfaces. Also for the interaction region the construction of a mock up is proposed, consisting of the central beam pipe, first SC quadrupole with its cryostat, support structures, stabilization system, and remotely controlled flanges.

FCC-ee Schedule

The technical schedule of the FCC integrated project foresees the start of FCC tunnel construction around the year 2030, the first e^+e^- collisions at the FCC-ee in the early or mid 2040s, and the first FCC-hh hadron collisions by 2065–70 (see Fig. 2).

CEPC

The Institute of High Energy Physics (IHEP) in Beijing, in collaboration with a number of other institutes in China as well as in many different countries, launched a study of the Circular Electron Positron Collider (CEPC).

The CEPC consists of a linear accelerator (Linac), a positron damping ring (DR), the Booster, the collider and several beam transport lines. The Booster ring is used by both electrons and positrons, while they are being injected into each of the two separated collider rings. The Linac and DR serve as part of the pre-injector complex. The Linac length is about 1.2 km. The pre-injector will be located at the ground level, while the Booster and Collider will be built in an underground tunnel. Careful and abundant efforts have been spent on balancing the construction investment, the operation cost, the data acquisition efficiency and the upgrade potential to allow for the later accommodation of the Super Proton Proton Collider (SPPC). As a compromise between these considerations, the optimum underground tunnel circumference was determined to be 100 km. Like for FCC-ee, the CEPC tunnel, at a depth of approximately 100 m, is shared by the Booster and the Collider ring.

Because of the high electron beam energy (~ 120 GeV) and high beam current, sufficient synchrotron photon flux is achievable with photon energy up to 300 MeV, three orders of magnitude higher than current synchrotron light sources. The CEPC can also provide high energy synchrotron gamma light line for multi-disciplinary sciences.

There are 8 straight sections in the collider ring: as for the FCC-ee, two of these accommodate the RF station, which at the Higgs energy and above are shared by the electrons and the positrons. Two straight sections host the CEPC interaction regions. The four other straights are used for injection & extraction sections, etc.

Similarly to FCC-ee, four distinct operation energies are foreseen: 45.5 GeV for Z, 80 GeV for W, 120 GeV for Higgs and eventually 180 GeV for $t\bar{t}$. In the W and Z operation

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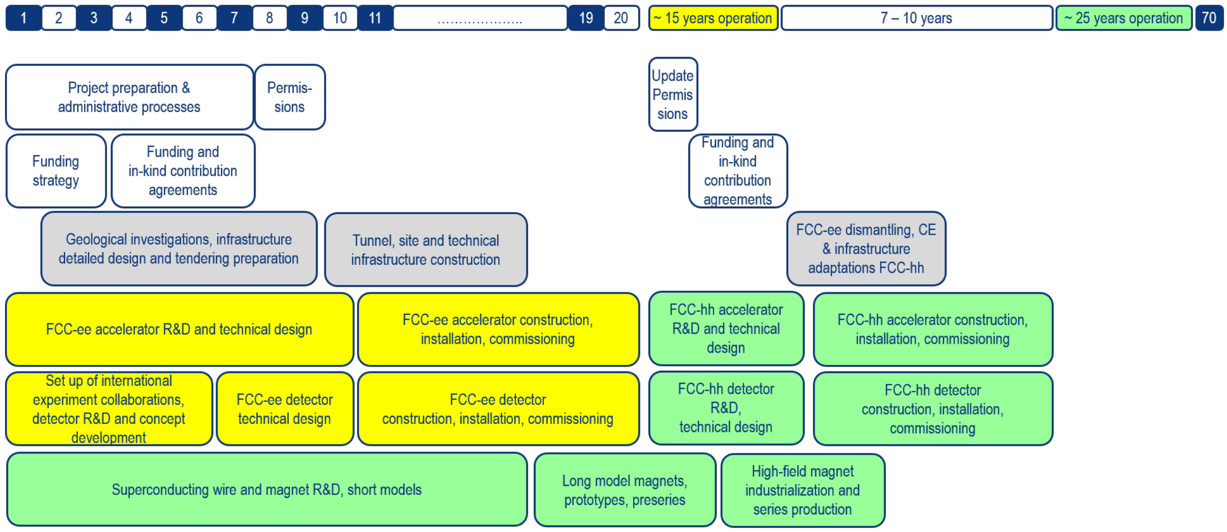

Figure 2: Technical schedule of the FCC integrated project with year 1 equal to 2021 (M. Benedikt).

modes, the beam is only injected from the booster to the collider with an off-axis injection scheme. For the Higgs operation mode, the beams are injected as well as extracted two times between the collider and the booster. The injection always is on-axis, whereas the extractions are off-axis.

The Booster uses 1.3 GHz SC cavities to raise the beam energy. The collider employs 650 MHz SC cavities to compensate the energy loss due to synchrotron radiation. Two long straight collider sections are hosting the RF stations. For the Higgs operation mode, these sections are used for both electron and positron beams. This achieved through the installation of two electrostatic deflectors, which combine and separate the beams at the straight entrance and exit. For the lower energy W and Z operation modes, one of the RF sections is bypassed for each beam, since a much lower RF voltage is needed here, and since, by separating the RF sections, the machine impedance is reduced.

The CEPC parameters are listed in the right column of Table 1. The luminosity is mainly limited by the SR power, which is chosen as 30 MW per beam, in order to reduce the electrical power consumption. However, the design reserves the possibility of upgrading to 50 MW operation and then the luminosities will increase proportionally, reaching a level similar to FCC-ee, of not exceeding it.

CEPC R&D on Key Technologies

The CEPC design team is carrying out extensive R&D on the key technologies. Significant progress has been made in many areas, including the SRF cavities, high efficiency P-band klystrons, and high field superconducting magnets.

CEPC requires two types of SRF cavities, the 1.3 GHz cavities for the booster and 650 MHz cavities for the collider. Extremely high quality factor ($> 1 \times 10^{11}$ up to 20 MV/m at 2 K) has been obtained on several medium-temperature furnace treated (mid-T) 650 MHz single cell cavities; the best cavity shows a Q value of 6.4×10^{10} for a gradient of 31 MV/m at 2 K, which is the highest quality factor in the world. The low-level RF (LLRF) system of the CEPC 650 MHz test cryomodule with two 2-cell cavities is under commissioning and a high-power test is foreseen in July 2022. The CEPC booster 1.3 GHz 9-cell cavities exhibit a quality factor of 4.7×10^{10} for a gradient of 24 MV/m at 2 K, which also is one of the highest factors in the world and exceeding the CEPC requirement. These cavities are now undergoing an industrialization process, in synergy with domestic CW Free Electron Laser projects. A complete high Q cryomodule will be ready for assembly in August, including the vacuum vessel, upper cold mass, eight high Q mid-T cavities with helium vessel and magnetic shield, input couplers, tuners, SC magnet, BPM etc., as well as the various associated tooling and cryogenic, HLRF and LLRF systems.

The conversion efficiency of the RF power sources is crucial for reducing the operation cost. CEPC aims at building a 650 MHz klystrom with 800 kW CW output power and 80% efficiency. Three prototypes were developed to accomplish this goal. The energy conversion efficiency of the first klystron prototype reached 62%, the standard level. It is the first domestic klystron in P-band, fulfilling the minimum needs of CEPC. The second prototype aims at 75% efficiency. Its conditioning and test are currently in process. So far, it has achieved an efficiency of 67.8% and a CW power of 547 kW. The third prototype adopts the multi-beam scheme (MBK), and its efficiency is expected to be around 80%. Presently, this prototype is being manufactured.

In parallel, already preparing for SPPC, a combined-coil SC magnet (NbTi+Nb_3Sn) has demonstrated a maximum field of 12 T. Another high-field dipole magnet prototype is under manufacture, aiming to reach 16 T at 4.2 K with Nb_3Sn coils plus HTS insert coils. The outside Nb_3Sn coils are scheduled to be ready for the performance test at the end of 2022, and the HTS insert coils will be ready for testing in the middle of 2023. The prototype HTS cable for the insert coils has been fabricated and tested at 77 K, reaching

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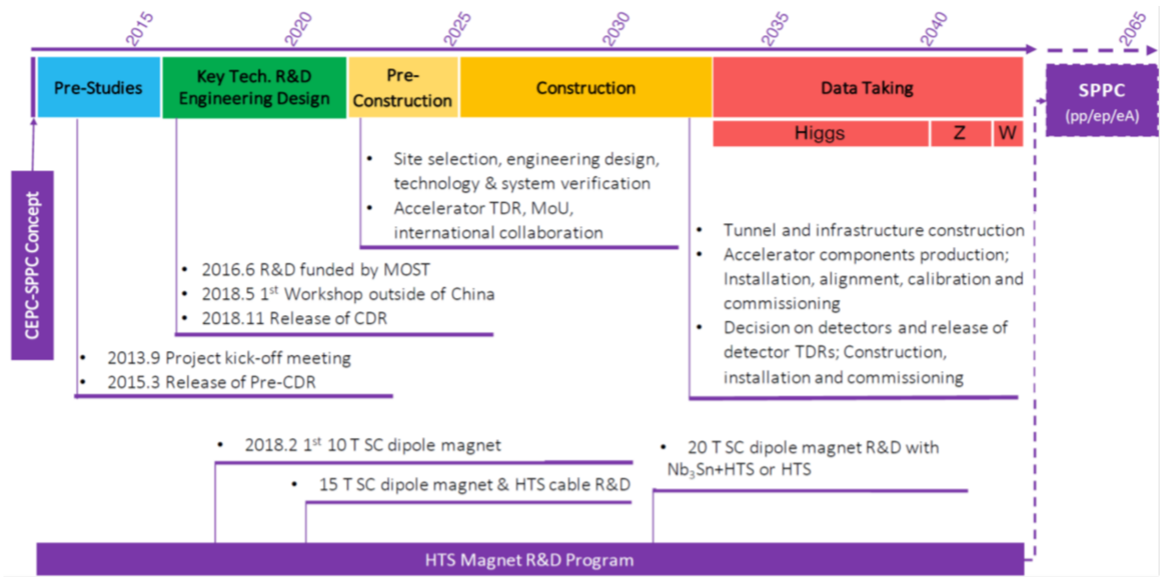

Figure 3: Technical schedule of the CEPC project.

over 2000 A. Production of the full functional HTS cable will begin soon. Some new solenoid coils from iron based superconductor (IBS) have been fabricated and tested at 32 T recently. The highest current I_c reached was 60 A, which represents a new record for IBS high field coils.

In addition to the afore-mentioned advanced technologies, CEPC has developed other important prototypes, including the dual aperture dipoles and quadrupoles, weak field dipoles for the booster, electrostatic deflector, advanced copper acceleration cavities, high power cryogenic refrigerator, etc. Several technical difficulties were overcome and the mass production technology was validated. Moreover, through other large accelerator facilities under IHEP responsibility, such as BEPCII, Chinese Spallation Neutron Source (CSNS), High Energy Photon Source (HEPS), etc., a large number of key technologies for CEPC have been fully developed and deployed in actual accelerator operation, including different types of instrumentation, magnet power supplies, vacuum system key technologies, kicker magnets, and so on.

CEPC Schedule

The CEPC study group is carrying out an extensive R&D program to soon complete the Technical Design Report of the CEPC accelerator. A comprehensive engineering design of all relevant components will start in the near future. The outline of the CEPC schedule, drafted in lock step with China's 5-year plan timing, is shown in Fig. 3.

SYNERGIES

Numerous possible synergies exist, and could be exploited, between the CEPC and FCC-ee designs. Strategically, joint effort and collaboration in the following areas may offer the greatest reward for the two circular collider projects: (1) important technical areas for circular e^+e^- colliders, in particular with regard to energy saving and cost reduction; (2) challenging domains that may limit the luminosity performance, taking into account the experience at previous and present colliders, e.g., at SuperKEKB; (3) new and innovative approaches that may bring the circular collider technology and/or performance to the next level, e.g., advanced SRF systems with higher gradient (for example, thin Nb_3Sn films on copper), the development of magnets based on high-temperature superconductors, and, more exotically, the possible use of plasma wakefield acceleration in part of the injector complex; (4) parallel or shared prototyping of key hardware components, such as highly-efficient klystrons, low-field dipole magnets for the full-energy booster, etc.; (5) instrumentation and infrastructure enabling the particle physicists to collect, store and analyze collision data under the best possible conditions; and (6) independent cross-checks of design concepts and simulation results.

Looking at a longer time scale, the FCC-ee or CEPC booster rings could also be used to deliver 45 GeV positrons at a high rate, for the production of low-emittance muon beams through positron annihilation [11]. Such muons could then used for a muon collider, perhaps in the 22ns century. The luminosity of such a collider FCC-$\mu\mu$ (or perhaps CMC — Circular Muon Collider in China) could be optimized through a combination of several new concepts [12].

CONCLUSIONS

Both FCC-ee and CEPC are compelling options for a future Higgs, electroweak and top factory. Either machine would also be the necessary first step on the way towards a future hadron collider (FCC-hh or SPPC), which would become the next high energy frontier machine.

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