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THE FUTURE CIRCULAR COLLIDER AND PHYSICAL REVIEW ACCELERATORS & BEAMS

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Abstract

The proposed integrated program of the Future Circular Collider (FCC) goes a huge step beyond LEP and LHC. The FCC consists, in a first stage, of an energy- and luminosity-frontier electron-positron collider, which will operate at centre-of-mass (c.m.) energies from about 90 to 365 GeV, and serve as electroweak factory. The second stage of the FCC will be a 100 TeV proton collider based on novel high-field magnets. A similar project is being proposed in China.

In parallel to the development of future colliders, also the field of publications is undergoing profound changes. Physical Review Accelerators and Beams (PRAB) was founded in 1997 as a pioneering all-electronic diamond open-access journal, far ahead of its time. For many years PRAB was the fastest growing journal in the Physical Review family. Authors, editors and referees are highly internationalized.

In this paper, on the occasion of the acceptance of the 2019 USPAS Prize for Achievement in Accelerator Science and Technology, I sketch the history, status, and challenges of FCC and PRAB.

FCC: FUTURE CIRCULAR COLLIDERS

Hadron colliders with collision energies far exceeding those of the Large Hadron Collider (LHC) have been considered since decades, e.g. [1–6]. A European workshop in 2010 again highlighted the cost advantages of a tunnel larger than the LHC's [7]. With first hints of a Higgs boson of mass around 125 GeV, in 2011 a circular Higgs factory e^+e^- collider was proposed [8], whose performance would equally profit from a larger ring circumference.

In 2014, the Future Circular Collider study (FCC) was launched in response to the 2013 Update of the European Strategy for Particle Physics (ESPP). The emerging global FCC collaboration has been developing a ~100 km tunnel infrastructure in the Geneva area, linked to CERN, comprising a highest-energy highest-luminosity circular e^+e^- collider (FCC-ee) as a potential first step, and a pp-collider (FCC-hh) as the long-term goal, the latter defining the infrastructure requirements. Reaching the pp target energy of 100 TeV in a ring of 100 km circumference requires dipole magnets with a field of about 16 T, which is achievable with Nb_3Sn as superconductor. The FCC study also includes a High-Energy LHC (HE-LHC) based on FCC-hh magnet technology, the corresponding ion colliders plus a number of lepton-hadron collision options.

In late 2018 the FCC Conceptual Design report was released, in time for the next ESPP Update. It covers the physics opportunities [9], the lepton collider FCC-ee [10], the hadron collider FCC-hh [11], and the HE-LHC [12].

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The FCC CDR results have led to an integrated program plan [13], where first the FCC-ee will operate for about 15 years, later followed by 25 years of FCC-hh operation. The entire FCC schedule extends almost through the end of the 21st century. This cost-effective staged long-term strategy of FCC-ee/FCC-hh, or CEPC/SPPC, is highly reminiscent of the successful earlier LEP-LHC sequence at CERN: The LEP design started in the 1970s and LHC operation is expected to end in the late 2030s, spanning more than 65 years. It is noteworthy that IHEP Beijing is proposing a similar set of consecutive lepton and hadron colliders for China, also in a ~100 km tunnel, named CEPC and SPPC, respectively, albeit both with somewhat lower luminosity and lower energy reach than their FCC counterparts (e.g., CEPC without $t\bar{t}$ operation, SPPC with an initial c.m. energy of 75 TeV) [14].

Figure 1 illustrates the FCC-ee and FCC-hh layouts: The two colliders follow a common footprint over most of the 97.8 km circumference. Only around the two primary interaction points (IPs) they are separated, by up to about 10 m. This is due to the 30 mrad crossing angle of the lepton collider and its asymmetric final-focus layout with smaller bending fields on the incoming side, introduced to minimize synchrotron radiation shining towards the detector, and stronger dipole fields after the IP [15]. The full-energy lepton injector (needed for top-up injection) follows the path of the hadron collider. The separation of the footprints at the IP conveniently allows the booster to bypass the experimental detectors of the lepton collider. The total duration of FCC tunnel construction is estimated at about 7 years. The first sectors could be ready for installation of technical equipment about 4.5 years after the start of civil construction.

FCC-ee plans to operate at four different beam energies — 45.6, 80, 142 and 182.5 GeV — corresponding to the production of Z, W and H boson, and the top quark, respectively. Figure 2 sketches how FCC-ee reaches highest luminosities and energies by combining ingredients and well-proven concepts of several recent colliders: The B-factories KEKB & PEP-II demonstrated the possibility of double-ring lepton colliders, high beam currents, positron sources with the required production rates, and top-up injection. At DAΦNE, another double-ring collider, still in operation, a novel collision scheme called crab waist was implemented in 2008. The crab waist tripled the DAΦNE luminosity [16]. All future circular colliders foresee the use of the crab-waist scheme. SuperKEKB, presently under commissioning, aims at operating with an extremely low β_y^* of 0.3 mm. It has already reached β_y^* of 2 mm, about equal or close to the design values of FCC-ee. LEP has operated at the highest lepton beam energy so far; it required a significant RF voltage and experienced the effects of synchrotron-radiation photons with MeV energies. VEPP-4M and LEP pioneered the precision

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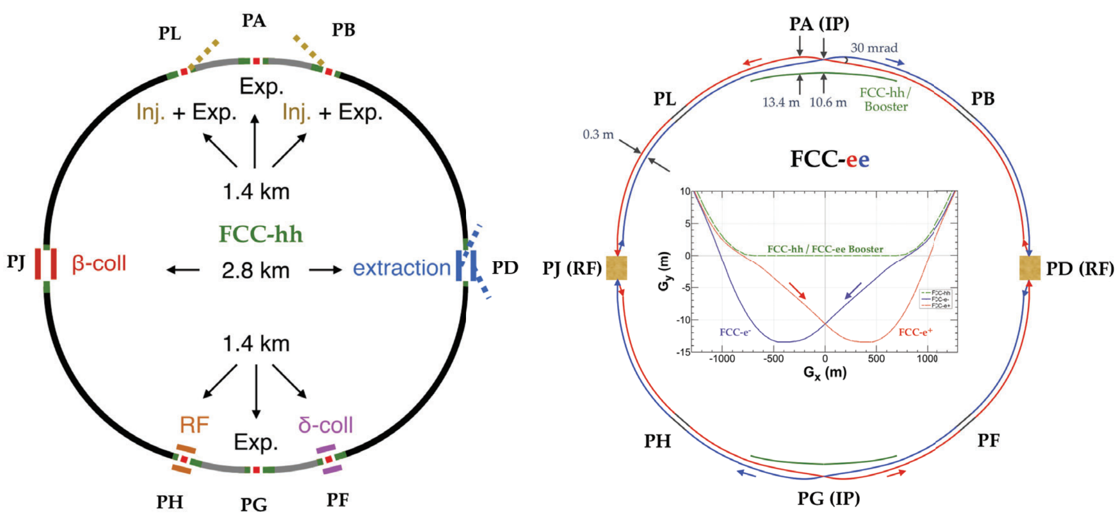

Figure 1: Collider layouts for FCC-hh and FCC-ee.

energy calibration based on resonant depolarisation, while HERA, LEP and RHIC all advanced spin gymnastics. The FCC-ee beam parameters at the Z pole resemble those of the two B factories, the FCC parameters at the $t\bar{t}$ threshold those of LEP.

Taking as the collider figure of merit the luminosity per electrical power, the FCC-ee, with an optimally staged radiofrequency system, offers by far the best performance of all proposed future lepton colliders (including linear and muon colliders) over the entire energy range from Z to $t\bar{t}$ [17].

For the hadron collider FCC-hh, the goal is to increase the performance by about one order of magnitude in both energy and luminosity w.r.t. LHC, translating to ≥100 TeV c.m. collision energy (vs. 14 TeV for LHC) and to at least 20 ab^{-1} per experiment collected over 25 years of operation (vs. 3 ab^{-1} for LHC). As seen in Fig. 3, this would correspond to similar performance increases as the transition from the Tevatron to the LHC. Table 1 compares the beam parameters of FCC-hh with those achieved in the 2018 LHC run. At FCC-hh, synchrotron radiation is much enhanced; the resulting strong radiation damping must be taken into account when maximizing the integrated luminosity [18–20].

The key technology of FCC-hh is high-field magnets, and the underlying superconductor [20]. The ongoing luminosity upgrade of the LHC (High-Luminosity LHC, HL-LHC [21]), already includes a few tens of dipole or quadrupole magnets with a peak field of 11–12 T, based on state-of-the art Nb_3Sn conductor. Various configurations of 16 T Nb_3Sn magnets for FCC-hh are under development in Europe (CEA, CERN, CIEMAT, INFN, and PSI), in the US (FNAL and LBNL, as part of the DOE's MDP program), and in Russia (BINP). In the US, FNAL has recently completed a 15 T accelerator dipole demonstrator [22]. In a staged approach, as a first step this magnet was pre-stressed for a maximum field of 14 T. In successful tests during spring 2019 its field indeed reached 14 T both at 1.9 K and at 4.5 K [22]. A second test is planned for the fall of 2019 with additional pre-stress to allow exceeding the design field of 15 T, only slightly below the FCC-hh target. Higher field is facilitated by a higher-quality conductor. Advanced US wires with Artificial Pinning Centres (APCs) produced by two different teams (FNAL, Hyper Tech Research Inc., and Ohio State; and NHMFL, FAMU/FSU) have recently reached the target critical current density for FCC, of 1500 A/mm^2 at 16 T [23, 24]. The artificial pinning centres allow for better performance; they decrease magnetization heat during field ramps, improve the magnet field quality at injection, and reduce the probability of flux jumps [25]. In parallel, after less than one year of starting their respective R&D programs, several new suppliers from Japan, Korea and Russia already achieve a high critical field B_{c2} corresponding to the HL-LHC conductor specification (28.8 T at 4.2 K).

PRAB: OPEN-ACCESS PIONEER AND COMMUNITY ORGANIZER

Research at accelerators has influenced one-third of all Physics Nobel Prizes awarded since 1939 [26]. Particle accelerators serve as similar engines of discovery for several other disciplines, e.g., chemistry, biology, and medicine. While members of the accelerator community make essential contributions to a broad range of sciences, "their peers are other accelerator scientists and their professional interests are related to accelerators and beams" [27]. Different from most other areas of science, almost all accelerator experts are working at the crossing point of universities, research centres, and industry, giving rise to highly specific collaboration models and research methodologies. To better serve and nurture this community, in 1997 the Division of Physics of Beams (DPB) of the American Physical Society (APS) [28] recommended establishing a scholarly, peer reviewed journal devoted to the science and technology of accelerators and beams that would (A) cover the full breadth of accelerators and beams, (B) be timely, (C) be inexpensive

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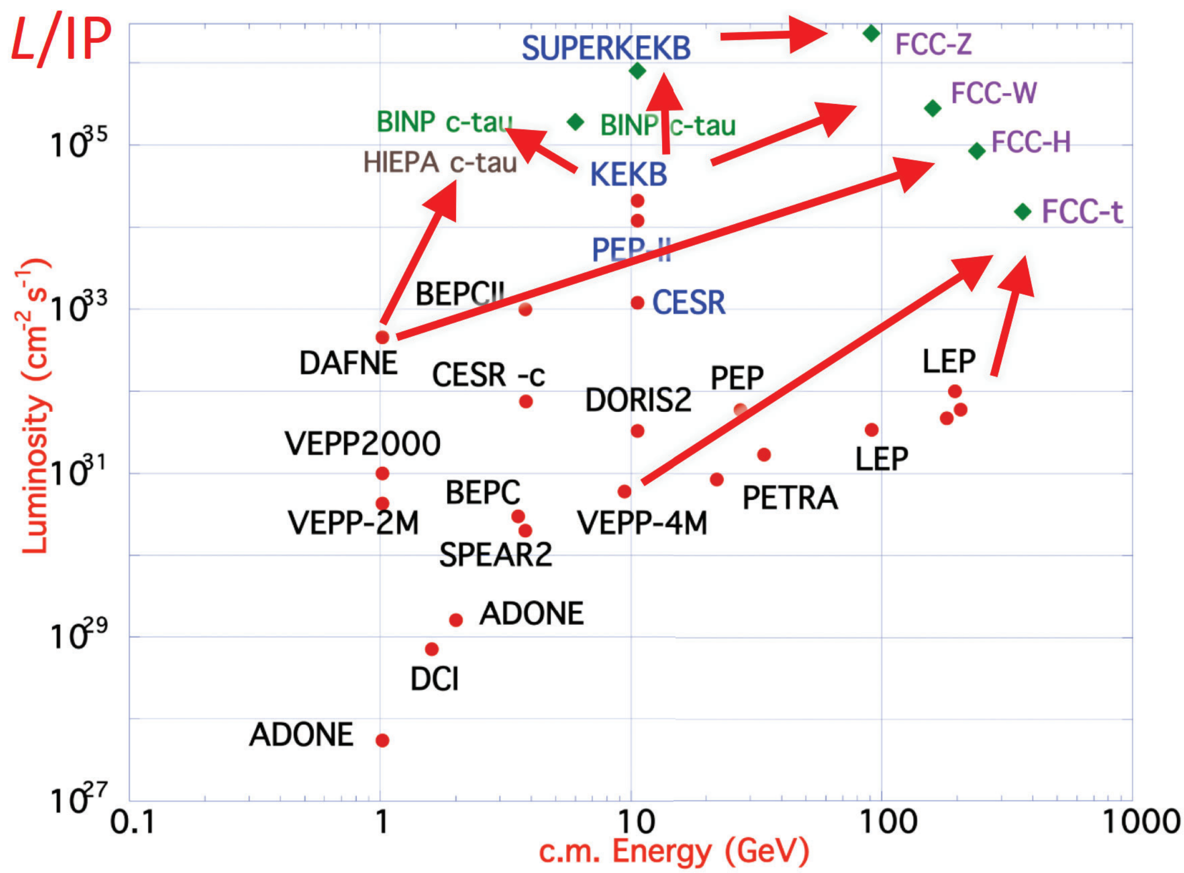

Figure 2: Luminosity vs. centre-of-mass energy for past, present and a few future circular e^+e^- colliders including the FCC-ee in its various stages (Courtesy M. Biagini).

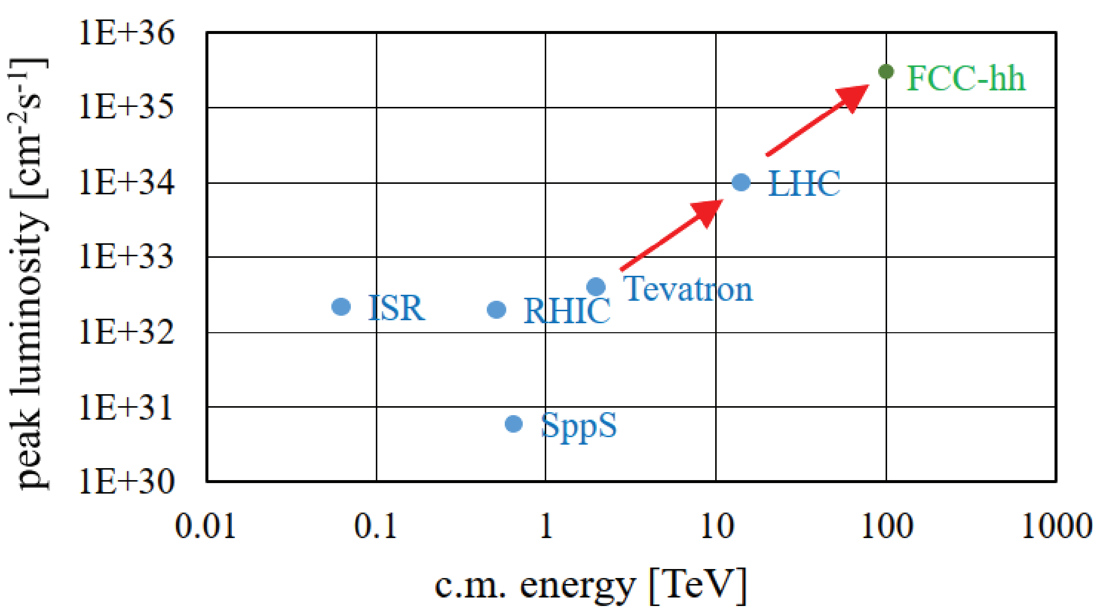

Figure 3: Luminosity vs. centre-of-mass energy for past and present (pp or p$\bar{p}$) colliders [blue] and the FCC-hh [green].

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Table 1: Parameters of the Proposed Future High-Energy Hadron Collider FCC-hh [11] Compared with the Present LHC [29]

	LHC2018	FCC-hh
Beam energy [TeV]	6.5	50
Circumference [km]	26.7	97.8
No. IPs	2(+2)	2(+2)
Int. luminosity/exp. [ab^{-1}/yr]	0.066	0.2–1.0
Peak luminosity [10^{34}/cm^2/s]	2.1	5–30
Peak event pile up	70	170–1000
Bunch spacing [ns]	25	25
Bunch length [rms, mm]	80	80
Rms IP beam size [μm]	9	6.8–3.5
Injection energy [TeV]	0.45	3.3
Transv. norm. rms emit. [μm]	1.9	2.2
IP beta function β^* [cm]	30–25	110–30
Beam-b. tune shift/IP [10^{-3}]	5	5–15
RF frequency [MHz]	400	400
Particles per bunch [10^{10}]	12	10
Bunches / beam	2556	10600
Av. beam current [mA]	550	500
Crossing angle [μrad]	320–260	104–200
Peak magnetic field [T]	8	16
SR power loss/beam [MW]	0.003	2.4
Stored energy / beam [GJ]	0.3	8
Peak AC site power [MW]	168	≤580

to promote wide circulation, and (D) be international with an international editorial board and pool of referees [27]. Martin Blume, the APS Editor-in-Chief at that time, understood the intimate connection between accelerator science and accelerator technology, and, departing from Physical Review (PR) tradition, he was willing to champion a journal covering the full spectrum of accelerator science and technology [27].

Publication of Physical Review Special Topics - Accelerators and Beams (PRST-AB), as it was called then, was approved by the APS Council in November 1997, and Robert H. Siemann of the Stanford Linear Accelerator Cente was appointed the first Editor shortly afterwards [30].

The first PRST-AB article was published on 12 May 1998. For more than a decade PRAB was the fastest growing APS journal. At present the number of PRAB publications per year is about 5 times higher than it was in the late 1990s. In parallel PRAB quickly became more international, as is illustrated in Fig. 4. In 1998, about 80% of the published articles originated in the Americas, only 15% from Europe plus Middle East, and 5% from Asia. In 2018, PRAB publications from the Americas amounted to only 33% of the total, while 41% and 23%, respectively, were contributed by the European and Asian regions, and 2% by the rest of the world (Latin America, Oceania, Middle East, Africa).

Perhaps unique in the Physical Review, following discussions between the North American and European accelerator communities in the founding years of the journals, PRAB is supported by two "Affiliated Professional Groups," the first being the APS-DPB [28], and the second the European Physical Society's Accelerator Group (EPS-AG) [31]. The APS-DPB and EPS-AG are jointly responsible for the health and vitality of PRAB by providing advice, e.g., on the membership of the Editorial Board, and by encouraging scholarly publication in accelerator science and technology.

PRAB operations are presently coordinated by a Lead Editor (the author), three Associate Editors (J. Delayen, Old Dominion U.; W. Fischer, BNL; D. Xiang, Shanghai Jiaotong U.) and a Journal Manager (D. Brodbar, APS). The Editors are assisted by an Editorial Board, which discusses policies and new initiatives. Board members also serve as referees in cases of contentions or questions on which the Editors need advice. The Editorial Board members are well-respected accelerator scientists, who represent different research specialities, strike a balance between universities and large laboratories, and connect PRAB with the three larger geographic regions. A list of present PRAB staff and Editorial Board members is posted at `https://journals.aps.org/prab/staff#ed`.

Taking into account feedback from the accelerator community, the late Robert Siemann, or "Bob" as we knew him, defined many of PRAB's characteristic features. Since its very start PRAB has been an all-electronic scientific journal, a daring novelty in 1998 and acting as a testing ground for other PR journals. Equally unheard of, thanks to regular financial contributions from the institutional "sponsors," PRAB was made available free of charge to both authors and readers around the world. Thereby, it became a pioneering "diamond" open access journal, 10 or 20 years ahead of the time. These innovative and forward looking features of PRAB, combined with the expertise and competency of the APS Editorial Office, rapidly established the reputation as the world's premier journal in accelerators and beams.

Singular in the PR family of journals, PRAB would not be possible without the generous support of its sponsors, who recognize the importance of publishing in accelerator science and technology. Initially eight large U.S. National Laboratories supported the journal financially. After some transatlantic discussions in person and through media [32–35], CERN and DESY became the first European institutes to join PRAB as sponsors. Since then, the initial sponsors were complemented by many others — in the Americas, in Europe, and more recently in Asia, as well as by various accelerator conference series. The fact that PRAB had been one of the first open access journals was one of the key factors in attracting new sponsors. Three years ago, PRAB also welcomed its first industrial sponsors — several companies active in the fields of accelerator physics or accelerator technology. At present more than thirty-five institutes and eight companies sponsor PRAB. A list of all sponsors is available at `https://journals.aps.org/prab/sponsors`. Alas, the journal is still not fully self-sustained financially. Any

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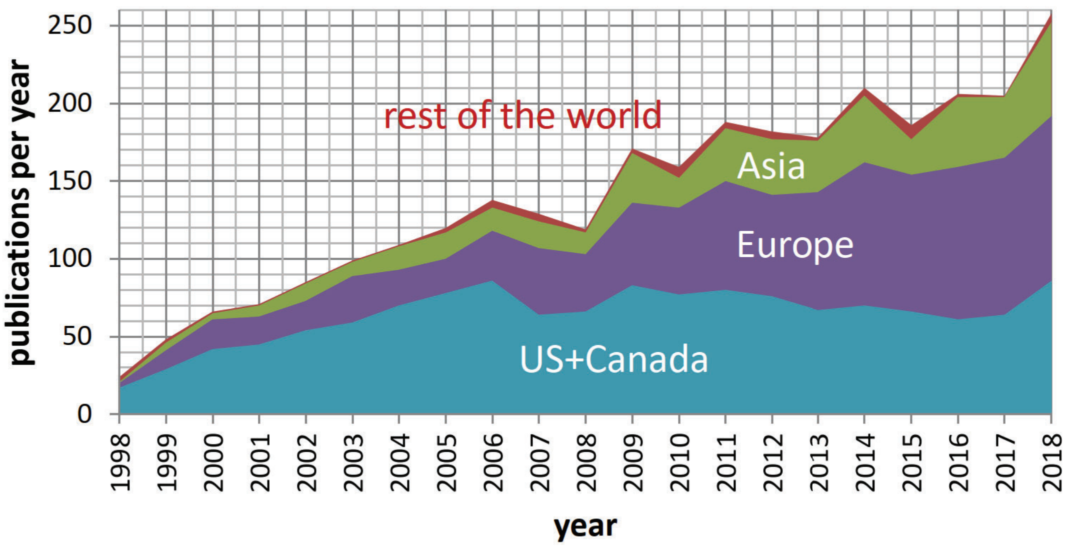

Figure 4: Number of PRAB publications versus year, separated by region.

deficit is gracefully covered by the APS. The effort of cultivating, maintaining and expanding the rows of sponsors remains a challenge.

Annual Meetings of the Editorial Board are scheduled during the International Particle Accelerator Conferences (IPACs). A few representatives from the sponsors are participating in these meetings. During the IPAC, the PRAB Editors also host a "Meet the Editors" reception for conference attendees interested in publication. In addition, PRAB always sponsors an APS booth at all IPACs and also at NAPACs. Recently introduced APS/PRAB breakfast tutorials for authors and referees, organized since 2018 during IPACs and NAPACs, have strongly resonated with the conference attendees, especially with students and younger colleagues.

Responding to another demand from the community, PRAB is presently publishing a special collection of articles reviewing user-facility accelerators [36]. M. Blaskiewicz from BNL is acting as the Special Editor of this collection. By definition, all accelerator-based experiments require an accelerator and other specialized components, like beam targets and beam lines. Yet often references to the relevant accelerator are missing, are out of date and/or do not include recent improvements and other relevant operating parameters. In an attempt to remedy this situation, the Editorial Board of PRAB and the APS DPB Publications Committee are jointly soliciting review articles describing the current state of user-facility accelerators, for publication in a PRAB special collection. Each user facility is encouraged to produce a document describing its machines and relevant systems. This will allow its users to give appropriate credit to the accelerator team which enabled the experiment to occur. In the future, regular articles describing upgrades and operational improvements are encouraged so that fresh up-to-date references will always be available.

CONCLUSIONS

The Future Circular Collider proposal offers an attractive strategy for optimizing the particle-physics output during the next 70 years. The first step, FCC-ee, is an "electroweak factory" which would operate, in stages, at centre-of-mass energies from 91 to 365 GeV. The second step is a highest-energy hadron collider, FCC-hh, based on the same tunnel and reusing the technical infrastructure of FCC-ee. The FCC-hh demands novel dipole magnets with a field of about 16 T. A comprehensive R&D effort is underway to develop the required high-performance superconductor and cost-effective prototype magnets over the next few decades. US teams are leading in both superconductor and magnet development.

Since more than 20 years, PRAB has been providing "diamond" open access publications, on the full spectrum of accelerator science and technology [37]. Through its monthly issues and special editions, invited contributions and Accelerator Prize articles, the careful review process, its informative web site, along with its receptions, tutorials, and Editorial Board meetings during the IPAC conferences, PRAB has become an important "Community Organizer," thereby realizing one of the intentions of its founding fathers. For the coming years, PRAB is looking forward to further transforming scientific publication in the field of accelerators.

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REFERENCES

[1] E. Keil, "Hadron colliders between 1 and 100 TeV beam energy," in *12th International Conference on High-Energy Accelerators*, Batavia, IL, USA, 11–16 Aug 1983, pp. 98; CERN-LEP-TH-83-39, 1983.

[2] A. Zichichi, "The Eloisatron Project: Eurasiatic Long Intersecting Storage Accelerator," in *4th INFN Eloisatron Project Workshop: New aspects of high-energy proton-proton collisions "Ettore Majorana"*, Erice, Italy, 31 May–7 Jun 1987, pp. 1–61, 1987.

[3] M. Tigner. P. Dahl, "The SSC status and outlook," in *12th IEEE Particle Accelerator Conference*, Washington, DC, USA, 16–19 Mar 1987, pp. 2003–2007, 1987.

[4] W.A. Barletta, "The design of hadron supercolliders of 200 TeV or more," LBL-34684, 1994.

[5] J.R. Ellis, E. Keil, G. Rolandi, "Options for future colliders at CERN," CERN-SL-98-004-AP, ERN-EP-98-003; CERN-TH-98-033, 1998.

[6] G. Ambrosio *et al.*, "Design study for a staged Very Large Hadron Collider," SLAC-R-591, FERMILAB-TM-2149, 2001.

[7] E. Todesco, F. Zimmermann (eds.), *Proceedings, EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider (HE-LHC10)*, Malta, Oct. 14–16, 2010, CERN-2011-003, 2011. arxiv.org/abs/1111.7188

[8] A. Blondel, F. Zimmermann, "A high luminosity e^+e^- collider in the LHC tunnel to study the Higgs Boson," CERN-OPEN-2011-047, 2011. arXiv.org/abs/1112.2518

[9] M. Mangano *et al.,* "FCC physics opportunities", *Eur. Phys. J. C,* vol. 79, no. 6, p. 474, 2019. doi.org/10.1140/epjc/s10052-019-6904-3

[10] M. Benedikt *et al.,* "FCC-ee: The lepton collider", *Eur. Phys. J. ST,* vol. 228, no. 2, pp. 261–623, 2019. doi.org/10.1140/epjst/e2019-900045-4

[11] M. Benedikt *et al.*, "FCC-hh: The hadron collider", *Eur. Phys. J. ST,* vol. 228, no. 4, pp. 755–1107, 2019. doi.org/10.1140/epjst/e2019-900087-0

[12] F. Zimmermann *et al.*, "HE-LHC: The High-Energy Large Hadron Collider", *Eur. Phys. J. ST,* vol. 228, no. 5, 1109–1382, 2019. doi.org/10.1140/epjst/e2019-900088-6

[13] M. Benedikt *et al.,* "Future Circular Colliders," *Ann. Rev. Nucl. Part. Science* vol. 69, 2019. doi.org/10.1146/annurev-nucl-101918-023748

[14] CEPC Study Group, "CEPC conceptual design report: volume 1 — accelerator," 2018. arxiv.org/abs/1809.00285

[15] K. Oide *et al.,* "Design of beam optics for the future circular collider e^+e^- collider rings," *Phys. Rev. Accel. Beams* 19, p. 111005, 2016.

[16] M. Zobov *et al.*, "Test of "crab-waist" collisions at the DAΦNE Φ factory," *Phys. Rev. Lett.,* vol. 104, p. 174801, 2010.

[17] E. Jensen, "Energy efficiency of HEP infrastructures," presented at *Open Symposium UESPP,* Granada, 2019. http://indico.cern.ch/event/808335/contributions/3365146/

[18] F. Zimmermann, "Luminosity limitations at hadron colliders," presented at *18th International Conference on High-energy Accelerators*, Tsukuba, Japan, 26–30 March 2001, pp.TU-08, and CERN-SL-2001-009-AP, 2001.

[19] M. Benedikt, D. Schulte, F. Zimmermann, "Optimizing integrated luminosity of future hadron colliders," *Phys. Rev. ST Accel. Beams* 18, 101002, 2015.

[20] M. Benedikt and F. Zimmermann, "Proton colliders at the Energy Frontier," *Nucl. Instrum. Methods Phys. Res., A* 907, 2018, pp. 200–208. doi.org/10.1016.j.nima.2018.03.021 and arxiv.org/abs/1803.09723.

[21] G. Apollinari *et al.*, "High-Luminosity Large Hadron Collider (HL-LHC): technical design report V. 0.1, " CERN-2017-007-M, 2017. doi.org/10.23731/CYRM-2017-004

[22] A. Zlobin *et al.*, "First measurements of magnet quench performance and field quality of the 15 T Nb3Sn dipole demonstrator MDPCT1," at *NAPAC2019*, Lansing, this conference, MOPL020.

[23] X. Xu *et al.*, "Achievement of FCC specification in critical current density for Nb_3Sn superconductors with artificial pinning centers", 2019. arxiv.org/abs/1903.08121

[24] S. Balachandran *et al.*, "Beneficial influence of Hf and Zr additions to Nb4at.%Ta on the vortex pinning of Nb_3Sn with and without an O source", 2019. arxiv.org/abs/1811.08867

[25] X. Xu, J. Rochester, M. Sumption, and J.-Y. Lee, "Flux pinning mechanism in Nb_3Sn conductors with artificial pinning centers," *CEC-ICMC 2019*, Connecticut (2019). indico.cern.ch/event/760666/contributions/3390792/

[26] E.F. Haussecker and A.W. Chao, "The influence of accelerator science on physics research," *Physics in Perspective,* vol. 13, no. 2, p. 146, 2011.

[27] R. Siemann, "Essay: Accelerators, Beams and Physical Review Special Topics–Accelerators and Beams," *Phys. Rev. ST Accel. Beams* vol. 11, p. 050003, 2008.

[28] APS-DPB, APS Division of Physics of Beams, www.aps.org/units/dpb/.

[29] J. Wenninger, "Operation and configuration of the LHC in Run 2", CERN-ACC-NOTE-2019-0007, 2019. cds.cern.ch/record/2668326

[30] M. Blume, "Bob Siemann and PRST-AB," *Phys. Rev. ST Accel. Beams,* vol. 11, p. 120012, 2008.

[31] EPS-AG, European Physical Society–Accelerator Group, www.eps.org/group/EPS-AG.

[32] K. Peach, "Join the open access revolution," *CERN Courier* vol. 45, no. 5, June 2005, p. 50, 2005.

[33] F. Zimmermann, "Open access in accelerator physics," *CERN Courier,* 18 July 2005, cerncourier.com/cws/article/cern/29385/6.

[34] M. Blume, "A question of sponsorship," *CERN Courier,* 18 July 2005.

[35] G.D. Sprouse and F. Zimmermann, "Funding open access," *Phys. World,* vol. 22 no. 03, p. 1, 2009.

[36] journals.aps.org/prab/speced/USER-ACCEL

[37] F. Zimmermann, "Physical Review Accelerators and Beams: open-access pioneer and community organizer," *APS News,* vol. 27, no. 4, 2018.