Charged-particle colliders have proven key instruments of discovery in high-energy physics. Pushing the frontiers of our knowledge ever further has relied on, and still keeps calling for, ever better performance and novel techniques. During more than four decades, Swapan Chattopadhyay has made numerous essential contributions to this endeavour. Often far ahead of his time, he helped advance many areas of collider development, notably in the domains of stochastic cooling, the development of asymmetric B factories, the design of next- and next-next-generation of high-energy colliders, and the harnessing of energy-recovery for particle colliders.

Keywords: High-energy colliders; stochastic cooling; B factories; energy recovery.

PACS numbers:

1. A Collider Century

Over the past 60 years, high-energy charged particle colliders have proven extremely efficient tools of discovery and precision physics. All the heavier elements of the Standard Model of particle physics were discovered (or co-discovered) at particle colliders: the charm quark and tau lepton at the SPEAR $e^+e^-$ collider, the gluon in $e^+e^-$ collisions at PETRA, the W and Z bosons in pp collisions at the SppS, the top quark at the pp collider Tevatron, and the Higgs boson in proton-proton collisions at the Large Hadron Collider. Also electron-proton collisions at HERA (parton distribution functions) and heavy ion collisions at both RHIC and the LHC contributed greatly to, e.g. to our understanding of quantum chromodynamics, the origin of nuclear spin, etc. Figure 1 presents the evolution of the centre-of-mass energies of both lepton and hadron colliders starting in the 1960s, with a tentative forecast featuring proposed future machines.

It is remarkable that Swapan Chattopadhyay made key contributions to basically all high-energy colliders from the 1980s onwards, and extrapolated till 2050,
as is illustrated in Fig. 2. Specifically: (1) he helped develop techniques of stochastic cooling and bunched beam stochastic cooling of antiprotons and heavy ions, which proved essential for the Sp"pS, Tevatron and RHIC; (2) he conceived the basic concepts underpinning the asymmetric $e^+e^-$ B factories, which enabled the successes of PEP-II, KEKB, and SuperKEKB, with dramatically higher luminosity than any previous machines; (3) he contributed essential elements to the research and development for highest energy hadron and lepton colliders, such LHC, HL-LHC, FCC, CLIC, ILC, muon colliders, $\gamma\gamma$ colliders, and plasma-based colliders; and (4) Swapan Chattopadhyay was the first to propose and promote the use of energy recovery for the Large Hadron electron Collider (LHeC) and variants thereof. The community has rarely witnessed so versatile an accelerator physicist, with activities covering all kinds of lepton and hadron colliders, including their injector chains, along with many far-future approaches.

2. Bunched-Beam Stochastic Cooling

Swapan Chattopadhyay belonged to a small group of pioneers who developed the theory of stochastic cooling.$^{3,4}$ In their historical review of stochastic beam cooling,
Fritz Caspers and Dieter Möhl noted: "Starting in 1981 S. Chattopadhyay (partly together with Bisognano) established the theory bringing to perfection earlier treatments."

On his own, and together with Daniel Boussard, Georges Dôme, and Trevor Lin necar, Swapan Chattopadhyay also studied the feasibility of bunched beam stochastic cooling was finally achieved at RHIC, leading to a five-fold increase in integrated RHIC luminosity, in collisions of uranium ions; see Fig. 3.

3. Optical Stochastic Cooling

Extending the concept of stochastic cooling to much higher frequencies and bandwidth gave rise to the idea of optical stochastic cooling (OSC), which Swapan helped to develop and attempted to demonstrate in the 1990s. With a few well-known co-authors, like Alexander Zholents and Max Zolotorev, he also proposed, and explored, the use of OSC for beam halo confinement at the VLHC, a future highest-energy hadron collider near Fermilab, then under consideration. OSC holds the promise to speed up beam cooling by four orders of magnitude compared to conventional stochastic cooling, thanks to its much larger bandwidth.
It is exciting that an OSC test has now been set up at FNAL’s IOTA facility,\textsuperscript{15} and that, here, with an electron beam, 3-dimensional OSC has been demonstrated for the first time in 2021\textsuperscript{16,17} (see Fig. 4) — almost 30 years after the initial proposals. This breakthrough opens up many intriguing possibilities.

Fig. 3. Schematic of the bunched beam stochastic cooling system at RHIC, consisting of “pickups” and “kickers” — and the fibre-optic and microwave links between these two; the 70 GHz microwave links for the longitudinal system are sent on received on the surface, while the fibre-optics links for transverse cooling are integrated in the tunnel\textsuperscript{9} (left); comparison of RHIC luminosity as a function of time in the store, without cooling (red), with only longitudinal cooling (brown), 2-D cooling (green), and 3-D cooling (blue).\textsuperscript{10}

4. Asymmetric B Factories

Swapan Chattopadhyay is one of the fathers of the highly successful asymmetric B factories, who contributed to developing this concept \textit{ab initio}.\textsuperscript{18,19} The luminosity performance rapidly achieved by the two B factories PEP-II at SLAC and KEKB at KEK more than validated the concept — see Fig. 5.

Fig. 4. OSC pick-up and kicker undulator installed at IOTA\textsuperscript{17} (left); evidence for OSC of an electron bunch in all three dimensions\textsuperscript{17} (right).
The successes of PEP-II and KEKB inspired an even more ambitious project, a Super B factory, SuperKEKB, presently under commissioning. SuperKEKB aims for still another factor 30–40 higher luminosity than KEKB, using a “nanobeam” or “crab-waist” collision scheme.

In 2020, a vertical beta function at the interaction point of \( \beta_y^* = 0.8 \) mm was achieved in both SuperKEKB rings, using a “virtual” crab-waist collision optics first developed for the FCC-ee. This \( \beta_y^* \) value is a world record. Figure 6 puts this value in perspective by comparing with previous \( e^+e^- \) colliders, with the design goal, and with proposed future colliders. On 23 December 2021, SuperKEKB also established a new world record for the peak luminosity of \( 3.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \).
5. Highest Energy Hadron and Lepton Colliders

It should come as no surprise that Swapan Chattopadhyay also contributed enormously to present and future highest-energy colliders, including LHC, HL-LHC, FCC, CLIC, ILC, muon colliders, $\gamma\gamma$ colliders, and plasma-based colliders.

Swapan Chattopadhyay wrote major parts of the conceptual design report (CDR) for the Superconducting Super Collider (SSC) from 1986.\footnote{SSC Conceptual Design Report, 1986} In particular, he developed an organizational structure and carried out a detailed cost estimate.

The present energy frontier is defined by the Large Hadron Collider (LHC) at CERN, a double ring of almost 27 km circumference (see Fig. 8, left picture), which since 2010 provides proton-proton collisions, at centre-of-mass energies that are approaching the design value of 14 TeV. The LHC including its luminosity upgrade HL-LHC is set to operate until about 2040. Farsightedly, as director of the Cockcroft Institute (CI), in 2008, Swapan Chattopadhyay concluded a comprehensive collaboration agreement with CERN (Fig. 8, right picture), cementing CI’s position and establishing the foundation for the UK’s subsequent leading role in the HL-LHC project.

Indeed, under Swapan Chattopadhyay’s directorship, in particular the CI assumed a prominent role in the LHC and Hi-Lumi LHC Upgrade, including leading the Collaboration Board, and carrying out pioneering developments of “crab cavities”, other RF R&D and multiple HL-LHC accelerator design efforts, e.g., on the machine detector interface. Figure 9 presents the HL-LHC time line as of 2020, and the HiLumi budget distribution, revealing that the largest share was attributed to the UK.
Following the HL-LHC the next energy frontier collider could be the Future Circular hadron Collider FCC-hh. Figure 10 shows the historical path of hadron colliders in the luminosity-energy plane. The step from the LHC to the FCC-hh will be as large as the step from the Tevatron to the LHC.

More specifically, the successful sequence of LEP and LHC, that will stretch over at least 65 years, has inspired the Future Circular Collider (FCC) “integrated program”, based on a three times larger tunnel and set to extend over 70–80 years. The latter offers a comprehensive long-term plan maximizing physics opportunities. Similar to LEP, the first stage is an electron-positron collider, FCC-ee, that will operate at four different energies, corresponding to the Z pole (at $10^5$ times the LEP luminosity), the W threshold, the Higgs (ZH) production peak, and the $t\bar{t}$ threshold, serving as a unique Higgs factory, electroweak & top factory at highest luminosities. In a second stage, the hadron collider FCC-hh, with a centre-of-mass energy of about 100 TeV, would provide the natural continuation at energy frontier, with heavy-ion and lepton-hadron collider options. FCC-ee and hh cover complementary physics, benefit from common civil engineering and technical infrastructures (see Fig. 11, both building on and reusing CERN’s existing installations. In addition, the FCC integrated project allows for a seamless continuation of High Energy Physics after the HL-LHC.
Swapan Chattopadhyay recognized the FCC merit and potential early on. Already in summer 2014, shortly after the FCC kick-off event, with the CI he joined the FCC collaboration; indeed, the CI was the first institute to enter this new collaboration (Fig. 12). Following the lead of the CI, about 150 other institutes from around the world equally joined the FCC effort (see Fig. 13).

6. Electron-Hadron Colliders: EIC and LHeC

Swapan Chattopadhyay was instrumental in the design of future electron-hadron colliders, such as the ELIC\textsuperscript{26} (an earlier, ERL-based version of the US Electron Ion Collider, now close to construction at BNL) and the LHeC at CERN\textsuperscript{27,28} see Fig. 14. These linac-ring type colliders based on a recirculating-electron linac can achieve significant luminosity, thanks to energy recovery. In particular, with
his experience from JLAB, Swapan Chattopadhyay brought the concept of energy recovery to the linac-ring LHeC design.\textsuperscript{27,28}

7. A Bird’s Eye View of Future Colliders

In addition to proposed high-energy electron-positron and hadron colliders, and lepton-hadron colliders, there are other types of future colliders, probably candidates for the next-next generation of colliders, such as muon colliders and colliders based on plasma acceleration.\textsuperscript{1} Figure 15, adapted from Ref.,\textsuperscript{1} illustrates approximate technically limited time lines of future large colliding-beam facilities for the next three decades based on the presentations by their proponents given and briefly discussed at the 2019 European Particle Physics Strategy Update Symposium.\textsuperscript{30}
and the European Strategy Update 2020 (ESU2020).

It is remarkable that Swapan Chattopadhyay has made essential contributions to all the various types of colliders, thereby laying a solid foundation for the future.

8. Recover the Energy!

The principle of energy recovery is shown in Fig. 16. Around 2002/2003 Swapan Chattopadhyay oversaw a pioneering experiment on the recirculating linear accelerator successfully, which demonstrated GeV scale energy recovery with a high ratio of accelerated-to-recovered energies (50:1).\(^{31}\)

Proposed future ERL-based lepton-hadron colliders at CERN include the LHeC and FCC-eh, where 50–60 GeV electrons from a racetrack-shape multi-turn ERL are collided with the 7 or 50 TeV protons of the LHC or future circular hadron collider.
Fig. 16. The principle of energy recovery\textsuperscript{32} (left); forward power required by a linac cavity with and without energy recovery as measured at the CEBAF experiment\textsuperscript{31} (right).

(FCC-hh), respectively. These are illustrated in Fig. 17. Aside from the ERL design, another common challenge for LHeC and FCC-eh is the interaction region, which must accommodate the two counterpropagating proton beams (colliding elsewhere around the LHC or FCC-hh rings), and the electron beam from the ERL. Figure 18 shows an example configuration for FCC-eh.

Fig. 17. Sketch of the 3-pass ERL layout for LHeC\textsuperscript{29} (left), and of the underground infrastructure for FCC-eh\textsuperscript{23} (right).

Fig. 18. Sketch of the 3-beam interaction region for FCC-eh.\textsuperscript{23}

\footnote{These are footnotes.}
ERL-based variants are also proposed for $e^+e^-$ colliders. An ERL-based upgrade option, or alternative, for the circular FCC-ee (see Fig. 19) promises higher luminosity and energy reach. ERL variants, like LERC\textsuperscript{33} and RELIC,\textsuperscript{34} are also being advocated for linear colliders. This would be in line with history as the very first proposals of linear colliders in the 1960s\textsuperscript{35} and 1970s\textsuperscript{36,37} were all based on energy recovery, and as, conversely, also the concept of energy recovery was first proposed with a linear collider in mind. For ERL-based linear colliders the accelerating and decelerating bunches should not collide. This could be achieved, for example, by introducing electrostatic separators\textsuperscript{38} or by use of a dual-axis linac.\textsuperscript{39}

![Luminosities for various options for high-energy $e^+e^-$ collider\textsuperscript{32,40} (left), and sketch of a possible layout of an ERL-based circular $e^+e^-$ collider with linacs separated by 1/6th of the 100 km circumference\textsuperscript{40} (right).](image)

Figure 19. Luminosities for various options for high-energy $e^+e^-$ collider\textsuperscript{32,40} (left), and sketch of a possible layout of an ERL-based circular $e^+e^-$ collider with linacs separated by 1/6th of the 100 km circumference\textsuperscript{40} (right).

Figure 20 illustrates the ERL landscape on a double-logarithmic scale and highlights the various ERL projects, to which Swapan Chattopadhyay made significant contributions in the various phases of his long career.

9. Neutrino Factories and Muons Colliders

At the same beam energy, muons bent in a circle lose $1.6 \times 10^9$ times less energy from synchrotron radiation than electrons or positrons. Also the beamstrahlung emitted during the collision is dramatically reduced. Swapan Chattopadhyay took an early interest in muon colliders and analyzed the critical issues.\textsuperscript{42}

Though muons radiate less, there are other challenges. The muons are unstable and decay within a few 100s to 1000s of turns. This requires rapid acceleration — perhaps plasma acceleration could be an option, since gradients are extremely high, and the muons typically of rather low intensity.

Another issue is the neutrino radiation hazard caused by the muon decay,\textsuperscript{43} which may limit the maximum muon energy attainable on earth to about 10 TeV or at most a few 10s of TeV. The cross section of neutrinos interacting with matter increases linearly with energy, and the maximum neutrino flux roughly with the square of the energy due to the Lorentz boost.
Several production schemes for muons are proposed. The first is proton-beam driven: Protons hitting a target generate pions, which decay into muons. In this scheme, developed by the US-MAP collaboration,\textsuperscript{44} the muon beams are generated with large emittance. For a collider the muon beam must, therefore, be cooled, and its 6D emittance be reduced — and rapidly — by six to eight orders of magnitude. The innovative technique of ionization cooling is proposed for this purpose. Ionization cooling was first demonstrated by the UK’s MICE experiment.

Another, more recently suggested production scheme, called LEMMA,\textsuperscript{45,46} is based on positrons at an energy of about 45 GeV, which annihilate with electrons at rest into muon pairs. For reasons of energy efficiency, this requires a large 45 GeV $e^+$ ring, like the full-energy booster of the FCC-ee, and offers a possible upgrade path to FCC-$\mu\mu$,\textsuperscript{47,48} which becomes most powerful if combined with the Gamma Factory concept\textsuperscript{49} to realize a highly-intense positron source.

In 1993, Swapan Chattopadhyay and co-workers considered yet another scheme of muon generation, namely photoproduction from a primary 60 GeV electron beam hitting a target, based on a proposal by W.A. Barletta and A.M. Sessler.\textsuperscript{50}

An intermediate step towards a muon collider could be a neutrino factory, e.g.\textsuperscript{51,52} Figure 21 shows a photograph from the $\nu$Fact’99 workshop lunch in Lyon, with Swapan Chattopadhyay surrounded by KEK and CERN experts.

10. Plasma and Crystal Colliders
Higher accelerating gradients than in conventional accelerators can be sustained in plasmas. Accelerating plasma waves can be excited either by a high-energy charged particle beam (beam-driven plasma wake field acceleration — PWFA) or by a high-power laser (laser-driven plasma wake field acceleration — LWFA). Detailed scenar-
ios have been developed for electron-positron colliders based on either PWFA\textsuperscript{53,54} or LWFA.\textsuperscript{55,56} Key parameters are rather similar for the two approaches, with plasma electron densities between $2 \times 10^{16}$ cm$^{-3}$ and $10^{17}$ cm$^{-3}$, energy gains per stage between 5 and 25 GeV, and geometric gradients of 1 to 2.3 GV/m. For e$^+$e$^-$ collider applications, it is necessary not only to accelerate electrons but also positrons, and to do so without unacceptable beam quality degradation. This is a major outstanding question and an active area of research. As a possible solution, for the case of LWFA, more complex schemes with multiple driving laser are being developed. An example is shown in Fig. 22.\textsuperscript{57}

Even much higher gradients still are possible in crystals. The maximum field is given by\textsuperscript{58}

$$E_0 \approx \frac{m_e c \omega_p}{e} \approx 100 \left[ \frac{\text{GeV}}{\text{m}} \right] \sqrt{n_0[10^{18} \text{ cm}^{-3}]},$$

with $\omega_p$ the angular plasma frequency and $n_0$ the electron density. With electron densities of order $n_0 \approx 10^{22}$ cm$^{-3}$ to $5 \times 10^{24}$ cm$^{-3}$ in a crystal, peak gradients of 10–1000 TV/m would be within reach.

Accelerating fields in a crystal waves could be excited by drivers with adequate wavelength, that is not by conventional lasers, but rather by X-ray lasers.\textsuperscript{58}

The recently developed thin film compression technique\textsuperscript{59} provides an economic path to generating single cycle coherent X-ray pulses and, thereby, to TV/cm acceleration at solid state densities. The concept of a far future X-ray driven crystal
Fig. 22. Schematic of positron ballistic injection scheme with two lasers. The blue and green colors are contour surfaces of electron densities for the “donut” and center “bubbles”, respectively. The red color represents injected positrons. For more details see Ref.57.

collider is illustrated in Fig. 23.

Fig. 23. Concept of a linear X-ray crystal muon collider (V. Shiltsev).60

11. Towards the Skies

The ultimate limit on electromagnetic acceleration in vacuum is given by the Schwinger critical field $E_{cr} \approx 10^{12}$ MV/m, or equivalently $B_{cr} \approx 4.4 \times 10^9$ T, at which the QED vacuum breaks down. To reach the Planck scale of $10^{28}$ eV, linear or circular colliders would need to have a size of order $10^{19}$ m, if operated close to the critical field.61,62 Such colliders are illustrated in Fig. 24. This prospect was
examined already in the 1990s and judged to be “not an inconceivable task for an advanced technological society”. Following the FCC a possible next or next-next step in this direction could be a circular collider on the moo

Fig. 24. Circular and linear Planck scale colliders operating at the Schwinger critical field comfortably fit into the solar system.$^{61, 62}$

12. Epilogue

During the past 40 years, the collider progress was stunning, as could be testified by the participants of ICFA Nanobeam workshop 2005 and the Slava Derbenev Symposium 2010 (see Fig. 25).

Fig. 25. Swapan Chattopadhyay lecturing at the ICFA Nanobeam workshop in Kyoto, Japan, 2005 (left); Frank Zimmermann, Anatoly Kondratenko, Mei Bai, and Swapan Chattopadhyay during the 70th anniversary symposium for Slava Derbenev, in Newport News, 2010 (right).

Thanks to eminent colleagues like Swapan Chattopadhyay, we are also well prepared for times ahead — thank you, Swapan, and my warmest wishes for the future!
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