Eur. Phys. J. Plus (2023) 138:12
https://doi.org/10.1140/epjp/s13360-022-03620-8

THE EUROPEAN PHYSICAL JOURNAL PLUS

Editorial

Focus point on high-energy accelerators: advances, challenges, and applications

R. B. Appleby[1], **A. Bazzani**[2], **M. Giovannozzi**[3,a], **E. Levichev**[4]

[1] The University of Manchester and the Cockcroft Institute, Daresbury Laboratory, Warrington, UK
[2] Dipartimento di Fisica e Astronomia, Università di Bologna and INFN Bologna, via Irnerio 46, Bologna, Italy
[3] Beams Department, CERN, Esplanade des Particules 1, 1211 Meyrin, Switzerland
[4] Budker Institute of Nuclear Physics, Novosibirsk, Russia

Particle accelerators are unique scientific tools that offer unrivalled energy per constituent of their charged particle beams compared to sources normally available in laboratories. Focused high-density beams of electrons, positrons, protons, antiprotons, ions, and other elementary particles are used. Since the early twentieth century, accelerators have been widely applied to physics research, and great progress in science and technology has been driven by the development of more and more powerful accelerators needed for fundamental physics research [1].

Circular accelerators, and specifically colliders, occupy a special place [2, 3] among particle accelerator facilities. These innovative scientific tools allowed fundamental advances in scientific discoveries in high-energy physics. Collider technology and beam physics have advanced greatly, and modern facilities are now operating with energy and luminosity of several orders of magnitude higher than those of pioneer colliders in the early 1960s.

Analysis of all Nobel Prize-winning physics research since 1939 [4] reveals that accelerators have played an integral role in influencing more than a quarter of physics prize recipients by either inspiring them or facilitating their research. Moreover, accelerators have contributed on average to one Nobel Prize in physics per three years [5], and four Nobel Prizes directly recognised breakthroughs in accelerator science and technology. Physics, however, is not the only domain of science to profit from the use of particle accelerators. Notably, synchrotron radiation sources based on accelerators have recently been instrumental in a number of Nobel Prize-winning research achievements in chemistry and biology. Nuclear physics is another field that has benefited from the progress made by particle accelerators [6].

According to recent data [7], currently about 140 accelerators of all types are devoted to fundamental research, while in 2012 the EU's TIARA project identified 125 European public sector accelerator infrastructures in 12 countries (Austria, Denmark, Finland, France, Germany, Italy, Poland, Slovenia, Spain, Sweden, Switzerland, and the UK).

Accelerator applications are particularly notable in medicine [8, 9] and industry in general [10–12].

Beyond the key role of particle accelerators as powerful instruments that is generally well known and unanimously accepted, they themselves represent an incredible source of exciting physical problems stemming from the dynamics of the charged particles that travel inside these devices. By restricting to the broad class of circular accelerators, it is nowadays fully recognised that the challenges posed by the analysis of the stability of particle beams are equivalent to those considered in Celestial Mechanics. This issue has become more relevant with the advent of superconducting accelerators, where unavoidable multipolar field errors in the main magnets make the beam dynamics intrinsically nonlinear. This has opened up the possibility of cross-fertilisation between accelerator physics and the vast and well-established field of nonlinear dynamical systems, and nonlinear physics became a fundamental background of an accelerator physicist. A circular accelerator with high-quality beam instrumentation, controllable nonlinearities, changeable tunes, etc. is an excellent tool not only for high-energy physics but also for dynamical studies (chaotic and regular motion, dynamic systems stability, etc.).

These general considerations led us to undertake the enterprise represented by this Focus Point, whose goal is to showcase a selection of topics related to advances, challenges, and applications of high-energy accelerator physics. The excellent contributions included in this Focus Point testify to the vitality and diversity of scientific problems that emerge from the analysis of beam dynamics. They all indicate clearly that particle accelerators are by far not mere tools for scientific experiments. In this respect, it is our hope that accelerator physics will find its appropriate way in academia in the next future.

Indeed, it is a common observation that accelerator physics is not taught in the physics departments and it is not part of the typical curriculum for master's degree in physics. Some exceptions to this rule are when a laboratory housing an accelerator is located in the vicinity of a university. It is hoped that this situation may change in the future, with a more generalised teaching of accelerator physics, particularly the more advanced aspects, such as nonlinear dynamics, collective effects, etc. It would be a great pleasure if this Focus Point could become an incentive to make some progress in this direction!

[a] e-mail: Massimo.Giovannozzi@cern.ch (corresponding author)

Published online: 09 January 2023

Contributions to this issue represent and attempt to cover a broad domain of topics in beam physics, with a loose classification into three categories of advances, challenges, and applications. References [13–21] provide a global overview of the applications of advanced beam dynamics concepts to existing or future machines. The nonlinear beam dynamics combined with the use of electron lenses has been considered in the framework of the High-Luminosity LHC Project and discussed in [21]. Various techniques devised to measure the available beam aperture in the LHC, which contributed to the astonishing performance reached during Run 2, are presented in [20]. A combined-function optics has been proposed as an alternative to the standard separate approach paradigm for high-energy colliders [19] with the goal of increasing the dipole filling factor. Machine learning entered accelerator physics, and applications to measurements of optical parameters at the LHC are reported in [18]. An interesting application to future muon colliders of a special optics concept based on skew quadrupoles is considered in [17]. The considerations of beamstrahlung effects [16] and the interplay between beam–beam interaction and impedance effects [13] are made in the framework of the Future Circular Lepton Collider. It should not be forgotten that the CERN LHC is also an ion collider, and its performance in this peculiar operation mode, together with the analysis of luminosity models, has been studied in [15]. Finally, the peculiar crab waist collision scheme successfully implemented in SuperKEKB is reviewed in [14].

The selected challenges are discussed in the contributions [22–25]. The quest for even more powerful accelerators brings beam dynamics towards limits imposed by collective effects and the related instabilities. Mitigation measures are essential to ensure the achievement of nominal performance, and a review of this topic is given in [22], while in [23] the space charge is the main phenomenon under consideration. The LHC has also shown the importance of controlling nonlinear effects due to magnetic field errors and the so-called electron cloud phenomenon. These two crucial aspects for the optimal operation of the LHC are discussed in [25] and [24], respectively.

Finally, a selection of papers discussing future advances is given in [26–29]. The use of nonlinear beam dynamics to extend the domain of possible beam manipulations is discussed in [26, 28], where resonances are used as a means to provide an alternative transition-crossing scheme [26]or to manipulate transverse emittances [28]. The Vlasov description of collective effects in circular accelerators is described in detail in [27] and, last, a novel diffusive model to describe the beam halo dynamics is presented in [29] with the focus on the determination of effective techniques to reconstruct the functional form of the diffusion coefficient with the longer-term goal of estimating the beam lifetime.

References

1. A.W. Chao, W.-R. Chou, editors. Rev. Accel. Sci. Tech.: Vol. 1: Overview of Accelerator Science and Technology. World Scientific, Hackensack, USA, (2009)
2. A.W. Chao, W.-R. Chou, editors. Rev. Accel. Sci. Tech.: Vol. 7: Colliders. World Scientific, Hackensack, USA, (2014)
3. V. Shiltsev, F. Zimmermann, Modern and future colliders. Rev. Mod. Phys. **93**, 015006 (2021)
4. Nobel Foundation. https://www.nobelprize.org/prizes/physics/. Accessed: 2022-11-18
5. E.F. Haussecker, A.W. Chao, The influence of accelerator science on physics research. Phys. Perspect. **13**(2), 146 (2011)
6. S. Nagamiya, H. En'yo, H. Tamura, Future possibilities for accelerators in nuclear physics. Rev. Accel. Sci. Technol. **10**(01), 13–32 (2019)
7. ELSA Working Group. http://www-elsa.physik.uni-bonn.de/accelerator_list.html. Accessed: 2022-11-18
8. A.W. Chao, W.-R. Chou, editors. Rev. Accel. Sci. Tech.: Vol. 2: Medical Applications of Accelerators. World Scientific, Hackensack, USA, (2009)
9. S. Myers, A. Degiovanni, J.B. Farr, Future prospects for particle therapy accelerators. Rev. Accel. Sci. Tech. **10**(01), 49–92 (2019)
10. A.W. Chao, W.-R. Chou, editors. Rev. Accel. Sci. Tech.: Vol. 4: Accelerator Applications in Industry and The environment. World Scientific, Hackensack, USA, (2011)
11. A.W. Chao, W.-R. Chou, editors. Rev. Accel. Sci. Tech.: Vol. 8: Accelerator Applications in Energy and Security. World Scientific, Hackensack, USA, (2015)
12. B.L. Doyle, F. McDaniel, R.W. Hamm, The future of industrial accelerators and applications. Rev. Accel. Sci. Technol. **10**(01), 93–116 (2019)
13. M. Migliorati, E. Carideo, D. De Arcangelis, Y. Zhang, M. Zobov, An interplay between beam-beam and beam coupling impedance effects in the future circular e^+e^- collider. Eur. Phys. J. Plus **136**(11), 1190 (2021)
14. Y. Ohnishi, T. Abe, K. Akai, Y. Arimoto, K. Egawa, S. Enomoto, H. Fukuma, Y. Funakoshi, K. Furukawa, N. Iida, H. Ikeda, T. Ishibashi, S. Iwabuchi, H. Kaji, T. Kamitani, T. Kawamoto, M. Kikuchi, T. Kobayashi, K. Kodama, H. Koiso, M. Masuzawa, T. Mimashi, G. Mitsuka, F. Miyahara, T. Miyajima, T. Mori, A. Morita, S. Nakamura, T. Nakamura, K. Nakanishi, M. Nishiwaki, S. Ogasawara, K. Ohmi, N. Ohuchi, K. Oide, T. Oki, M.A. Rehman, Y. Seimiya, K. Shibata, Y. Suetsugu, H. Sugimoto, H. Sugimura, M. Tawada, S. Terui, M. Tobiyama, R. Ueki, X. Wang, K. Watanabe, R. Yang, S. Yoshimoto, T. Yoshimoto, D. Zhou, X. Zhou, Z. Zong, SuperKEKB operation using crab waist collision scheme. Eur. Phys. J. Plus **136**(10), 1023 (2021)
15. R. Bruce, M.A. Jebramcik, J.M. Jowett, T. Mertens, M. Schaumann, Performance and luminosity models for heavy-ion operation at the CERN Large Hadron Collider. Eur. Phys. J. Plus **136**(7), 745 (2021)
16. M.A. Valdivia Garcia, F. Zimmermann, Beam blow up due to beamstrahlung in circular e^+e^- colliders. Eur. Phys. J. Plus **136**(5), 501 (2021)
17. S. Machida, Circular accelerator lattices with skew quadrupoles. Eur. Phys. J. Plus **137**(4), 489 (2022)
18. E. Fol, R. Tomás, G. Franchetti, Supervised learning-based reconstruction of magnet errors in circular accelerators. Eur. Phys. J. Plus **136**(4), 365 (2021)
19. M. Giovannozzi, E. Todesco, Combined-function optics for circular high-energy hadron colliders. Eur. Phys. J. Plus **137**(3), 361 (2022)
20. N. Fuster-Martínez, R.W. Aßmann, R. Bruce, M. Giovannozzi, P. Hermes, A. Mereghetti, D. Mirarchi, S. Redaelli, J. Wenninger, Beam-based aperture measurements with movable collimator jaws as performance booster of the CERN Large Hadron Collider. Eur. Phys. J Plus **137**(3), 305 (2022)
21. D. Mirarchi, R.B. Appleby, R. Bruce, M. Giovannozzi, A. Mereghetti, S. Redaelli, G. Stancari, Nonlinear dynamics of proton beams with hollow electron lens in the CERN high-luminosity LHC. Eur. Phys. J. Plus **137**(1), 7 (2021)
22. E. Métral, General mitigation techniques for coherent beam instabilities in particle accelerators. Eur. Phys. J. Plus **137**(1), 47 (2021)
23. A. Burov, Space charge effects for collective instabilities in circular machines. Eur. Phys. J. Plus **137**(5), 624 (2022)
24. G. Skripka, G. Iadarola, L. Mether, G. Rumolo, Non-monotonic dependence of heat loads induced by electron cloud on bunch population at the LHC. Eur. Phys. J. Plus **137**(7), 849 (2022)

25. E.H. Maclean, F.S. Carlier, J. Dilly, M. Le Garrec, M. Giovannozzi, R. Tomás, Prospects for beam-based study of dodecapole nonlinearities in the cern high-luminosity large hadron collider. Eur. Phys. J. Plus **137**(11), 1249 (2022)
26. M. Giovannozzi, L. Huang, A. Huschauer, A. Franchi, A novel non-adiabatic approach to transition crossing in a circular hadron accelerator. Eur. Phys. J. Plus **136**(11), 1189 (2021)
27. S.V. Furuseth, X. Buffat, Vlasov description of the beam response to noise in the presence of wakefields in high-energy synchrotrons: beam transfer function, diffusion, and loss of Landau damping. Eur. Phys. J. Plus **137**(4), 506 (2022)
28. A. Bazzani, F. Capoani, M. Giovannozzi, Manipulation of transverse emittances in circular accelerators by crossing nonlinear 2D resonances. Eur. Phys. J. Plus **137**(5), 594 (2022)
29. C.E. Montanari, A. Bazzani, M. Giovannozzi, Probing the diffusive behaviour of beam-halo dynamics in circular accelerators. Eur. Phys. J. Plus **137**(11), 1264 (2022)